SECTION III

TITLE PAGE OF PUBLISHED PAPERS

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Failure of the Allowed Assumption in the ϵ/β^+ Decays of ^{145g}Gd and ^{143g}Sm—Experimental Evidence for Interference Effects in Nuclear β Decay

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Anomalous ϵ/β^+ decay branching ratios for "hindered allowed" transitions (measured by $\gamma^{\pm}$-γ and x-γ coincidence techniques) have been found in $^{145g}\mathrm{Gd} \rightarrow {}^{145}\mathrm{Eu}$(808.5-keV state) and $^{143g}\mathrm{Sm} \rightarrow {}^{143}\mathrm{Pm}$(1173.2-keV state). These ratios exceed theoretical predictions by factors of 24 and 5, respectively. Thirteen additional ratios from these nuclei and ^{143}Eu agree with the predictions. This is the first conclusive evidence of the failure of the allowed assumption in nuclear β decay and of the presence of interference effects.

Numerous past measurements of ϵ/β^+ (electron-capture to positron) decay branching ratios[1-4] tend to support modern β-decay and weak-interaction theory. These measurements generally involved simple, fast allowed transitions and were quite difficult to perform inasmuch as only very small deviations from the theoretically predicted ratios were involved and are difficult to detect. With the discovery of parity nonconservation and the success of the universal $V-A$ interaction, most of the interest in measuring these ratios disappeared, and in recent years only a few additional values have been measured. Studies on ^{145g}Gd decay in this laboratory[5] indicated an anomalous branching ratio involving a highly hindered allowed transition. In this work we study this transition more thoroughly and report a similar anomaly in ^{143g}Sm decay. We then discuss some of the ramifications of our findings.

All activities discussed here were prepared with beams from the Michigan State University sector-focused cyclotron. ^{145g}Gd ($t_{1/2}=22.9$ min) was prepared by the reaction ^{144}Sm(^{3}He, $2n$) using a 20-MeV ^{3}He beam on a target enriched to 95.10% in ^{144}Sm. ^{143}Eu ($t_{1/2}=2.6$ min) was produced by ^{144}Sm(p, $2n$) using a 28-MeV p beam on similar targets, and its daughter ^{143g}Sm ($t_{1/2}=8.83$ min) was studied along with it.

The relative β^+ feedings were measured by the $\gamma^{\pm}$-γ triple coincidence method described by Kelly and co-workers.[6] Briefly, the two halves of an 8×8-in. NaI(Tl) split annulus were gated on the 511-keV $\gamma^{\pm}$ radiation indicative of a β^+ event and a third γ-ray coincidence was sought in a large Ge(Li) detector inside the annulus tunnel. A resolving time of 50 nsec and the triple-coincidence requirement made chance events very rate. The relative β^+ feedings to each level were inferred from the coincident γ-ray spectrum after correcting for γ-ray feeding from higher-lying levels. The high efficiency of the annulus (60% at 511 keV) caused significant chance summing of annihilation quanta with γ rays in coincidence with those detected in the Ge(Li) detector, so only levels de-exciting primarily through a single direct ground-state transition could be studied. Fortunately, the nuclei discussed here decay predominantly to levels de-exciting directly to the ground states.

Relative ϵ feedings were measured by an x-γ coincidence experiment. A 5-mm-thick planar Ge(Li) detector with 550-eV resolution at 122 keV

Discovery of the Missing Two-Particle, Two-Hole 0^+ States in ^{40}Ca

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A good-resolution study of the reaction ^{42}Ca$(p,t)^{40}$Ca has revealed the existence of three new 0^+ states in ^{40}Ca at 7698, 8284, and 8438 keV excitation. Arguments are presented to show that these states are indeed the long sought-after 0^+, $T=0$ states with predominantly two-particle, two-hole configurations.

Ever since Gerace and Green[1] identified the $0_2{}^+$ state at 3353 keV in ^{40}Ca as being predominantly four-particle, four-hole (4p-4h) in nature, the most intriguing and challenging question in the spectroscopy of ^{40}Ca has been that relating to the crucially important 0^+ states of the 2p-2h, $T=0$ configuration which have been predicted to lie between 7- and 9-MeV excitation,[1-3] but which have eluded experimental identification so far.[4] In the earlier studies of the reaction ^{42}Ca$(p,t)^{40}$Ca,[4-8] $L=0$ transitions could only be identified to the ground state (g.s.) $0_1{}^+$, the 3353-keV $0_2{}^+$ state, and the 0^+ states with $T=1$ and $T=2$ at about 9.4 and 12.0 MeV, respectively. Further, while the 2p-2h 0^+ states in the 7–9-MeV excitation region were not found, it was noted that the so-called 4p-4h $0_2{}^+$ state at 3353 keV is populated about an order of magnitude more strongly than expected. These observations have led[6-8] to the speculation that perhaps the main part of the 2p-2h, 0^+

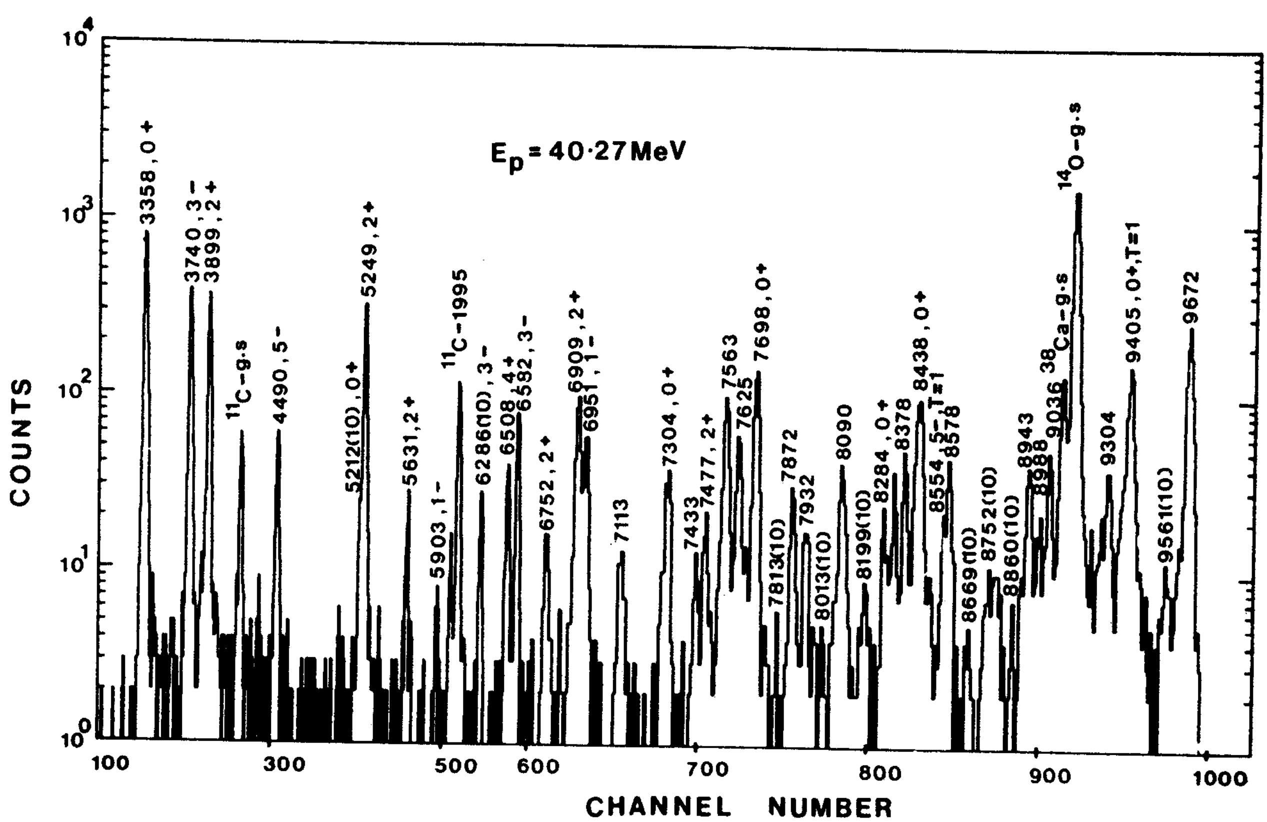

FIG. 1. Spectrum at θ(lab) = 6° for the reaction ^{42}Ca$(p,t)^{40}$Ca. The g.s. transition is not displayed. Excitation energies (in keV) are from the present experiment. Errors are ±5 keV unless otherwise specified. The abscissa has been expanded by a factor of 2 beyond channel number 600.

Hexadecapole Deformations in W and Os Nuclei from Perturbed Rotational Band Structure*

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The spectroscopic data for even-parity rotational and intrinsic states in ^{181}W and ^{187}Os are shown to be incompatible with very large static nuclear hexadecapole deformations ($\epsilon_4 \cong 0.2$) implied by conventional analysis of recent Coulomb excitation measurements of $E4$ transition moments in ^{182}W and ^{186,188}Os.

In recent months, at least two groups have reported measuring very large electric hexadecapole transition moments for nuclei in the W-Os region.[1,2] These results are based on Coulomb excitation measurements carried out with α particles. For the case of ^{182}W, the Oak Ridge National Laboratory data[1] imply static nuclear hexadecapole deformations that appear to be in serious disagreement with the nuclear charge distribution derived from the muonic x-ray data of Davidson *et al.*,[3] and in substantial disagreement with the nuclear inelastic scattering result of Hendrie.[4] The data for the osmium isotopes 186, 188, and 190 are presently only from sub-Coulomb measurements, but large $E4$ moments appear to be experimentally established in this region as well.[2] While it is possible that the discrepancy between Coulomb and nuclear measurements of the nuclear shape may be due to a real difference in the proton and neutron mass distribution, the discrepancy between Coulomb excitation and muonic x-ray data for ^{182}W is not so easily dispatched.

The implication of large values of the nuclear hexadecapole deformation for interpreting (d, t) and $(^3\text{He}, \alpha)$ transfer-reaction cross sections for populating states in ^{181}W and ^{183}W has been dealt with by Casten in a recent Letter.[5] Casten finds that the unusual $l = 6$ cross-section patterns can be explained by a wide range of ϵ_4 values, and he concludes that the data are not inconsistent with hexadecapole deformations as large as $\epsilon_4 = 0.16$, well within the limits of error ($\beta_4 = -0.19 \pm 0.06$) quoted by Bemis *et al.*[1] for ^{182}W. (In this region, $\epsilon_4 \cong -\beta_4$.) However, reaction strengths into rotational bands based on the various Ω states of the relatively pure $i_{13/2}$ Nilsson manifold are dominated by transfer to spin-$\frac{13}{2}$ band members. Since other members of the bands are populated very weakly or not at all, it is not possible to set definite limits on the hexadecapole deformation from the $l = 6$ transfer data alone, because the projection quantum numbers Ω cannot be assigned.

In addition to the transfer-reaction data, there has also recently accumulated a substantial quantity of data on the so-called parity-unique $i_{13/2}$ rotational band structure in the odd-A W and Os isotopes. In this note, we show that the experimental data on even-parity rotational and intrinsic states in ^{181}W and ^{187}Os are consistent only with the smaller hexadecapole deformations ($\epsilon_4 \cong 0.06$) predicted by Nilsson *et al.*[6] and deduced by Hendrie[4] ($\epsilon_2 \cong 0.23$, $\epsilon_4 \cong 0.08$) from nuclear inelastic scattering on ^{182}W.

The primary data for this consideration are those derived from $(\alpha, 3n\gamma)$ reactions on targets of ^{180}Hf and ^{186}W. Both targets in these experiments were self-supporting metal foils prepared at the Niels Bohr Institute.[7] Details of these experiments will be published elsewhere. For the purposes of this Letter, we show in Fig. 1 the even-parity states presumed to be associated with the $i_{13/2}$ intrinsic structure in ^{181}W and ^{187}Os. Even-parity levels known in addition to those identified in the $(\alpha, 3n\gamma)$ experiments are also shown. The levels shown for ^{181}W are in agreement with similar results recently published by Lindblad, Ryde, and Kleinheinz.[12]

The procedure used to fit rotational band structure in deformed odd-A nuclei is by now standard and reasonably well understood. The core moment of inertia is assumed to be approximately the average of the neighboring even-even nuclei, and a variable moment of inertia may be introduced by including the second-order B term in the rotational energy expression.[13]

In our calculations, the diagonal quasiparticle energies are determined by selecting appropriate values for the Fermi energy λ, and for the gap parameter Δ, based on the best empirical data available for single-particle states and odd-even mass differences.[6,14] The enigmatic, but well-documented, reduction factors required for the off-diagonal matrix elements near the Fermi sur-

Decoupled $i_{13/2}$ Neutrons and Backbending in W and Os Isotopes

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Analysis of rotational band structure in odd-N deformed rare-earth nuclei shows that if rotation-particle decoupling is the correct explanation for backbending in the region $N = 92-96$, then it can also explain the phenomenon in ^{180}W and ^{182,184,186}Os.

The discovery in 1972 of the so-called "backbending" effect[1] in the *yrast* band structure of even-even rare-earth nuclei prompted an initial interpretation that the data confirmed the breakdown of nuclear superfluidity at high spins, an effect proposed ten years earlier by Mottelson and Valatin.[2] More recently, however, Stephens and Simon[3] (SS) proposed that the observed effect could be explained in a much simpler, albeit related, way as arising from the recoupling of a single pair of $i_{13/2}$ neutrons in a "rotation-aligned" coupling scheme.

Subsequent experimental data, especially those obtained in the odd-A neighbors of the "backbending" nuclei, have for the most part tended to support the SS model. If indeed the $i_{13/2}$ neutrons

Complete Isobaric Quintet*

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By experimental observation of the lowest $T=2$ states in ^8B and ^8Li, an isobaric quintet has been completed for the first time. The $T=2$ state in ^8B, populated via the reaction $^{11}B(^3He,^6He)^8B$, lies at 10.619 ± 0.009 MeV excitation, and its analog in ^8Li, found in $^{10}Be(p,^3He)^8Li$, lies at 10.8222 ± 0.0055 MeV. The excitation of the previously known $T=2$ state in ^8Be was measured by $^{10}Be(p,t)^8Be$ to be 27.4922 ± 0.0027 MeV. A significant departure from the isobaric-multiplet mass equation is indicated.

Until recently no more than three members of any isobaric quintet ($T=2$ multiplet) were known, because $T=2$ states had not been observed in nuclei with a proton excess. However with the observation[1] of the $T_z=-2$ nuclides ^8C and ^{20}Mg, prospects for completing a quintet have been much improved. The isobaric-multiplet mass equation (IMME), which predicts that the mass excesses ΔM of analog states should be described by a three-parameter quadratic equation

$$\Delta M = a + bT_z + cT_z^2,$$

has been shown to apply to a high degree of precision in a large number of isobaric quartets ($T=\frac{3}{2}$). Nevertheless, when sufficient experimental accuracy can be brought to bear, deviations become apparent which substantially exceed the small theoretical corrections arising from known effects.[2,3] If we represent the deviations by additional terms, dT_z^3, eT_z^4, etc., two such terms can be determined in a quintet, but only one in a quartet. One might hope, therefore, by completing a quintet to test the IMME more rigorously, and, in the event of a violation, to gain some insight into the mechanisms causing it. In particular, the explicit nature of many-body charge-dependent forces could be tested in a quintet. We wish to report the identification and precise mass measurements of the lowest $T=2$ states in ^8B, ^8Be, and ^8Li, which, with the known masses of ^8C [1] and ^8He,[4-6] form a complete isobaric quintet.

Although it has long been recognized that the (^3He, ^6He) reaction could in principle be employed to reach $T=2$ states in $T_z=-1$ nuclei by an isospin-allowed process, in practice the reaction also unselectively populates $T=1$ states in the same region of excitation. For this reason, it might be expected that the most favorable case would be a very light nucleus where the $T=1$ states (which can decay by isospin-allowed nucleon emission) would be so broad that a sharp $T=2$ state would stand out clearly on a continuum of $T=1$ states. Our experiments on $^{11}B(^3He,^6He)^8B$ show that this is indeed the case.

Beams of 72-MeV ^3He ions from the Michigan State University cyclotron impinged on targets enriched to 97.2% in ^{11}B. Emergent ^6He particles were analyzed in an Enge split-pole spectrograph and detected with a position-sensitive propor-

COMMENTS

Absolute Measurements of Anomalous ϵ/β^+-Decay Branching Ratios

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Absolute values of ϵ/β^+-decay branching ratios for decay of ^{145}Gd to twelve levels in ^{145}Eu have been measured. These measurements are all shown to deviate substantially from the calculated ϵ/β^+ ratios of Gove and Martin. Skew ratios (exp/theor) are found to range from 1.5 to 40. These "anomalies" are ascribed to second-order corrections to allowed decay which have not been included in the calculations.

In a previous Letter[1] we reported exciting evidence of large anomalous ϵ/β^+-decay branching ratios, relative to theoretical predictions,[2] for ^{145}Gd and ^{143}Sm decays. These were not absolute but relative measurements, and so we were forced to normalize our results to fast transitions where the ratio was assumed to be normal. The anomalies were proven, but this in itself made the normalization procedure somewhat suspect.

We have now completed absolute measurements of the ϵ/β^+-decay branching ratios for ^{145}Gd decay. Thin sources were prepared by depostion on Mylar tape at the nozzle of a helium-jet recoil transport system.[6] Annihilation radiation and K x rays were counted in a 7.6-cm×7.6-cm NaI detector, and coincident γ rays tagging the ϵ/β^+-fed levels in ^{145}Eu were detected in a large[4] Ge(Li) detector. The source was surrounded by a plastic annihilator to ensure total annihilaton at the source. The two energies were recorded along with the coincidence time on magnetic tape for off-line analysis. The NaI pulse-height spectra in coincidence with γ rays depopulating the 808.5- and 1757.8-keV levels in ^{145}Eu are presented in Fig. 1. The relative efficiency ratio between the x-ray region (45 keV) and 511 keV was measured, by use of internal γ-ray sources,[5] to be 2.00 ±0.14. This compares favorably with the predicted value[6] of 1.95, which is corrected for window thicknesses.[7] The ϵ/β^+ ratios were then determined for various transitions by incorporating well-known fluorescence yields[8] and $\epsilon(K)/\epsilon(\text{tot})$ ratios[8] to obtain the total electron-capture intensities. The β^+ feedings were corrected for annihilation in flight in the plastic absorber, an ≈4% effect.[9] The transitions to the 1041.9-, 1757.8-, and 1880.6-keV levels in ^{145}Eu were measured sufficiently accurately to be used as primary absolute ϵ/β^+ ratios. Using the more extensive x-γ and β^+-γ coincidence data referred to in our earlier paper,[1] we then calculated the absolute ϵ/β^+ ratios to other levels. Total β-feeding intensities were calculated by use of our coincidence data; they compared favorably with γ-ray

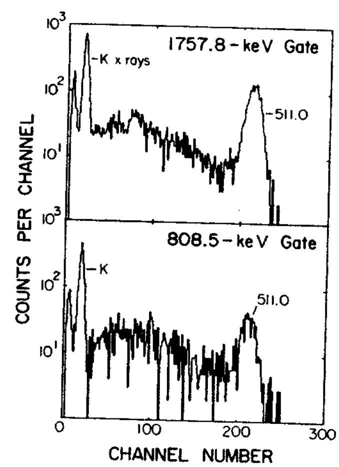

FIG. 1. NaI(Tl) coincidence spectra for the 1757.8- and 808.5-keV gates in the decay of ^{145}Gd to ^{145}Eu. Note that the $\gamma^\pm$ peak is severely depressed in the 808.5-keV gated spectrum, although normal decay-energy calculations would predict it to be much larger in that spectrum than in the 1757.8-keV gated spectrum. It should also be noted that β decay to states de-exciting through the 808.5-keV state accounts for nearly all of the $\gamma^\pm$ peak but only about half of the K x-ray peak.

Comment on "Prediction of Weak-Coupling Structure from a Shell-Model Basis"

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The theoretical predictions of Wildenthal, Nann, and Seth about weak-coupling relations between the $0_{1,2}^+$ states of ^{32}S and the $\frac{3}{2}_1^+$ and $\frac{3}{2}_3^+$ states have been experimentally confirmed and the weak-coupling picture shown to extend to a quadruplet of states in ^{33}Cl which have significant parentage in the 2_1^+ state of ^{32}S.

It was demonstrated in a recent Letter[1] that calculations for the (p,t) reaction on odd-mass targets, made with mixed-configuration shell-model wave functions for *sd*-shell nuclei,[2] yielded anomalously pure $L=0$ (p,t) angular distributions for selected excited states as well as for the ground states. The calculated results strongly resembled phenomena observed in (p,t) experiments on odd- and even-mass *fp*-shell nuclei[3,4] which had been interpreted in terms of a weak-coupling relation between the 0_2^+ state (second 0^+ state) in an even-mass residual nucleus and an excited state of $J^\pi = J^\pi$ [target ground state (g.s.)] in the adjacent residual odd-mass nucleus. The weak-coupling explanation for the phenomena was confirmed in the case of the calculated results for *sd*-shell nuclei by computing single-nucleon overlaps between the excited 0^+ states and excited $J^\pi = J^\pi$(target g.s.) states.

In this Comment we present experimental results of the (p,t) reaction on the *sd* nuclei previously treated theoretically. These results confirm the predictions of the theory, in particular those aspects which can be interpreted as weak-coupling structure. They also suggest a similar relationship between the first-excited 2^+ state and the multiplet of $\vec{J}^\pi = \vec{2}^+ \otimes \vec{J}^\pi$(target g.s.) states in the adjacent odd-mass nucleus.

The reactions $^{35}Cl(p,t)^{33}Cl$ and $^{34}S(p,t)^{32}S$ were studied at $E_p = 40$ MeV at the Michigan State University cyclotron, using a split-pole spectrograph with a single-wire proportional counter in its focal plane. The ^{35}Cl target was prepared from NaCl (enriched in ^{35}Cl), and the sandwich-type ^{34}S target was evaporated from enriched ^{34}S. An energy resolution of about 30 keV full width at half-maximum was achieved. In order to resolve ^{21}Na levels from those of ^{33}Cl, auxiliary runs (with an energy resolution of about 15 keV) were made in certain excitation-energy regions

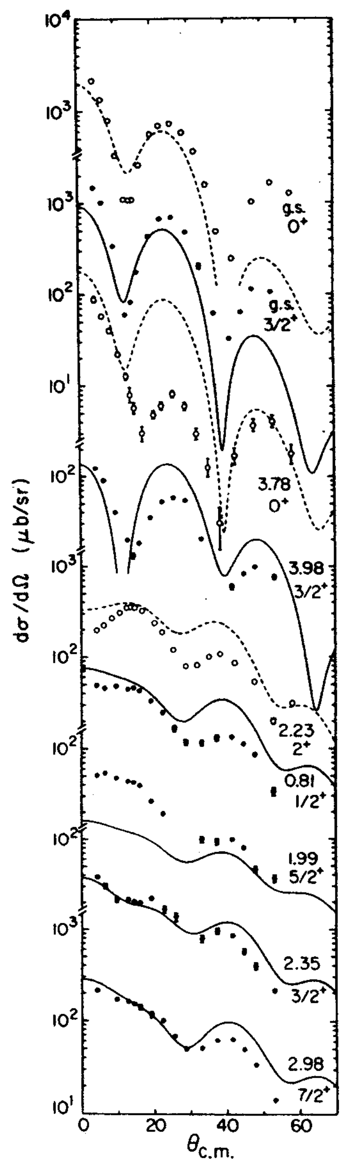

FIG. 1. Differential cross sections at $E_p = 40$ MeV for the reactions $^{34}S(p,t)^{32}S$ (open circles, data; dashed lines, DWBA predictions) and $^{35}Cl(p,t)^{33}Cl$ (closed circles, data; solid lines, DWBA predictions).

Anomalous ϵ/β^+ Decay Branching Ratios: A Theoretical Explanation

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Anomalous ϵ/β^+ branching ratios for hindered allowed transitions in ^{145}Gd and ^{143}Sm decay are explained in terms of second-order corrections to normal allowed theory. These calculations lead to correction factors as large as 1000 in nuclei near $Z=80$, and explain a smaller anomaly for ^{22}Na decay. A simplified equation is presented to estimate skew ratios, $(\epsilon/\beta^+)_{\text{expt}}/(\epsilon/\beta^+)_{\text{theor}}$, for moderately hindered transitions.

In a previous Letter[1] we reported two large ϵ/β^+ branching-ratio anomalies relative to calculated values for allowed transitions.[2] Our subsequent Comment[3] on absolute measurements of these ratios showed that all twelve measurable transitions from ^{145g}Gd decay were substantially anomalous. These results are presented in Table I along with results from ^{143g}Sm decay which were relative measurements. A value for ^{22}Na decay[4] is also included in Table I. This is, perhaps, the most accurately measured ϵ/β^+-decay branching ratio in the literature, and, although it was studied looking for Fierz interference effects, the discrepancy was never adequately explained. We now believe that we can explain these anomalous ratios in terms of second-order (off-center) corrections to allowed decay. Calculations of these corrections are explained below, and they qualitatively describe the magnitude of the anomalies.

The second-order corrections to allowed β decay are proportional to $(pR)^2$ or $(pR)(v_N/c)$ and are normally about (1–2)% of the allowed matrix elements $\int 1$ and $\int \sigma$. For heavier nuclei these contributions become increasingly important because $R \approx 0.426aA^{1/3}$. A general correction term to the positron-decay probability can be written as[5]

$$C(W_e)=[M_0(1,1)]^2+[m_0(1,1)]^2-\frac{2\mu_1\gamma_1}{W_e}[M_0(1,1)][m_0(1,1)]$$
$$+\lambda_1\left\{[M_1(1,1)]^2+[m_1(1,1)]^2-\frac{2\mu_1\gamma_1}{W_e}[M_1(1,1)][m_1(1,1)]\right\}$$
$$+\lambda_1\left\{[M_1(1,2)]^2+[M_2(1,2)]^2-\frac{2\mu_1\gamma_1}{W_e}[M_1(1,2)m_1(1,2)+M_2(1,2)m_2(1,2)]\right\}$$
$$+\lambda_2\left\{[M_1(2,1)]^2+[M_2(2,1)]^2-\frac{\mu_2\gamma_2}{W_e}[M_1(2,1)m_1(2,1)+M_2(2,1)m_2(2,1)]\right\}. \quad (1)$$

$\alpha + \alpha$ Reaction and the Origin of ^{7}Li

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Cross sections are presented for the production of ^{7}Li and ^{7}Be in the $\alpha + \alpha$ reaction between threshold and 140 MeV. Implications of these measurements for the problem of the origin of ^{7}Li in the universe are discussed.

The observed abundances of most stable nuclides can be understood in terms of two main processes: (1) nucleosynthesis during stellar evolution,[1] which applies principally to carbon and heavier elements, and (2) spallation of interstellar matter by galactic cosmic rays,[2] which is most important for the elements with $A < 12$. There are, however, a few nuclides whose abun-

Reaction ^{40}Ar (p, n) to the Antianalog State in ^{40}K†

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We have measured ^{40}Ar$(p,n)^{40}$K(antianalog) differential cross sections at 24 MeV and made microscopic distorted-wave Born-approximation calculations for these cross sections. Unlike the (^{3}He,t) reaction to the same state, where it is necessary to invoke a two-step mechanism, the (p,n) data are fitted by the one-step calculation. A one-step calculation also fits ^{40}Ar$(p,n)^{40}$K(isobaric analog) data with the same nucleon-nucleon interaction used in the antianalog-state calculation.

Just as a transition to the isobaric analog state (IAS) of a target is strong and insensitive to details because of the near-perfect overlap of target and IAS wave functions, a transition to the antianalog state (AAS) may be expected to be small and sensitive to details because of the almost complete orthogonality of target and AAS wave functions. This sensitivity has been seen in (^{3}He, t) reactions to the AAS in several nuclei, where it was found that the $L = 0$ angular distributions expected of $0^+ \rightarrow 0^+$ transitions were not observed.[1] Cross sections for ^{40}Ar(^{3}He, t)^{40}K(AAS) computed by Schaeffer and Bertsch[2] with the direct microscopic model were one to two orders of magnitude below the observed values, but a reasonable fit was obtained when the two-step pickup-stripping process (^{3}He, α)-(α, t) was included.[2] The data and calculations are shown in Fig. 1. Similar results were obtained by Coker, Udegawa, and Wolter[3] who fitted both 35-MeV[1] and 18-MeV[4] data. Experimental discrepancies with expected shapes of angular distributions have also been noted when the transferred L was greater than 0.[5] For the reaction ^{48}Ca(^{3}He, t)^{48}Sc, two-step calculations using (^{3}He, α)-(α, t)[2,6] or, in addition, (^{3}He, d)-(d, t)[7] have produced fits to data where one-step calculations clearly disagreed with experiment. It seems well documented that a reaction mechanism including two-step amplitudes is needed to describe (^{3}He, t) reactions.

In order to test for the presence of a two-step amplitude in (p, n) reactions, we have investigated the reaction ^{40}Ar$(p, n)^{40}$K(AAS) with 24-MeV protons. As for (^{3}He, t) reactions to the AAS, the near orthogonality of the target and final-state wave functions should produce small one-step (p, n) amplitudes, thus allowing us to see in the AAS transition a two-step amplitude which might be masked in the IAS transition.

Neutrons were detected with a liquid-scintillator, time-of-flight spectrometer[8] having an instrumental resolution of ~0.5 nsec. To achieve an energy resolution sufficient to resolve cleanly the AAS neutron group $[E_x(^{40}\text{K}) = 1.64$ MeV$]$ from the stronger group at 1.96 MeV, flight paths were increased from our normal value of ~4.5 m to 11–15 m. At these flight paths the geometry of our laboratory permitted neutrons to be observed only in the angular ranges 10–35° and 135–152°. It would be best to resolve the AAS and measure its cross section at all angles. However, it will be seen that the information obtained at this combination of forward and backward angles is sufficient to conclude that a significant two-step

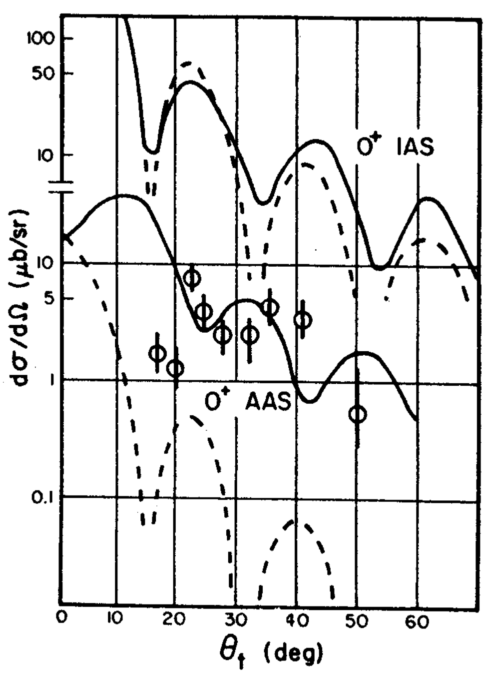

FIG. 1. Comparison of the one-step (dashed curves) and the one-step–plus–two-step (solid curves) calculations of Ref. 2 with the data of Ref. 1 for the reaction ^{40}Ar(^{3}He,t)^{40}K to the IAS and the AAS.

Residual Interactions in Four-Quasiparticle $K^\pi = 14^-$ Isomer in ^{176}Hf†

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We have for the first time located and identified a four-quasiparticle isomer in a deformed nucleus. Its energy may be used as a test for the effective interaction between quasiparticles. We can account for the energy quite well with a simple δ-function interaction, but not with an interaction derived from Brueckner theory.

Information on the residual interaction in rare-earth deformed nuclei has come primarily from the singlet-triplet splittings of Gallagher-Moszkowski pairs in odd-odd nuclei,[1] and to a much lesser extent from similar splittings of two-quasiparticle (2-qp) states in even-even nuclei. The off-diagonal matrix elements of the residual interaction have also recently been obtained from the mixing between two-neutron and two-proton configurations[2-4] in even-even nuclei. To date, however, no attempt has been made to extract information on the residual interactions in the rare-earth region from a study of states of seniority greater than two, despite the fact that many 3-qp states are known. To begin such an investigation it is, in fact, preferable to study a 4-qp system for which the energies of the constituent 2-qp states are already known. In this case, the effects of the residual interaction may be extracted from the observed 2- and 4-qp energies without having to calculate explicitly the individual qp energies. The interactions thus deduced may then be used as a test of chosen effective interactions.

The twofold goals in the present investigation were to isolate experimentally a 4-qp state and, using its energy, to test the applicablity of a "realistic" force and a δ force as effective interactions for rare-earth deformed nuclei. We prefer to search for very high-K ($\geqslant 12$) states, since these should be rather pure because of the low density of such states even at the ~3-MeV excitation expected. An accompanying attractive feature is the fact that the large K should lead to isomerism, greatly simplifying the identification of the state.

The nucleus ^{176}Hf is a particularly favorable candidate for investigation since the lowest 2-qp excitations have been identified[2] and, furthermore, have high K so that one may expect the lowest 4-qp states to have very large K. In addition the decay of the 4-qp isomer should proceed through known[2] bands built on the lower-lying 2-qp configurations, further simplifying the observation of the isomer.

The reaction ^{176}Yb$(\alpha, 4n)^{176}$Hf at 41-50 MeV bombarding energy was used to populate high-K states in ^{176}Hf. The following experiments in which γ rays were detected by Ge(Li) detectors were performed: (a) observation of delayed γ rays in a 5-msec interval between irradiation periods of 1 msec duration; (b) search for short-lived isomers, in which the interval between beam bursts varied from 50 to 500 nsec; (c) conventional three-parameter γ-γ-t coincidence; (d) excitation function; and (e) angular distribution measurements. In addition to two previously known[2] 10-μsec isomers, a new 401 ± 6-μsec isomer was discovered at 2866.0 keV. The decay scheme of the isomer is shown in Fig. 1. All the γ rays in the figure with relative intensities greater than 0.6 were found to decay with a 401-μsec component. No other isomers with half-lives greater than a few nanoseconds were found in ^{176}Hf. It is interesting to observe that the population of the 401-μsec isomer accounts for an unusually large fraction (~30%) of the total $(\alpha, 4n)$ cross section.

The new isomer decays through two $K^\pi = 8^-$ bands which had previously been identified[2] to spin 12. The energies, branching ratios, and relative signs of the $M1$ and $E2$ matrix elements of the band members can all be accounted for in a model[2] in which there is increasing mixing between levels with increasing spin. On the basis of this model, there is little doubt that the 2827.3-keV level is the lower 13^- band member. (The higher 13^- level, not shown in Fig. 1, is found at

Observation of Giant Gamow-Teller Strength in (p,n) Reactions*

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In $^{90}Zr(p,n)^{90}Nb$ spectra for $E_p = 35$ and 45 MeV, we observe a strong enhancement of the $T=4$ continuum over a range of excitation energies (full width at half-maximum of 4.2 ± 0.4 MeV) centered at 8.4 ± 0.3 MeV. The data are consistent with an interpretation of the broad peak as a $(\pi g_{7/2}, \nu g_{9/2}^{-1})_{1^+}$ excitation wich corresponds to the giant magnetic-dipole resonance. Similar structure is observed near the isobaric analog state of ^{48}Ca, ^{120}Sn, and ^{208}Pb.

Allowed β decays between nuclei with $N > Z$ are generally found to be hindered with respect to calculated single-particle rates.[1] An analogous phenomenon for electromagnetic transitions is understood in terms of the concentration of $E1$ strength near $E_x = 75/A^{1/3}$ MeV in the giant electric-dipole resonance. The corresponding resonance which exhausts the Fermi β-decay strength to or from a $T_z = T$ ground state is its $T_z = T-1$ isobaric analog (IAS), first identified in nuclei heavier than the mirror pairs by Anderson and Wong[2] in 1961 via the (p,n) reaction. In 1963, Ikeda, Fujii, and Fujita[3] suggested that the Gamow-Teller strength function may be similarly localized near the IAS as part of a badly broken, but persistent, Wigner supermultiplet. However, except possibly in light proton-rich nuclei,[4] such a resonance has been heretofore unseen.[1] In this Letter, we present evidence for the first direct observation of the giant Gamow-Teller resonance in nuclei with $N > Z$.

We have recently completed a series of (p,n)-IAS differential-cross-section measurements on targets of ^{48}Ca, ^{90}Zr, ^{120}Sn, and ^{208}Pb with 25-, 35-, and 45-MeV protons from the Michigan State University cyclotron. These data have been acquired with conventional neutron time-of-flight and pulse-shape-discrimination techniques. Experimental details and the results of a microscopic distorted-wave-Born-approximation (DWBA) analysis of the (p,n)-IAS cross sections are available in a previous publication.[5] Many of the neutron time-of-flight spectra reveal structure in addition to the IAS in the giant-resonance region. Such a spectrum, of neutrons produced at a scattering angle of 0° from the bombardment of a ^{90}Zr target with 35-MeV protons, is shown in Fig. 1. The prominent peak around channel 400 is the isobaric analog of the target ground state. The neutron energy resolution in the vicinity of the IAS is approximately 170 keV, which should certainly be adequate to resolve several analogs of excited states (EAS) of ^{90}Zr. The expected positions of the first few are indicated in the figure. The apparent absence of EAS with even 5% as much as the IAS cross section (2.7 mb/sr) at this angle is an indication of the direct nature of the (p,n) reaction at $E_p = 35$ MeV.[6] Although the $T=5$ EAS are not prominent, there is an obvious enhancement of the $T=4$ background states over a broad region centered about 3 MeV in excitation energy above the IAS. Note that the low-excitation tail of this peak extends below the expected location of the first EAS.

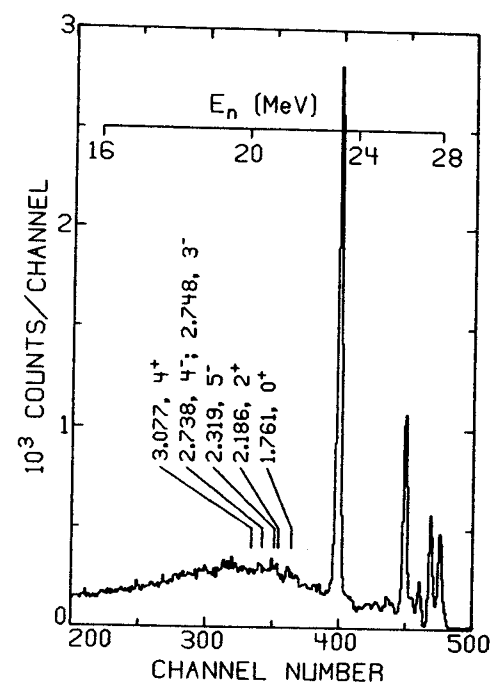

FIG. 1. Neutron time-of-flight spectrum at $\theta = 0°$ for $^{90}Zr(p,n)^{90}Nb$ at $E_p = 35$ MeV. Expected EAS positions are labeled with the excitation energies of the parent analog states in ^{90}Zr.

High-Spin Level Systematics in $^{186-194}$Pt and Rotation-Alignment Coupling*

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Systematic investigations of the shape-transitional nuclei ^{186}Pt to ^{194}Pt by $(\alpha, xn\gamma)$ reactions have revealed a rich variety of high-spin structural phenomena, which can be qualitatively understood in terms of rotation-alignment coupling and the interplay between collective and single-particle excitation modes. Acute backbending in the positive-parity yrast sequences of ^{188,190,192,194}Pt is attributed to the intersection of rotation-aligned $(\nu i_{13/2}^{-2})$ and $(\pi h_{11/2}^{-2})$ bands with the ground bands.

The level structure of the nuclei $^{186-194}$Pt, which span an important nuclear-shape transition region, has been intensively studied by $(\alpha, xn\gamma)$ spectroscopy. In this Letter we wish to focus attention on several striking systematic aspects of the dominant low-lying high-spin excitation modes in this nuclei, which include (i) well-decoupled $\nu i_{13/2}^{-1}$ bands in all the odd-A nuclei which indicate that the Pt nuclei with $A \geq 187$ are basically oblate; (ii) backbending behavior at about spin 10 in the positive-parity yrast sequences of all the even nuclei, which becomes increasingly more pronounced from ^{186}Pt to ^{192}Pt; (iii) semidecoupled 5^- bands occurring systematically across the even Pt nuclei; (iv) related $\frac{21}{2}^{(-)}$ bands in the odd Pt nuclei, which can be attributed to the coupling of an $i_{13/2}$ neutron hole with the members of the aforementioned 5^- bands.

The experiments were performed by bombarding isotopically enriched ^{192}Os (98%), ^{190}Os (95%), ^{188}Os (87%), and ^{186}Os (62%) targets with 28–50-MeV α-particle beams from the Michigan State University cyclotron. The techniques employed included comprehensive prompt and delayed γ-ray singles and $\gamma\gamma$ coincidence measurements, lifetime measurements, and γ-ray angular-distribution and excitation-function determinations. On the basis of the results, extensive level schemes incorporating a wealth of new spectroscopic information have been constructed. For ^{186,188,190,192}Pt we generally confirm earlier results,[1,2] which were however incomplete and limited to levels with spins ≤ 10. Nothing was previously known about the high-spin level structure of the odd Pt nuclei. Our data for ^{194}Pt are much less extensive than for the other nuclei, since the $(\alpha, 2n)$ reaction only could be studied, and our proposed level scheme is based in part on earlier radioactivity findings.[3,4]

The detailed results for the nine nuclei studied will be presented in forthcoming publications, and the simplified level schemes of Fig. 1 display only the main systematic features of the level spectra. In the odd Pt nuclei, the $\frac{13}{2}^+$ states are low-lying isomers but in Fig. 1 they are displaced to zero excitation energy in order to accentuate the strong correlation between the energy spacings in the $\nu i_{13/2}^{-1}$ decoupled bands and the ground bands of the adjacent core nuclei. Since in this region the low-Ω orbits of the $i_{13/2}$ subshell are close to the Fermi surface only for negative values of β, the observation of these decoupled bands implies oblate deformations for the Pt nuclei with $A \geq 187$.[5] This conclusion must be qualified by a recognition that there is growing evidence for triaxial nuclear shapes in this region.[6]

The energy spacings in the positive-parity yrast sequences of the even-A nuclei are most remarkable, particularly those of ^{190}Pt and ^{192}Pt, which have the appearance of extreme backbending-type structures.[7] For the 192- and 105-keV transitions in ^{190}Pt and ^{192}Pt, we have determined $B(E2; 12^+ \to 10^+)$ values of about 15 and 39 single particle units (s.p.u.), which are appreciably smaller than the $B(E2; 2^+ \to 0^+)$ values of 70–80 s.p.u. reported for these nuclei.[8] In an earlier study,[4] the $B(E2)$ for the 339-keV $10^+ \to 8^+$ transition in ^{194}Pt has been estimated to be about 0.2 s.p.u. In all the even Pt nuclei the 2^+, 4^+, 6^+, and 8^+ levels

MASS MEASUREMENTS OF ^{19}Na AND ^{23}Al USING THE (^{3}He, ^{8}Li) REACTION[☆]

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The mass excesses of ^{19}Na and ^{23}Al have been measured with the (^{3}He, ^{8}Li) reaction. The values obtained are 12928 ± 12 keV and 6767 ± 25 keV, respectively. The first excited state of ^{19}Na, observed to lie at 120 ± 10 keV, completes a mass quartet which agrees with a quadratic isobaric multiplet mass equation.

In this letter we discuss the use of a new reaction (^{3}He, ^{8}Li) in measurements of atomic mass excesses. The cross section and Q-value are roughly equivalent to those of the (p, ^{6}He) reaction, which accomplishes the same transfer, but its utilization offers several advantages. Since the highest ^{3}He energy of a cyclotron is always at least 50% higher than the top proton energy, more nuclei are accessible. For example the $A = 4n + 3$, $T_z = -3/2$ nuclei are easily reached with the (^{3}He, ^{8}Li) reaction ($Q \approx -34$ MeV) using the 76 MeV beam from the Michigan state University cyclotron, but studying the same nuclei via the (p, ^{6}He) reaction ($Q = -38$ MeV) would be much more difficult at the top proton energy, 50 MeV. In the case of the ^{24}Mg target, the cross section for (^{3}He, ^{8}Li) is 300 nb/sr which is three times larger than the 100 nb/sr given by Cerny et al. [1] for ^{24}Mg(p,^{6}He). In addition the (^{3}He, ^{7}Li) reaction provides an excellent calibration reaction for (^{3}He, ^{8}Li) since it produces particles of similar rigidity. The analogous (p, ^{5}He) reaction is, of course, not observable in a spectrograph. A comparison of (p, ^{4}He) to (p, ^{6}He) is very dependent on an accurate knowledge of the beam energy and the spectrograph calibration. The best calibration for (p, ^{6}He) Q-value measurements has been the same reaction on a different target. In this case the target thickness correction becomes important.

The ^{24}Mg(^{3}He, ^{8}Li)^{19}Na and ^{28}Si(^{3}He, ^{8}Li)^{23}Al reaction were produced at 76.8 MeV, and the reaction products were detected in a magnetic spectrograph time-of-flight combination described previously [2]. The targets were 80 μg/cm^2 ^{24}Mg on a 20 μg/cm^2 carbon backing and a 370 μg/cm^2 self-supporting SiO foil. Angles of 7.6° and 10.0° were employed. Spectra of the two reactions at 7.6° are given in figs. 1 and 2. In the case of ^{19}Na, the spectrum shown is a composite of three runs, and the energy resolution is about 60 keV. In one of the runs at 7.6° a resolution of 40 keV was obtained. The 150 keV resolution of the ^{23}Al spectrum was dominated by target thickness, whereas for ^{19}Na it is mainly due to the spatial resolution of the counter.

The ^{19}Na mass can be determined in two ways. First, the rigidity of the particles from ^{24}Mg(^{3}He, ^{6}Li) and ^{24}Mg(^{3}He, ^{8}Li) can be compared. Since the mass of ^{21}Na is accurately known, the dominant error comes from the beam energy determination, which was carried out by comparing ^{12}C(^{3}He, ^{3}He) to ^{12}C(^{3}He, ^{6}He). The second method, comparison of ^{24}Mg(^{3}He, ^{8}Li)

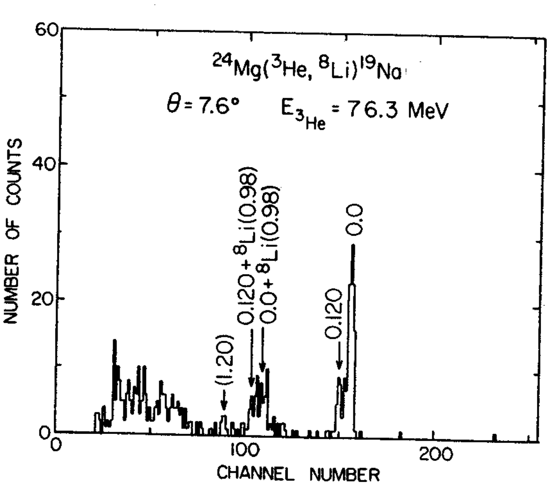

Fig. 1. A composite spectrum from three runs on the ^{24}Mg(^{3}He, ^{8}Li)^{19}Na reaction at 76.3 MeV and 7.6°.

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* On leave of absence from Institut de Physique Nucleaire de Lyon-France.

J-DEPENDENCE OBSERVED IN ^{61,62}Ni(p, d) REACTIONS AT 40 MeV ☆

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The angular distributions of several $l = 3$ transitions observed in the ^{61,62}Ni(p, d) reactions demonstrate a very stable *j*-dependence over a range of intensities and excitation energy.

The dependence of the angular distribution upon the total angular momentum, *j*, transferred in a (d, p) reaction was first reported by Lee and Schiffer [1]. More extensive studies [2–7] have shown the presence of this effect in both pick-up and stripping reactions which involve the proton and deuteron as well as the triton, ^{3}He and ^{4}He. Sherr et al. [3] have studied the (p, d) reaction at 28 MeV on several even-even nuclei in the Ni region, and first noted the angular shift of the $l = 3, j = 5/2$ distribution relative to the $l = 3, j = 7/2$ distribution. Glashausser et al. [4] have studied the ^{56}Fe(p, d) and ^{58}Ni(p, d) reactions and observed the persistence of this *j*-dependence effect over the incident energy range of 18 to 27.5 MeV. In both cases, only one $f_{5/2}$ transfer has been compared to one or more $f_{7/2}$ transfers within a nucleus.

In the present experiment, four $f_{7/2}$ and three $f_{5/2}$ transfers have been observed in the ^{62}Ni(p, d) reaction at $E_p = 40$ MeV. From the pronounced and consistent *j*-dependence of the shapes of these angular distributions, the 2.47 MeV level in ^{61}Ni can be inferred to be $7/2^-$ instead of $5/2^-$ as previously suggested [7]. Also three $l = 3$ transfers in the ^{61}Ni(p, d) reaction can be identified as relatively pure $5/2^-$ transfers.

A 40 MeV proton beam of the Michigan State University Cyclotron was used to bombard isotopically enriched targets (92.9% and 98.8%, respectively) of ^{61}Ni and ^{62}Ni. The outgoing deuterons were analyzed in a split-pole magnetic spectrograph and detected in a position-sensitive single-wire proportional counter with an energy resolution of about 50 keV. A deuteron spectrum from ^{62}Ni(p, d) at 30° is shown in fig. 1. Angular distributions were measured from 4° to 60°. A strong *j*-dependence was observed for $l = 3$ transfer, while no evidence of such an effect was seen for $l = 1$ over the angular range studied. Figs. 2a and 2b show three $f_{5/2}$ transfers leading, respectively, to states at 0.07, 0.91, 1.61 MeV in ^{61}Ni, and four $f_{7/2}$ transfers leading to states at 1.46, 2.47, 2.90 and 3.30 MeV in the same nucleus. The solid and the dashed lines drawn for each distribution are obtained from smooth curves drawn through the data of the $5/2^-$, 0.07 MeV state and the $7/2^-$ 3.30 MeV state, respectively.

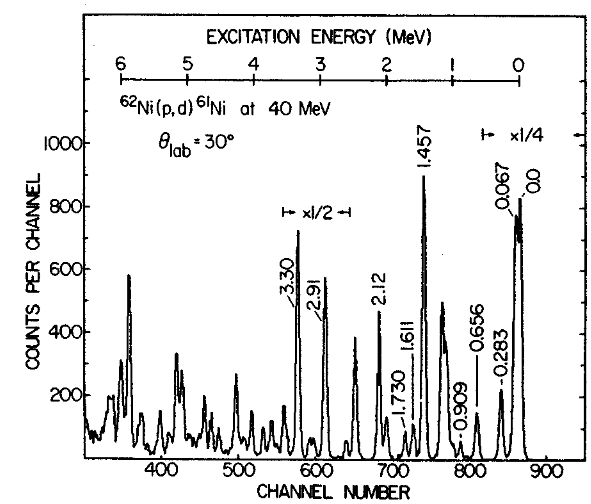

Fig. 1. Deuteron spectrum of the ^{62}Ni(p, d) reaction at 30° lab.

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ANALOGUE STATES IN ^{47}Ca ☆

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The ^{48}Ca(^{3}He, ^{4}He)^{47}Ca and ^{48}Ca(p, d)^{47}Ca reactions were used to observe six levels in ^{47}Ca above 12 MeV excitation. Analysis of the data has yielded precise excitation energies for the lowest $T = 9/2$ levels in ^{47}Ca, which are analogs of low-lying levels in ^{47}K. Comparison of experimental and calculated Coulomb displacement energies for the K-Ca isotopes is made.

In this letter we present results for six levels in ^{47}Ca above 12 MeV excitation and discuss the Coulomb displacement energy systematics of analogue states in the odd K-Ca isotopes. The levels in ^{47}Ca were observed by means of the ^{48}Ca(^{3}He, ^{4}He)^{47}Ca and ^{48}Ca(p, d)^{47}Ca reactions. Beams of 69.7 MeV ^{3}He particles and 40.2 MeV protons from the Michigan State University cyclotron were employed. The outgoing ^{4}He particles and deuterons were momentum analyzed in an Enge split-pole magnetic spectrograph. The detection system consisted of a position-sensitive-wire proportional gas counter backed by a plastic scintillator for time-of-flight information. The method and electronics have been previously described [1].

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Fig. 1 shows the spectra of ^{4}He particles from the ^{48}Ca(^{3}He, ^{4}He)^{47}Ca reaction at 9.0° and 22.5°. The 1.0 mg/cm^2 thick self-supporting ^{48}Ca target which was used contained ^{16}O and ^{12}C from which the calibration lines were obtained. No evidence of strong

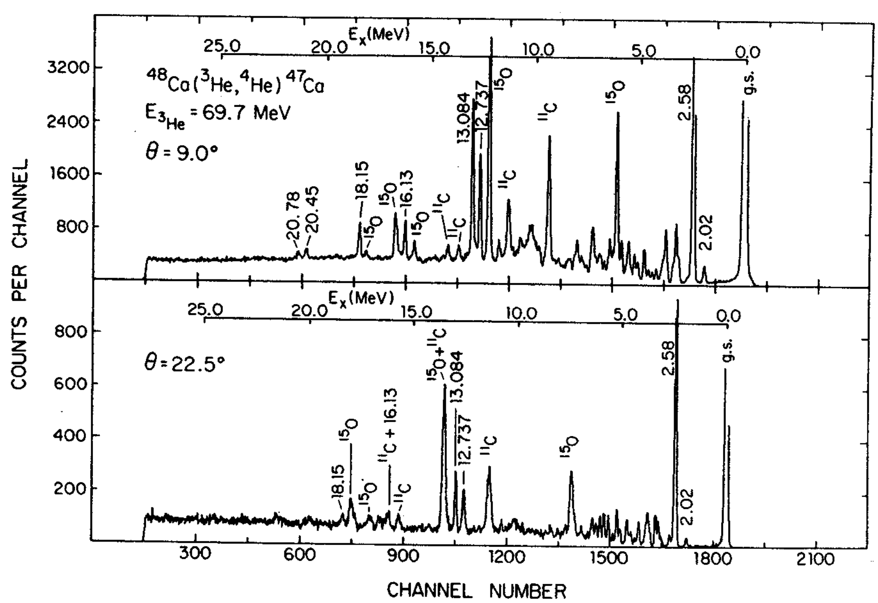

Fig. 1. Spectra of ^{4}He particles at θ_{lab} = 9° and 22.5°.

SPLITTING OF THE LOWEST $T = 2$ STATES IN ^{44}Ti, ^{48}Cr AND ^{52}Fe ☆

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A high-resolution study of the ^{46}Ti, ^{50}Cr, ^{54}Fe(p, t)^{44}Ti, ^{48}Cr, ^{52}Fe reactions provides evidence for the splitting of the lowest double analog states in ^{44}Ti and ^{48}Cr. The splitting is 20 ± 2 keV in ^{44}Ti and 10 ± 2 keV in ^{48}Cr. Splitting of the $T = 2$ state in ^{52}Fe could not be identified. Together with the previously observed splitting in ^{56}Ni the present results suggest that splitting is a common occurrence for self-conjugate nuclei in the $f_{7/2}$ shell.

The lowest excited double analog states [1] in light and medium weight nuclei have been observed as final states in isospin allowed direct processes such as (τ, n) and (p, t) reactions [1, 2], and as compound nucleus resonances in isospin forbidden reactions initiated by protons and α-particles [3, 4]. These states were also found to decay by isospin forbidden proton and α-particle emission [5], and hence their properties are especially interesting from the point of view of isospin mixing [6]. In a recent study of the ^{58}Ni(p, t)^{56}Ni reaction [7] a triplet of $J^{\pi} = 0^+$ states was observed in the excitation energy region where the lowest $T = 2$ state is expected indicating isospin mixing of the double analog state with nearly 0^+ states of lower isospin. In order to examine if this is a general property of the $T = 2$ states in self-conjugate nuclei in the $1f_{7/2}$ shell we searched for similar splitting in ^{44}Ti, ^{48}Cr and ^{52}Fe.

The $T = 2$ states were populated via the ^{46}Ti(p, t)^{44}Ti, ^{50}Cr(p, t)^{48}Cr and ^{54}Fe(p, t)^{52}Fe reactions using a 46 MeV proton beam from the Michigan state University Cyclotron. The ^{46}Ti and ^{54}Fe targets were enriched self-supporting foils of 270 μg/cm^2 and 240 μg/cm^2 thickness, respectively. The ^{50}Cr target was 120 μg/cm^2 thick on a 25 μg/cm^2 carbon foil backing. The tritons were analyzed with an Enge split-pole magnetic spectrograph and were detected with a position sensitive Si detector (1 cm long) and a single-wire proportional counter (35 cm long). The Si detector was used to extract precise excitation energies for levels in the vicinity of the $T = 2$ states. The overall resolution was 8 to 10 keV, FWHM. The proportional counter spectra, limited to a resolution of 35 keV FWHM, were useful to identify the $T = 2$ states.

Typical spectra as recorded with the Si detector are shown in fig. 1. The excitation energies obtained in the present work are used to label the peaks corresponding to the $T = 2$ and nearby states. Fig. 2 shows the angular distributions for the ^{44}Ti and ^{48}Cr levels of fig. 1. Also shown in fig. 2 are the angular distributions for the $T = 2$ state and the known 0^+ level in ^{52}Fe at 6.84 MeV, as obtained from the proportional counter. We were able to make a new assignment of 0^+ to a level at 9.31 MeV in ^{44}Ti and to a level at 8.75 MeV in ^{48}Cr. These assignments were made possible by the very unique shape of the differential cross section for $L = 0$ transfer. The unambiguous nature of the new assignments can be seen from fig. 2. The intensity of the transitions to the 0^+ states found in ^{44}Ti is $\sigma_{9.33}/\sigma_{9.31} = 4.0 \pm 0.4$ while that in ^{48}Cr is $\sigma_{8.76}/\sigma_{8.75} = 1.1 \pm 0.1$.

In a previous study of the ^{46}Ti(p, t)^{44}Ti reaction, Rapaport et al. [8] by using nuclear emultion plates could obtain an overall resolution comparable to that of our experiment. However, strong deuteron peaks interfered with the identification of weak states in ^{44}Ti above 7.7 MeV. The 0^+, $T = 2$ state in ^{48}Cr was reported by Dorenbusch et al. [9]. These authors identified a doublet at 8.75 MeV, the full angular distribution of which could not be obtained because of competing deuteron groups.

The double analog state in ^{52}Fe was reported by Viano et al. [10]. However, there are at least two lev-

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STRUCTURE OF POSITIVE PARITY STATES IN ^{29}P AND TWO-STEP PROCESSES IN (p, t) REACTIONS

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From a study of (p, t) reactions on ^{31}P and ^{30}Si it is suggested that in ^{29}P the states with $J^\pi = 1/2_1^+$ and $1/2_2^+$, the pair $3/2_2^+, 5/2_1^+$, and the pair $7/2_3^+, 9/2_1^+$ are related by weak coupling of a $s_{1/2}$ proton with the states $0_1^+, 0_2^+, 2_1^+$ and 4_1^+ respectively of ^{28}Si. Completely atypical $L = 2$ angular distributions have been obtained for the $3/2_1^+$ and $5/2_2^+$ states in ^{29}P and it is suggested that this is due to contribution by two-step processes.

The positive parity states in the mirror nuclei ^{29}Si–^{29}P have been alternately explained in terms of the strong-coupling Nilsson model [1, 2] or of the intermediate core-coupling model [3, 4]. In the Nilsson model the ground-state band is a $K^\pi = 1/2^+$ [211] band whose other members are the $3/2_2^+$ and $5/2_1^+$ states, and the $K^\pi = 3/2^+$ [202] band consists of $3/2_1^+, 5/2_2^+$ and perhaps $7/2_1^+$ states. In the intermediate coupling calculations $2s_{1/2}$, $1d_{3/2}$, and $1d_{5/2}$ single-particle states are coupled to the ^{28}Si quadrupole phonon states. While qualitatively both these calculations are equally satisfactory neither provide quantitative agreement with particle transfer as well as decay data. In this letter we present experimental data which bears on an alternate empirical explanation for the structure of some of the positive parity states in ^{29}P.

It has recently been shown that (p, t) reactions on odd-A nuclei provide a powerful means of identifying weak-coupling core-excited states [5, 6]. The identification is done by noting that such states can be reached by the same L-transfer, and with nearly the same cross sections and angular distributions as the core states in (p, t) reactions on adjoining even-A nuclei. We report here on our study of the reactions ^{31}P(p, t)^{29}P and ^{30}Si(p, t)^{28}Si and show that the data suggest a weak-coupling description for certain positive parity states in ^{29}P.

The ^{31}P(p, t)^{29}P and ^{30}Si(p, t)^{28}Si reactions were studied at $E_p = 40$ MeV at the Michigan State University cyclotron using an Engesplit-pole spectrograph with a single-wire position sensitive proportional counter backed by a plastic scintillator. This system gave a 0.8–1.0 mm position resolution [corresponding to an energy resolution of 25–30 keV FWHM] and excellent particle discrimination. Many new states in ^{29}P were identified.

In fig. 1, we show the observed angular distributions for the positive parity states in ^{29}P and ^{28}Si. The integrated cross sections are displayed in fig. 2. The two ground-state cross sections are essentially identical. The $1/2_2^+$ cross section is however a factor four smaller than the 0_2^+ cross section. The angular distribution shapes for the $L = 2$ transitions to the 2_1^+, $5/2_1^+$ and $3/2_2^+$ states are almost identical and the sum of the cross sections for the $5/2_1^+$ and $3/2_2^+$ states (49 μb) in ^{29}P is equal to the cross section for the 2_1^+ state in ^{28}Si (45 μb). The $L = 4$ transitions in ^{29}P corresponding to that to the 4^+ state in ^{28}Si present some difficulty. Four $L = 4$ transitions in ^{29}P were identified. The one to the 5045 keV state is a factor five weaker than the three illustrated in fig. 1, which are of comparable strength. If we take the identity in angular distribution shapes seriously we select the states at 4640 keV (known $9/2^+$) [7] and 5290 keV (conjectured to be $7/2^+$ in analogy with mirror

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THE STRONGEST $L = 6$ TRANSITIONS OBSERVED IN THE (α, d) REACTION ON ODD-MASS $A = 33 - 41$ TARGET NUCLEI ☆

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Angular distributions of the (α, d) reaction on ^{33}S, ^{35,37}Cl and ^{39,41}K have been measured at $E_\alpha = 40$ MeV. Excited states of the residual nuclei with the $[(\mathrm{target})_{J=3/2} \otimes (1f_{7/2})^2_{J=7}]_{17/2^+}$ configuration are suggested to correspond to the strongest observed $L = 6$ transition in each nucleus.

Previous (α, d) experiments on even-even nuclei [1–4] have shown that the states most strongly populated in this reaction are those in which the transferred proton and neutron enter the same shell-model orbit and couple to the maximum angular momentum with zero isobaric spin. Levels with configurations $[(\mathrm{core})_{J=0} \otimes (1d_{5/2})^2_{J=5}]_{5^+}$, $[(\mathrm{core})_{J=0} \otimes (1f_{7/2})^2_{J=7}]_{7^+}$ and $[(\mathrm{core})_{J=0} \otimes (1g_{9/2})^2_{J=9}]_{9^+}$ were suggested based on three criteria: (a) largest cross section, (b) similar angular distributions, and (c) monotonic increase of the formation Q-value with mass number.

The present letter reports the extension of the search for the highest-spin states of the $[(\mathrm{core}) \otimes (1f_{7/2})^2_7]$ configuration to the $A = 35-43$ odd-mass region. These levels are expected to be the most prominent in the spectra, and the corresponding transitions to be characterized by an $L = 6$ angular distribution. The (α, d) reaction was carried out on enriched ^{33}S, ^{35,37}Cl and ^{39,41}K targets with a 40 MeV α-particle beam from the Michigan State University Cyclotron. The target thicknesses were determined by measureing the elastic scattering and normalizing to calculations with standard optical model parameters. Absolute cross sections thus obtained are estimated to be accurate to within ± 30%. The reaction products were detected in the focal plane of a split-pole magnetic spectrograph with a position-sensitive proportional counter. Fig. 1 shows, as an example, a spectrum from the ^{33}S(α, d)^{35}Cl reaction. The resolution was about 60–80 keV. One level dominates the spectrum. The states corresponding to the largest peak in the (α, d) spectra on the different targets are at 8.84 ± 0.03 MeV in ^{35}Cl, at 7.07 ± 0.01 MeV in ^{37}Ar, at 5.54 ± 0.01 MeV in ^{39}Ar, at 5.22 ± 0.01 MeV in ^{41}Ca and at 4.61 ± 0.03 MeV in ^{43}Ca.

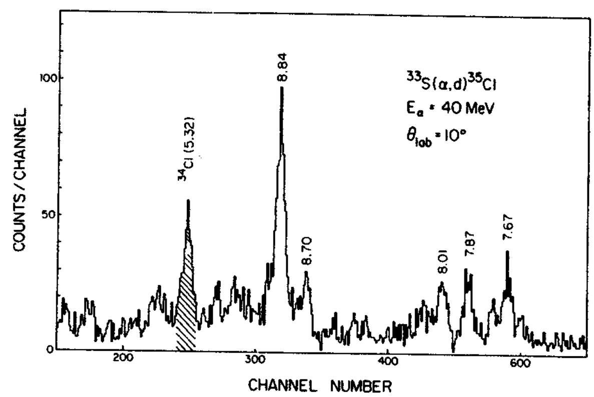

Fig. 1. Alpha-particle spectrum from the ^{33}S(α, d)^{35}Cl reaction.

The angular distributions for the transitions to these states are displayed in fig. 2. In order to identify the expected $L = 6$ angular distributions, an experimental $L = 6$ shape was obtained from the ^{40}Ca(α, d) reaction [5] leading to the known 7^+ state in ^{42}Sc at 0.62 MeV [6]. This shape is superimposed in dashed line on the distributions of the present data. It is clear that all of the displayed angular distributions are consistent with $L = 6$ patterns. It can thus be concluded that the proton-neutron pair is transferred in these cases in the $(1f_{7/2})^2_{J=7,T=0}$ configuration, since this configuration is the one most likely to produce a pure

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EVIDENCE FOR TRIAXIAL SHAPES IN Pt NUCLEI☆

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Positive parity levels in ^{191}Pt obtained from $(\alpha, xn\gamma)$ reactions and β-decay are presented as a first example of a rather complete $i_{13/2}$ level family. The spectrum confirms triaxial shapes found before from $h_{11/2}$ and $h_{9/2}$ proton structures in this mass region. In addition to the usual decoupled yrast band, a second $\Delta I = 2$ band within the $i_{13/2}$ family, built on a low-lying $j-1 = 11/2$ state, is observed in agreement with theory.

From a theoretical standpoint, there are significant advantages in studying the motion of a high-j particle (e.g. $i_{13/2}$ or $h_{11/2}$) around a deformed core. First, these high j-orbitals have unique parity and hence the high-j system may be treated to a good approximation by considering only a single j-shell. Furthermore, positive (negative) parity states in odd nuclei in the mass region $A = 150-200$ may be immediately associated with a predomiantn $\nu i_{13/2}$ ($\pi h_{11/2}$ or $\pi h_{9/2}$) component. Second, the large Coriolis force acting on the high-j particle tends to align its spin along the rotation vector giving rise to characteristic decoupled level structures [1]. The degree to which the particle couples to or decouples from the intrinsic axes of the core strongly depends on the shape of the core, not only on its deformation β but also in a rather sensitive way on the γ-parameter which distinguishes between prolate ($\gamma = 0°$), oblate ($\gamma = 60°$), and various asymmetric, triaxial ($0° < \gamma < 60°$) shapes [2,3]. This leads to striking variations of the odd-A spectrum as a function of γ. As one of the characteristic features, second and third states of the same spin are considerably lowered in energy for triaxial shapes, parallel to the 2_2^+, 3_1^+, 4_2^+ ... states of the even core. This is important for odd-A Pt nuclei.

A number of these features have previously been noted [2,3] in the $h_{11/2}$ and $h_{9/2}$ proton structures of some odd-A Ir, Au, and Tl nuclei. It thus appears that the shape change from the axially symmetric deformed rare-earths to the spherical Pb nuclei proceeds through a triaxial region. The levels of the doubly even Pt nuclei which lie in this transitional region do indeed suggest triaxial shapes, with the 2_2^+ levels lying below the 4_1^+ levels.

In light of the above discussion, we have examined the positive parity structures of a series of odd-A Pt nuclei to obtain information on their shapes. The pertinent experimental information comes from an extensive $(\alpha, xn\gamma)$ investigation of a series of odd- and even-Pt isotopes ($A = 184-194$) which we have recently completed. Prompt and delayed γ-ray singles, prompt and delayed γ-γ coincidence, excitation function and angular distribution measurements were performed, using 26–50 MeV α-particle beams from the Michigan State University cyclotron. The main systematic fea-

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IS MONOPOLE CORE POLARIZATION IMPORTANT IN THE INELASTIC EXCITATION OF LOW LYING 0^+ STATES?☆

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The monopole transition density between the ground and first excited 0^+ states in ^{28}Si and ^{46}Ti is discussed. Both electron scattering and inelastic ^{3}He and α scattering support models of the state which use multiparticle-multihole configurations and disagree with macroscopic or 1p1h models. Thus we conclude that the giant monopole admixture in the low lying 0^+ states is small.

Very little is known about 1p1h monopole admixtures in low lying states although it enters, at least in part, into several different problems such as the isotope shift and the Nolen–Schiffer anomaly. In general this effect of monopole core polarization is difficult to investigate, and so far only qualitative limits on its coupling strength have been obtained [1]. Recently inelastic monopole transitions to low lying 0^+ states have been measured, and it was found that their angular distributions are particularly sensitive to the interaction form factor [2, 3], thus providing a direct test of the importance of monopole core polarization in the excitation of low lying 0^+ states.

These low lying monopole transitions in the sd and $f_{7/2}$ shell have been analyzed by use of form factors due to *n* particle-*n* hole configuration mixing only [2, 3]. Although good fits have been obtained, it is important to know whether core polarization, i.e. 1p1h excitation through two major shells, should be taken into account, because this would drastically change the spectroscopic information extracted. In particular, this could answer the question as to whether for E0 transitions effective operators in the form of a renormalization of the E0 matrix element should be introduced (similar to those for quadrupole transitions, for example) which would give a better agreement of shell model predictions with experimental E0 matrix elements in the sd shell (see ref. [3]).

This is of considerable interest also in connection with the investigation of the nuclear breathing mode which can give information on the compressibility of nuclear matter. Although no such mode has been found experimentally, it has been the subject of many theoretical investigations, with considerable differences in its predicted excitation energy. However, through the mixing into low lying 0^+ states, information on the breathing mode energy may be obtained from the monopole transitions in question.

In the present study 1p1h form factors are discussed for the excitation of first excited 0^+ states in inelastic α scattering from ^{28}Si and ^{3}He scattering from ^{46}Ti. 1p1h admixtures in the wave functions of ground and excited 0^+ state give rise to two different form factors, one due to 1p1h excitations and the other due to recoupling of 1p1h components in ground and excited state. Because the second term employs the overlap of small core polarization components in both channels, in first order its contribution can be neglected. The detailed structure of the 1p1h excitation form factor is given in ref. [4]. Its absolute normalization is obtained by adjusting the 1p1h amplitudes to reproduce the experimental E0 matrix elements. This microscopic description of the monopole core polarization is compared with collective models in ref. [5].

1p1h excitations were considered for ^{28}Si from 1p and $1d_{5/2}$ shell nucleons, for ^{46}Ti from 1p, sd and $f_{7/2}$ shell nucleons. Simple $(d_{5/2})^0$ and $(f_{7/2})^6$ wave functions were used for the ground state configurations. Using a more complicated structure, including e.g. for ^{28}Si $2s_{1/2}$ and $1d_{3/2}$ particle components, leads only to minor changes in the 1p1h form factor. Details of the calculations are the same as in ref. [4]. For the calculations of collective model densities

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Decay of ^{177}Ta to levels in ^{177}Hf

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The locations of 13 energy levels have been deduced from γ-ray singles and γ-γ coincidence measurements on the EC-β^+ decay of ^{177}Ta to ^{177}Hf. Four energy levels and 14 γ rays associated with ^{177}Ta decay were unknown from the previous NaI(Tl) work. The logft values have been assigned to ^{177}Ta EC-β^+ decay, and multipolarities of several transitions have been determined with use of earlier conversion electron data.

[RADIOACTIVITY ^{177}Ta; Measured E_γ, I_γ, γ-γ coin; deduced logft ^{177}Hf; deduced levels, I,\ π. Ge(Li) detectors.]

I. INTRODUCTION

Recent years have seen intense study of the odd neutron Hf and W isotopes because of the presence near the ground state of the positive-parity states associated with the strongly mixed $i_{13/2}$ family of Nilsson single-particle orbitals. Much of this earlier work employed in-beam γ-ray spectroscopy, using primarily $(\alpha, xn\gamma)$ reactions on appropriate Yb or Hf targets. The study of the rotational band structure in such nuclei can yield significant information on the wave functions associated with the intrinsic single-particle configurations. Such data are of special interest because of their apparent relevance to the phenomenon of "backbending" rotational structure recently observed in several even-even rare earth nuclei. Theoretical analysis of the perturbed rotational band structure in both odd-A and even-even nuclei requires as much information as possible about the higher-lying perturbing Nilsson states and their associated rotational bands that mix into the lower-lying bands observed in the $(\alpha, xn\gamma)$ experiments. Such information on higher states can often be obtained from decay scheme studies.

The EC-β^+ decay of ^{177}Ta to levels in ^{177}Hf offers hope for a better understanding of at least one such case where the $i_{13/2}$ single-particle Nilsson orbits lie low in the quasiparticle spectrum; the high-spin behavior of neighboring even-even isotopes may be directly influenced by the intrinsic configuration of these high-j neutrons. The most recent ^{177}Ta decay scheme is that proposed by West, Mann, and Nagle[1] from their work using NaI(Tl) scintillation detectors. It thus seemed reasonable to expect that Ge(Li) detectors might produce a considerable amount of new data on this decay.

II. EXPERIMENTAL

A. Target and source preparation

Sources of 56.6-h ^{177}Ta were produced by the Michigan State University (MSU) sector-focused cyclotron by the ^{175}Lu$(\alpha, 2n)^{177}$Ta reaction on foil targets of natural lutetium. Typical bombardments lasted 8–10 hours at a beam current of 1 μA. The activity was allowed to decay for 3–4 days to eliminate 8-h ^{176}Ta before beginning chemical separation of Ta.

The Ta activity was separated from other reaction products by dissolving the foil in 6 N HCl and extracting the Ta with 2, 4-dimethyl-3-pentanone (diisopropyl ketone), a procedure described in detail by Felber.[2] The γ-ray sources were prepared on sheets of plastic film by evaporating to dryness small amounts of the extracted carrier-free Ta in aqueous solution.

B. Experimental apparatus

The γ-ray singles data were taken using a Ge(Li) detector with 1333-keV photopeak efficiency of 7.5% [relative to a 7.6×7.6 cm NaI(Tl) detector] and resolution of 2.1 keV full width at half-maximum. The source was counted at a source-to-detector distance greater than 5 cm, and a graded Cd-Cu absorber was employed to attenuate the intense x rays which result from predominant (98%) EC-β^+ feeding to the ground and first excited states of ^{177}Hf. The absorber-detector combination was calibrated for efficiency using ^{75}Se, ^{182}Ta, ^{110}Ag^m, and ^{177}Lu^m as standards.

The γ-γ coincidence data were obtained using the previously mentioned detector and another of 7% efficiency. The detectors were placed at 180° geometry to maximize coincidence efficiency and the activity was sandwiched between graded Pb-Cd-

PHYSICAL REVIEW C VOLUME 10, NUMBER 3 SEPTEMBER 1974

$(p, {}^3He)$ and (p, t) reactions on ^{29}Si†

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Differential cross sections of the $^{29}Si(p, {}^3He)^{27}Al$ and $^{29}Si(p,t)^{27}Si$ reactions between $\theta_{lab} = 4$ and 60° have been measured at 40.1 MeV bombarding energy. Assignments of the L transfers on the basis of comparisons to distorted-wave Born approximation (DWBA) calculations yield several new spin and parity assignments for states in ^{27}Si. The experimental differential cross sections of the transitions to several of the low-lying mirror pairs of final states in ^{27}Al and ^{27}Si are compared to the results of microscopic DWBA calculations in order to study the spin-isospin dependence of the interaction potential in the two-nucleon transfer reaction and to test current shell-model wave functions for the nuclear states involved.

[NUCLEAR REACTIONS $^{29}Si(p, t)$, $^{29}Si(p, {}^3He)$, $E_p = 40.1$ MeV; measured $\sigma(E_t, E_{^3He}, \theta)$; enriched target, deduced energies, L values, normalization factors for states of ^{27}Al and ^{27}Si.]

I. INTRODUCTION

The simultaneous investigation of $(p, {}^3He)$ and (p, t) reactions on $T_z = \frac{1}{2}$ targets leading to mirror states in the residual nuclei is of interest for two reasons. Firstly, since the wave functions of the mirror states are essentially identical, the effects of a spin and isospin dependent interaction potential in the distorted-wave Born approximation (DWBA) analysis of the two-nucleon transfer reactions[1] can be studied by comparing the $(p, {}^3He)$ and (p, t) cross sections. Secondly, since the $(p, {}^3He)$ reaction permits the transfer of a proton-neutron pair both in the singlet ($S=0, T=1$) and in the triplet ($S=1, T=0$) states, whereas the (p, t) reaction allows the transfer of two neutrons only in the singlet ($S=0, T=1$) state, it is possible to study in a comparative way different parts of the wave functions of the target and the residual nuclei. It is a complicating feature of the problem that these two aspects are coupled to each other. The accuracy of the determination of the characteristics of the spin-isospin term in the interaction potential depends upon the reliability of the wave functions used in the analysis and, conversely, a meaningful test of wave functions by means of a $(p, {}^3He)$-(p, t) comparison can only be carried out with an accurate knowledge of this same spin-isospin dependent part of the interaction potential used in the DWBA analysis.

Previous work[2-8] in the comparative study of $(p, {}^3He)$ and (p, t) reactions to mirror levels has been carried out principally with $1p$ shell and, to a lesser extent, $2s$-$1d$ shell nuclei. These investigations have been handicapped generally by the lack of theoretical wave functions for the nuclear states involved. The present availability of rather thoroughly tested wave functions for $2s$-$1d$ shell nuclei[9-12] suggests that further work on this topic in this region might be rewarding. The present study of the (p, t) and $(p, {}^3He)$ reactions on ^{29}Si is a part of a systematic investigation of the $({}^3He, p)$, $(p, {}^3He)$, and (p, t) reactions on $T_z = \frac{1}{2}$ target nuclei in the $2s$-$1d$ shell.[13-16] The dual aims are, as mentioned, to arrive at the most secure conclusions possible about the spin-isospin dependence of the interaction potential by studying the widest feasible variety of experimental and theoretical examples, and in each individual case, to make whatever critique is possible about the model wave functions used in the analysis. In addition, the experimental data should yield some new spectroscopic assignments independent of the detailed theoretical analysis.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with a 40.1 MeV proton beam from the Michigan State University cyclotron. The target consisted of SiO and SiO_2, enriched to 95% in ^{29}Si, deposited by vacuum evaporation on a thin layer of Formvar. The effective thickness of the Si + O layer was approximately 0.06 mg/cm^2. The reaction products were detected in a 30 cm long position-sensitive single-wire gas proportional counter placed in the focal plane of a split-pole magnetic spectrograph.[17] The proportional counter was backed by a scintillation counter which was run in coincidence with it to provide background suppression and particle identification. An over-all energy resolution of 25–30 keV was obtained with this system.

Production of the light elements lithium, beryllium, and boron by proton-induced spallation of ^{16}O†

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Astrophysically important cross sections for the production of isotopes of lithium, beryllium, and boron in the proton-induced spallation of ^{16}O were measured for proton energies between 30 and 42 MeV. A time-of-flight method was used for mass identification. The astrophysical significance of the results is discussed.

[NUCLEAR REACTIONS $^{16}O+p$; $E=30.0$, 33.7, 37.9, 41.9 MeV; measured spallation σ for producing masses 6, 7, 10, 11. Gas targets. Discuss astrophysical significance.]

I. INTRODUCTION

Proton- or α-induced spallation of heavier elements is the process most likely responsible for the creation of the bulk of the light elements Li, Be, and B.[1-4] Of the probable targets, chiefly ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{24}Mg, and ^{28}Si, ^{16}O is the most abundant.[5] For this reason, $^{16}O+p$ reactions contribute roughly as much to galactic cosmic ray synthesis[2,3,6] of Li, Be, and B as do $^{12}C+p$ and $^{14}N+p$ reactions, in spite of the fact that the effective Q values[1] are more negative for $^{16}O+p$. This conclusion[6] rests on measurements of the $^{16}O+p$ cross sections at proton energies above 135 MeV, but at lower energies it was necessary to guess the cross sections. Since a crude estimate (based on a typical cosmic ray proton energy spectrum[6] and assuming constant cross sections above effective thresholds near 30 MeV) indicates that 40% or more of the isotope production in $^{16}O+p$ is due to protons with energy below 135 MeV, cross section measurements near threshold are necessary if one wishes to calculate isotope production with confidence. The production of ^7Li is particularly interesting since it has been found that cosmological creation, cosmic ray synthesis, and autogenic production apparently cannot account for the observed abundance.[7]

This paper describes measurements of cross sections for the proton-induced spallation of ^{16}O in the threshold energy region between 30 and 42 MeV. The experimental technique is described in Sec. II, the resulting production cross sections are presented in Sec. III, and their astrophysical significance is discussed in Sec. IV.

II. EXPERIMENTAL TECHNIQUE

A. Detection method

The experimental technique was essentially the same as previously described.[8,9] The target was oxygen confined in an ultra-thin-window[9] gas cell. Double differential cross sections, $d^2\sigma/d\Omega dE$, of the $^{16}O+p$ spallation products were measured and then integrated over angle and energy to yield the total production cross sections. Mass identification was performed using a time-of-flight technique. The proton beam arrived in bursts of 0.5 nsec duration spaced precisely at the period of the cyclotron radiofrequency (rf). Hence, reaction products originated at a well defined time correlated with the rf. After traversing a flight path $d\approx 27$ cm in a time t they were stopped in a silicon surface barrier detector which yielded a timing pulse as well as a signal proportional to the particle energy E. The relationship $Et^2=md^2/2$ then identified the mass m of the particles.

This time-of-flight technique has the advantage over identification by radioactivity or mass spectroscopy of being equally sensitive to all isotopes and the advantage over standard ΔE-E particle identification of being sensitive to heavy reaction products down to energies of 0.1 MeV/amu. Although one does not determine the charge of the particle, knowledge of mass is sufficient for many astrophysical applications since only one isobar per mass number is stable in the region $6\leq A\leq 11$, and most other isobars of the same A produced in this experiment decay to it in a time short compared to astrophysical time scales. Thus the measured cross sections for a given mass can be identified, for most astrophysical purposes, with a particular isotope as follows: mass 6 = ^6Li, mass 7 = ^7Li, mass 10 = ^{10}B, and mass 11 = ^{11}B. Due to its long half-life ^{10}Be is an exception but it is expected to contribute little to the total mass-10 yield (see Sec. IV).

B. Gas cell

The gas cell containing the oxygen gas was the same employed in the ^{14}N spallation measure-

Cross sections for the production of mass-6 and mass-7 nuclides in the proton-induced spallation of ^{20}Ne†

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Cross sections for proton-induced spallation of ^{20}Ne leading to nuclides with mass 6 or mass 7 were measured at proton energies between 30 and 40 MeV. Time-of-flight techniques were used for mass identification.

[NUCLEAR REACTIONS ^{20}Ne+p; E=30.0, 35.0, 40.0 MeV; measured spallation σ for producing masses 6, 7; gas targets. Discuss astrophysical significance.]

I. INTRODUCTION

Since ^{6}Li and ^{7}Li do not survive the hydrogen-burning stage in stars[1] and are not made in their observed abundance by primeval events,[2] it has become clear that these nuclides must be formed by $\alpha+\alpha$ reactions and by the proton- or α-induced spallation of heavier targets.[1-6] Reactions induced by the galactic cosmic rays appear to produce the required amount of ^{6}Li but too little ^{7}Li.[2] While a number of other reaction mechanisms can lead to ^{7}Li production,[2] it is still far from clear which of these are possible or important. Whatever the detailed mechanism, however, measured cross sections for the relevant reactions are a necessary ingredient of a sound creation theory. Spallation cross sections for proton energies from threshold to 40 MeV and above are available for ^{12}C, ^{14}N, and ^{16}O (see Refs. 3, 7–10) but none exist for ^{20}Ne which is nearly as abundant as ^{14}N.

The measurements for ^{20}Ne presented in this paper are part of a program designed to provide spallation cross section measurements on astrophysically interesting targets at proton energies

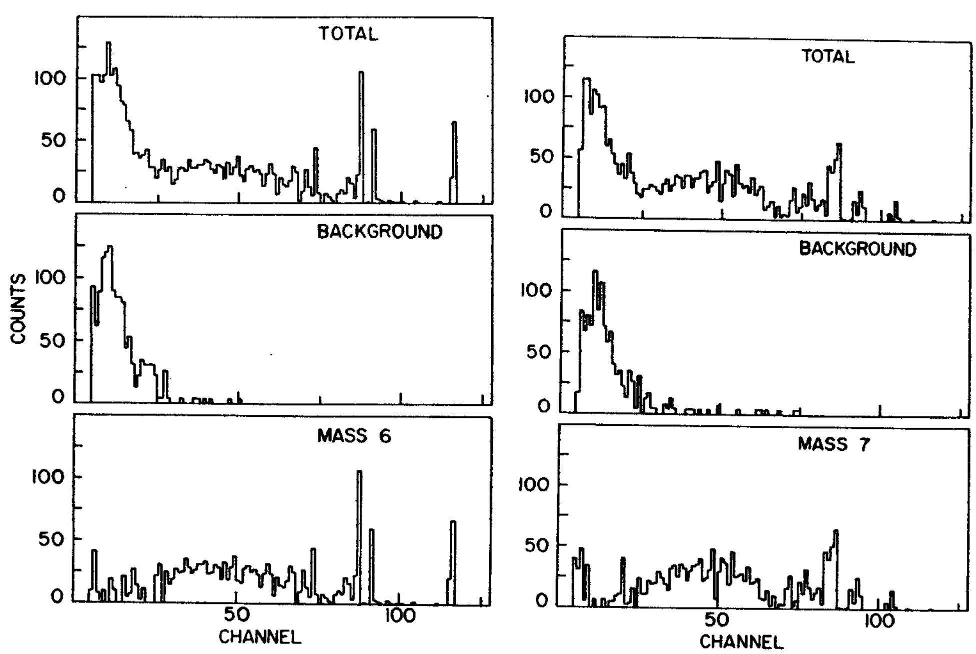

FIG. 1. Particle energy spectra at E_p=40.0 MeV, θ_{lab}=17°. These spectra were derived from a 128 channel × 128 channel array of Et^2 vs E by defining mass bands and projecting them on the E axis. Spectra for 42.0 Torr gas pressure (labeled TOTAL) and for 0.0 Torr gas pressure (labeled BACKGROUND) and their differences (labeled MASS 6 or MASS 7) are shown. The energy scale is 0.18 MeV/channel.

PHYSICAL REVIEW C VOLUME 10, NUMBER 4 OCTOBER 1974

Structure of ^{62}Zn and ^{64}Zn through (p,t) reactions at 35 MeV †

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Energy levels in ^{62}Zn and ^{64}Zn have been investigated via the (p, t) reaction at 35 MeV. Many new levels are reported up to an excitation energy of 5.3 MeV, with spin and parity assignments determined for most levels, including the 0^+ member of the two phonon triplet in ^{62}Zn at 2.33 MeV. A comparison between the states populated in these two reactions is made. Standard distorted-wave calculations give reasonable agreement with the data. However, 3^- and 4^+ states cannot be unambiguously distinguished.

[NUCLEAR REACTIONS ^{64}Zn$(p,t)^{62}$Zn, E=35 MeV, ^{66}Zn$(p,t)^{64}$Zn, E=35 MeV; measured $\sigma(E_t, \theta)$; ^{62}Zn, ^{64}Zn, deduced levels, J, π.]

I. INTRODUCTION

The nucleus ^{62}Zn has been studied in a rather detailed way only recently, primarily by the (p, t) reaction at 27.5[1] and 51.9[2] MeV. Less complete studies of the $(^3\text{He}, n)$[3] and $(^6\text{Li}, d)$[4] reactions to ^{62}Zn, as well as $(p, 2n\gamma)$,[2] have yielded additional information about the low-lying states of this neutron-deficient nucleus. The purpose of this study was to determine with good resolution the excitation energies, spins, and parities of levels in ^{62}Zn as seen by the ^{64}Zn(p, t) reaction. As much of the use of the (p, t) reaction as a spectroscopic tool rests upon the extraction of spins and parities by a comparison of the shapes of the angular distributions with those from states of known J^π, the reaction ^{66}Zn$(p, t)^{64}$Zn was also studied at the same bombarding energy of 35 MeV. More information is available on ^{64}Zn as it is amenable to inelastic scattering studies. However, little information has been gathered on ^{64}Zn via the (p, t) reaction, since earlier studies[5] were done with poor resolution. Therefore, new information regarding the energy levels in ^{64}Zn could also be obtained in this experiment.

II. EXPERIMENT

The experiment used a beam of 35 MeV protons from the Michigan State University sector-focused cyclotron. The outgoing tritons were bent by an Enge split-pole spectrograph and, when using a thick (1.0 mg/cm^2) self-supporting target, were incident upon a single-wire proportional counter in the spectrometer focal plane. The wire counter was mounted in front of a plastic scintillator which allowed gating of the tritons. A resolution of 35 to 40 keV was obtained by this method. Angular distributions were taken for laboratory angles between 3 and 90°.

A higher resolution study at several angles for both nuclei was also carried out by using a thin (200 μg/cm^2) carbon-backed target and Kodak 25 μm NTB photographic emulsions. The exposed plates were hand-scanned and 20 keV resolution obtained. Typical triton spectra from these thin-target runs are shown in Fig. 1 for the reaction ^{64}Zn$(p, t)^{62}$Zn and in Fig. 2 for ^{66}Zn$(p, t)^{64}$Zn.

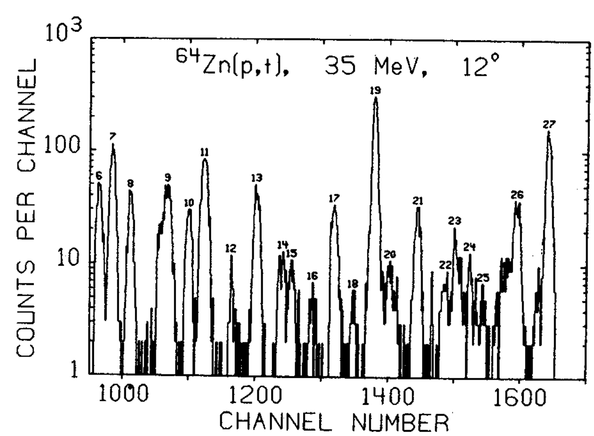

FIG. 1. Spectrum of tritons obtained with a photographic emulsion plate for the reaction ^{64}Zn$(p,t)^{62}$Zn at a laboratory angle of 12° for higher excitation energies. The peak numbers correspond to those listed in Table I.

Levels of ^{56}Ni†

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The ^{58}Ni(p, t)^{56}Ni reaction was studied at 40 and 45 MeV beam energy. An energy resolution of 10–25 keV permitted observation of 60 levels with excitation energy up to 10.5 MeV. Spin and parity are assigned to levels which were excited with characteristic angular distributions. These include 0^+ states at 3.95, 5.00, 6.44, 7.91, 9.92, 9.99, and 10.02 MeV.

[NUCLEAR REACTIONS ^{58}Ni(p,t), E_p =40.0 and 45.5 MeV; measured $\sigma(E_t, \theta)$; enriched target. ^{56}Ni deduced levels, L, J, π.]

I. INTRODUCTION

In the shell-model description, ^{56}Ni is a doubly closed shell nucleus. Therefore the excitations and nature of levels in this nucleus are of considerable importance in nuclear structure calculations. The level structure of ^{56}Ni has been investigated by several authors with only two reactions, ^{58}Ni(p, t)^{56}Ni [1,2] and ^{54}Fe(^{3}He, n)^{56}Ni.[3-6] Since all these studies suffered from a lack of good energy resolution, some discrepancies exist even for low lying states. In the present paper these discrepancies are shown to arise from doublets only one of which had been previously resolved by a ^{54}Fe-(He, $n\gamma$)^{56}Ni experiment.[7] As an example, in (p, t) experiments a spin-parity value of 4^+ was assigned to the level at 3.95 MeV, whereas a value of 0^+ was found in the (^{3}He, n) experiments. In order to resolve this type of discrepancy we measured the ^{58}Ni(p, t)^{56}Ni reaction with better energy resolution than had been previously obtained in studies of ^{56}Ni.

Angular distributions were obtained from 4° to 55° for approximately 60 resolved levels. A beam energy of 40 MeV was employed, at which energy the angular distributions displayed characteristic shapes for each L transfer except for excitation energies greater than 6.5 MeV, where only $L = 0$ could be distinguished. This behavior is due to the low energy of the emitted tritons, which has been shown previously[8] to produce angular distributions which lack distinguishing features. The region of the $T = 2$ state in ^{56}Ni (≈ 10 MeV) was repeated at 45.5 MeV beam energy to determine unambiguously the L transfers in that region.

II. EXPERIMENTAL PROCEDURE

The wire-counter plastic-scintillator combination[9] used in previous (p, t) experiments with the Michigan State University cyclotron was adequate for most of the levels studied in the present experiment. This equipment provides excellent particle identification, but the approximately 1 mm spatial resolution corresponds to 25 keV which is larger than the spacing of many of the doublets in ^{56}Ni. For this reason close lying doublets required use of a silicon position-sensitive detector which permitted a spatial resolution of about 0.5 mm. The wire counter data were taken in two passes; one from 0 to 6 MeV excitation energy, and the other from 5 to 11 MeV. The silicon detector covered only 700 keV excitation and was used for three regions; one around 4 MeV, the second near 5.7 MeV and the third in the 10 MeV region where the $T = 2$ state is expected to lie. A composite spectrum from the wire and silicon detector is given in Fig. 1.

The targets used in the present experiments were ^{58}Ni metal either self-supporting or on an enriched ^{12}C backing. The thicknesses were 240 and 130 μg/cm^2, respectively. A monitor counter detected elastically scattered protons at 90° to normalize the data. The angle subtended by the spectrometer entrance aperature was 1° for forward angles (less than 20°) and for the angular region around 35° where the angular distributions are rapidly varying. At all other angles a 2° aperature was employed. The absolute cross section normalization was obtained by measuring the ground state transition with a thick natural Ni foil which was weighed. The accuracy of the absolute cross section is about 15%.

Considerable attention was given to determining the excitation energies with good accuracy. The method, which was similar to that employed previously,[10] does not rely on the linearity of the detector. The magnetic field of the spectrograph was adjusted to put each peak of interest on the same location of the focal plane. The agreement with previous γ-ray work,[7] when it exists, is ex-

Rotational band structure in $N = 105$ and 107 isotones: I. Evidence for the transition to $|I R j\rangle$ coupling at high spins in ^{179}W[†]

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The ^{177}Hf(α, $2n\gamma$) and ^{181}Ta(p, $3n\gamma$) reactions have been employed in a study of the ^{179}W rotational band structure. Attention is focused on the unique-parity $9/2^+$[624] band and its highly perturbed rotational structure. The higher-spin members of the even-parity band in ^{179}W are not well characterized by a single K quantum number and are better represented in the $|I R j\rangle$ weak-coupling scheme. Limits are placed on the hexadecapole deformation consistent with the rotational band structure in ^{179}W. The relevance of the even-parity band structure in ^{179}W to backbending in neighboring even-A nuclei is discussed.

[NUCLEAR REACTIONS ^{177}Hf(α, $2n\gamma$), $E_\alpha = 26$ MeV, ^{181}Ta(p, $3n\gamma$), $E_p = 26$ MeV; measured E_γ, I_γ, γ-γ coin. Enriched ^{177}Hf target. Deduced ^{179}W levels, I, π, K. Coriolis calculations, implied nuclear deformation, relevance to "backbending."]

I. INTRODUCTION

Recent studies of rotational band structure in odd-A deformed rare-earth nuclei have contributed a wealth of new information on the so-called "parity-unique" Nilsson orbitals arising from the $h_{11/2}$ and $i_{13/2}$ shell-model states. The band structures of the respective odd-proton and odd-neutron orbitals associated with these states have typically been highly perturbed as a consequence of the large Coriolis matrix elements connecting the Nilsson orbitals, Ω and $\Omega \pm 1$.

It is of great interest to develop further the experimental systematics of the unique-parity rotational bands for several reasons: (1) The single-particle structure associated with the transition from well-deformed to spherical nuclei has been poorly understood and indeed little investigated until most recently. Systematic studies of unique-parity band structures, with their known tendency toward decoupling of the odd particle from the rotation of the nuclear core at relatively modest rotational frequencies, offer an opportunity to study in the same nucleus band structure that is at once characteristic of well-deformed and of "transitional" nuclei. (2) Data on the marked increase in the yrast-band moment of inertia in even-even deformed nuclei at high rotational frequencies[1] have given rise to numerous attempts to explain the phenomenon. At least one of the explanations, that proposed by Stephens and Simon,[2] has features that depend on a correct understanding of the behavior of the $i_{13/2}$ neutron orbitals in the presence of a rotating deformed core. In particular, the frequently reported but still apparently unexplained attentuation of Coriolis matrix elements near the Fermi surface, required to reproduce in odd-mass nuclei the experimental energy spacing in rotational bands based on high-j Nilsson orbitals, is apparently essential to the understanding of the yrast states in even-even nuclei within the model of Ref. 2. (3) Finally, further data on isotopic and isotonic odd-A deformed nuclei may clarify the systematic changes in the ordering of the Nilsson single-particle states as a function of quadrupole and hexadecapole deformation. It is to be hoped that rotational band structure and the rapidly accumulating transfer-reaction data will provide a consistent picture of these deformation parameters and the strength of the Coriolis interaction.

The systematics of rotational band structure for the lower-Ω $i_{13/2}$ neutron orbitals are now relatively well documented for the odd-A erbium and hafnium isotopes at least.[3,4] The general trend of the $\frac{5}{2}^+$[642] and $\frac{7}{2}^+$[633] bands in these isotopic series is toward increasing perturbation (and stronger Ω mixture) as one moves toward the more neutron-deficient, less deformed species. Similar data for the higher-Ω $i_{13/2}$ orbitals in the $N \geq 105$ isotones are still relatively incomplete, however, and in view of the special importance of such data for the understanding of both odd-A and, it now appears, even-even species, it seems worthwhile to carry out a systematic study of the even-parity band structure in this region.

The $\frac{9}{2}^+$[624] Nilsson state lies very near the ground state in the $N = 105$ isotones ^{175}Yb, ^{177}Hf, ^{179}W, and presumably ^{181}Os, and is the ground state orbital of the $N = 107$ isotones ^{177}Yb, ^{179}Hf, ^{181}W, and ^{183}Os. Extensive information on nuclear structure has already been deduced from a careful anal-

High resolution (p, p') on ^{207}Pb and ^{209}Bi†

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The inelastic scattering of protons from ^{207}Pb and ^{209}Bi has been measured with energy resolution on the order of 1/5000. Many states were observed and a number of weak coupling multiplets were identified. Use of the collective model and weak coupling theory enabled spin and parity assignments to be made. Calculations for the observed single particle states with noncentral forces and with core polarization are presented.

[NUCLEAR REACTIONS ^{207}Pb(p,p'), ^{209}Bi(p,p'), $E = 35$ MeV; measured $\sigma(\theta)$, $\theta = 10-100°$. Deduced L, β_L; microscopic DWBA analysis.]

I. INTRODUCTION

Nuclei that are only one or two particles away from a shell closure permit the valence nucleon-core interaction to be investigated. The lead mass region is well suited for such investigation due to the purity of the double shell closure and the knowledge of many states in ^{208}Pb. This paper reports the (p,p') study of ^{207}Pb and ^{209}Bi which can be considered as a ^{208}Pb core with a valence neutron hole or proton particle. Inelastic proton scattering was used to excite a variety of states in these nuclei. Collective, single particle, and apparently complex excitations have all been observed and angular distributions recorded.

Experimentally, ^{207}Pb and ^{209}Bi are difficult to study because of the high level density and fractionation of inelastic transition strength. In ^{208}Pb many levels are well separated. In ^{207}Pb or ^{209}Bi, however, weak coupling to core excitations produces a spread of inelastic transition strength among many levels. Often, members of the multiplet are separated from one another or other states by only a few keV of excitation energy. For example, the 3.1 MeV multiplet in ^{209}Bi, apparently arising from the $h_{9/2}$ valence proton weak coupled[1] to the 3.2 MeV 5^- vibration in ^{208}Pb, has doublet members separated by less than 5 keV, spans an excitation energy region of only 225 keV, and lies within 15 keV of other states. Such problems necessitate the use of ultra-high resolution techniques for separation and identification of multiplet members from other levels. With data of high quality spin-parity assignments for multiplet constituents and searches for weak coupled states built on high ($E_x \approx 5$ MeV) excitation energy collective core states are possible.

Aside from the weak coupling excitations, inelastic proton scattering from these nuclei allows study of the single particle and single hole states and of the extent of core polarization in their excitation. Core polarization effects in transitions to the most well known single hole states in ^{207}Pb[2-4] and to the $i_{13/2}$ proton state in ^{209}Bi[5] have been examined previously. Here it was hoped to determine the importance of both the ^{208}Pb core and the noncentral forces in the excitation of some of the ^{209}Bi states.

Section II discusses the experimental setup and procedure. The reduction of the data, angular momentum transfer identification, and comparison with previous work are discussed in Sec. III. Calculations involving the weak coupling theory and the microscopic distorted wave Born approximation (DWBA) are shown in Secs. IV and V.

II. EXPERIMENTAL PROCEDURE

The experiment used 35 MeV protons extracted from the Michigan State University cyclotron with beams on target ranging between $\frac{1}{2}$ and 1 μA, the smaller current being used on the lower melting point bismuth. Protons scattered from targets of ^{209}Bi and ^{207}Pb were observed using both a wire proportional counter and photographic emulsions in the focal plane of the Enge split-pole spectrometer. The high resolution cyclotron-spectrograph system were used to obtain typical plate data resolution of 5-10 keV full width at half maximum (FWHM). The plate data spanned the region of excitation energy between about 0.5 and 8.0 MeV. The counter data had a resolution which was detector limited to about 50 keV FWHM and examined the lowest 5 MeV of excitation.

Initially, angular distributions were measured using thick lead and bismuth targets and the wire counter-scintillator setup.[6] Protons exciting the low-lying states were generally well resolved with good statistics. Measurement of the elastic angular distribution was also made. Comparing the

Population of levels in ^{199}Hg following ^{199}Tl decay and intermediate coupling calculations for ^{199}Hg†

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The electron capture decay of ^{199}Tl to levels in ^{199}Hg has been reinvestigated. Twenty new transitions are assigned to the ^{199}Tl decay scheme and the population of two new levels in ^{199}Hg at 750.4 and 1221.2 keV is confirmed. A quasiparticle-phonon coupling model is applied to low-lying levels in ^{199}Hg. Good agreement with experiment is obtained for the eigenvalues, spectroscopic factors, and electromagnetic transition rates and moments by variation of the $f_{5/2}$ neutron energy and by introducing a phenomenological reduction factor in the coupling matrix element.

[RADIOACTIVITY ^{199}Tl measured E_γ, I_γ, γ-γ coin, deduced logft. ^{199}Hg deduced levels, J, π.
NUCLEAR STRUCTURE ^{199}Hg calculated levels, J, π, S, μ, q, $B(E2)$, $B(M1)$, δ, branching ratios. Quasiparticle-phonon coupling.]

I. INTRODUCTION

The level structure of ^{199}Hg has been of considerable theoretical and experimental interest because of its apparent amenity to various interpretations. In the core excitation model of de-Shalit[1] and an extension by Kalish and Gal,[2,3] the one and two phonon 2^+ vibrations of the core are rather strongly mixed among the two observed $\frac{3}{2}^-$, $\frac{5}{2}^-$ doublets which represent core coupling to the ground $p_{1/2}$ neutron. The assumption of small single particle admixture in the core-coupled doublets can apparently account for a number of the decay properties of those states, although problems remain, particularly with regard to the $(\frac{5}{2})^2 \to (\frac{5}{2})^1$ and $(\frac{3}{2})^2 \to (\frac{3}{2})^1$ transitions.[2] Transfer reaction data[4] have indicated an apparent fragmentation of the $p_{3/2}$ and $f_{5/2}$ strength throughout the low-lying levels of ^{199}Hg, which suggests in addition that the assumption of small single particle admixture in several of the low-lying "phonon" states is incorrect. Microscopic pairing plus quadrupole calculations[5,6] employing different treatments of the pairing interaction have met with another difficulty in this region in that they predict a $\frac{3}{2}^-$ ground state. In Sec. IV of this work consideration is given to an intermediate coupling description of the levels in ^{199}Hg. Rather good agreement with experiment is obtained.

In view of the theoretical importance of the relative γ-ray branching intensities from the presumed core-coupled excited states, and the desirability of obtaining a complete picture of the low-lying spectrum of states in ^{199}Hg, it seemed worthwhile to supplement the early NaI(Tl) investigation by Bauer, Grodzins, and Wilson[7] of the 7.4-h electron capture decay of ^{199}Tl to levels in ^{199}Hg. Subsequent experiments detailed the decay of the $\frac{13}{2}^+$ isomeric state (532 keV, $t_{1/2} = 43$ min) and verified the existence of the $\frac{5}{2}^-$ member of the second particle-core coupled doublet seen in Coulomb excitation work.[2,8] Confirming many of the results of these later studies, the present work assigns two new states in ^{199}Hg at 750.4 and 1221.2 keV and places 20 new γ rays in the ^{199}Tl decay scheme.

II. EXPERIMENTAL

Sources of 7.4-h ^{199}Tl were prepared by the ^{199}Au$(\alpha, 2n)^{199}$Tl reaction. Three layers of 12 mg/cm^2 gold foil (99.99%) were bombarded with 29-MeV α particles from the Michigan State University cyclotron. Several hours were allowed for 5.3-h ^{198}Tl to decay before counting was begun.

The γ-ray singles spectra were obtained both with a 10.4% Ge(Li) detector (2.4 keV full width at half-maximum (FWHM); 35 : 1 peak-to-Compton ratio at 1333 keV) and with a 1 cm^3 high-resolution spectrometer (650 eV FWHM at 122 keV). The

States in $N=81$ ^{141}Nd populated by the decay of ^{141}Pm

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The decay of 20.90-min ^{141}Pm has been studied with Ge(Li) and NaI(Tl) γ-ray detectors in a variety of singles and coincidence configurations, including Ge(Li)-Ge(Li) two-parameter "megachannel" coincidence experiments, anticoincidence experiments, and pair ($\gamma^{\pm}$-γ) experiments to determine the relative β^+ feedings. Fifty-two γ rays were identified from this decay, and 43 of these (> 99% of the γ intensity) were placed in a decay scheme containing 23 levels in ^{141}Nd. J^π assignments or limits were made for all of the states. The structures of the lower-lying states in ^{141}Nd are discussed in terms of the shell model, and possible structures are also suggested for many of the higher-lying states. We compare our results with those of previous studies and also with particle-transfer data.

[RADIOACTIVITY ^{141}Pm; measured E_γ, I_γ, $\gamma\gamma$ coin, $\gamma^{\pm}\gamma$ coin, deduced α_K; ^{141}Nd deduced levels, J, π.]

I. INTRODUCTION

^{141}Pm is twice removed from stability on the neutron deficient side of the $N=82$ closed shell and decays with a 20.9-min half-life to 2.5-h $^{141}_{60}Nd_{81}$. The character of ^{141}Nd is such that the decay of ^{141}Pm might be expected to populate rather low-lying neutron-hole states in the daughter which exhibit significant single-particle properties. This is indeed the case, and it is possible to compare the β-decay results presented here with the results of recent particle-transfer experiments. These include ^{142}Nd(p,d)^{141}Nd by Jolly and Kashy[1] and a similar (p,d) study by Chameaux *et al.*[2] as well as the results of Foster, Dietsch, and Spalding[3] from studies of the ^{142}Nd(d,t)^{141}Nd reaction and those of Yagi, Sato, and Aoki[4] on the ^{143}Nd(p,t)-^{141}Nd reaction.

The first positive identification of ^{141}Pm was made in 1952 by Kistiakowsky Fischer.[5] She produced it by bombarding isotopically enriched samples of $^{142}Nd_2O_3$ with 20–30-MeV protons. The half-life was determined to be 22 ± 2 min, in good agreement with our results of 20.90 ± 0.2 min. Prior to 1967, little else had been published about the decay of ^{141}Pm. Then Bleyl, Munzel, and Pfinning[6] reported the half-life to be 20.9 ± 0.05 min, identified several of the strong transitions, and compared their results with the study of Arl't *et al.*[7]; no attempt was made to construct a decay scheme. More recently, Hesse[8] observed 11 transitions that he identified with the decay of ^{141}Pm. These were identified as a by-product of his study of the decay of ^{141}Sm^m. To date the most complete study has been performed by Charvet *et al.*[9] This study identified 24 transitions arising from the decay of ^{141}Pm. Of these 24 transitions, 19 were placed in a decay scheme containing 11 levels.

The present investigation was undertaken as a part of a series of studies of the decay schemes of the neutron deficient $A=141$ isobaric chain. We have identified a total of 52 γ transitions as being associated with the 20.9-min ^{141}Pm decay. Using a variety of coincidence techniques, we place 43 of these in a consistent decay scheme having 23 states. These results are compared with the γ-ray work of previous investigators[7-9] and with the particle transfer experiments.[1-4]

II. SOURCE PREPARATION AND IDENTIFICATION

Most of the 20.9-min ^{141}Pm activity was produced by the ^{142}Nd($p,2n$) ^{141}Pm reaction on targets of Nd_2O_3, with the neodymium enriched to ≈90% ^{142}Nd. The bombarding times were typically 1–2 min with ≈1-μA beams of 24-MeV protons from the Michigan State University sector-focused cyclotron. Counting began within 2 min of the end of the bombardment, and each source was not counted longer than 50 min.

A study of the excitation function was made by varying the incident beam energy in ≈3-MeV steps from below the 14-MeV threshold of the ($p,2n$) reaction to 30 MeV, which is 5 MeV above the

Structure of ^{33}S from a study of the $^{34}S(p, d)^{33}S$ reaction at 35 MeV*

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The $^{34}S(p, d)^{33}S$ reaction has been studied at a proton energy of 35 MeV. Deuteron spectra were analyzed in a magnetic spectrograph with an over-all energy resolution, full width at half-maximum, of about 8 keV. Excitation energies were measured for levels in ^{33}S through 7.5 MeV excitation with an accuracy of ±(1.0 keV + 0.5 keV per 1 MeV of excitation). Values of the orbital angular momenta of neutrons transferred in these transitions, and the corresponding spectroscopic factors, were extracted from the data by means of distorted-wave Born-approximation calculations. Several new $J^\pi = \frac{1}{2}^+$ assignments were made. The experimental results are compared to the predictions of current nuclear structure theories for this nucleus.

[NUCLEAR REACTIONS $^{34}S(p, d)$, $E_p = 35$ MeV; measured $\sigma(E_d, \theta)$; enriched target; deduced energies, l_n values, and spectroscopic factors for states of ^{33}S.]

I. INTRODUCTION

The properties of the low-excitation-energy states of ^{33}S have been studied rather extensively with particle-transfer reactions,[1-7] which have mapped out most of their dominant one- and two-particle features, and with various γ-ray-decay experiments,[8-12] which have yielded a detailed picture of their electromagnetic features. The observed properties of this nucleus have been interpreted in terms of strong-coupling rotational models,[13] weak-coupling vibrational models,[14] and several mixed-configuration shell models.[15-17] The qualitative structure features of ^{33}S and its neighbors do not offer unambiguous guidance as to what theoretical approach would be most satisfactory for this region. Hence choices as to the most advantageous theoretical approach to interpreting the data must be made in large part on the basis of detailed comparisons between observed and predicted phenomena.

The most extensive comparisons between theory and experiment for ^{33}S have been made for the shell-model wave functions of Ref. 17. Those results were obtained by diagonalizing two different Hamiltonians, one constrained to the modified surface δ interaction form (MSDI) and one a combination of free and surface δ elements (FPSDI), in a space spanned by those configurations $d_{5/2}^{n_1}s_{1/2}^{n_2}d_{3/2}^{n_3}$ for which $n_1 \geq 10$. At the present level of knowledge, it appears that this approach, of using a large, albeit moderately truncated, basis space which includes configurations of all three sd-shell orbits, together with a Hamiltonian that gives consistent agreement between calculated and observed level energies for several neighboring nuclei, gives the best representation of observed phenomena.

The present study has two aims. One is to make a reasonably definitive catalog of the levels of ^{33}S which can be excited in a pickup reaction and, where possible, to extend the list of spin-parity assignments of these levels. The other is to derive a set of spectroscopic factors for single-nucleon pickup to ^{33}S from ^{34}S to supplement those previously available.[1] New or more reliable information in either of these areas will provide still more rigorous constraints on what can be considered as an adequate theoretical accounting for this system.

II. EXPERIMENTAL PROCEDURES

The present experiment was carried out with 35 MeV protons from the Michigan State University sector-focused cyclotron. The uncertainty in the absolute calibration of the beam energy was ~50 keV. The deuterons were analyzed with an Enge split-pole magnetic spectrograph and spectra were recorded alternatively with nuclear emulsions (two abutting 25 cm long plates) and a 20 cm long single-wire position-sensitive gas proportional counter. The nuclear emulsions were used to obtain spectra with high energy resolution and precise excitation-energy calibration. The proportional-counter spectra were limited to a resolution of 50 keV, full width at half-maximum (FWHM), by the characteristics of the counter, but these spectra were very useful supplements to those recorded on the emulsions, especially for intense peaks which sometimes could not be counted accurately because of too high a density of track images.

The beam currents on target for this experi-

Decays of the $f_{7/2}$ isomers $^{53}Fe^g$ and $^{53}Fe^m$

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The decays of 8.5-min $^{53}Fe^g$ and 2.5-min $^{53}Fe^m$ have been studied with a variety of γ and β^+ detectors in many different singles and coincidence configurations. States in ^{53}Mn populated by $^{53}Fe^g$ decay were found to lie at 0 ($J^\pi=\frac{7}{2}^-$), 377.9 ($\frac{5}{2}^-$), 1288.0 ($\frac{3}{2}^-$), 1619.9 ($\frac{9}{2}^-$), 2273.5 ($\frac{5}{2}^-$), 2685.6 ($\frac{7}{2}^-$), 2946.6 ($\frac{9}{2}^-$), 3126.7 ($\frac{9}{2}^-$, $\frac{7}{2}^-$, $\frac{5}{2}^-$), and 3248.0 keV ([$\frac{9}{2}$]$^-$). States in ^{53}Fe populated by 3040.6-keV ($\frac{19}{2}^-$) $^{53}Fe^m$ decay were confirmed at 0 ($\frac{7}{2}^-$), 1328.1 ($\frac{9}{2}^-$), and 2339.6 keV ($\frac{11}{2}^-$). In addition, a 3040.6-keV $E6$ and a 1712.6-keV $M5$ transition were found to compete with the 701.1-keV $E4$ isomeric transition in deexciting ^{53}Fe, this being the first observation of such high multipolarities. The $E6$ has an intensity of 6.0×10^{-4} and the $M5$ an intensity of 1.3×10^{-2} relative to the $E4$ transition. The $E4$, $M5$, and $E6$ transitions are retarded by respective factors of 7.6, 4.2, and 4.3 with respect to single-particle estimates and by somewhat larger factors with respect to simple shell-model estimates.

[RADIOACTIVITY $^{53}Fe^{g,m}$ [from ^{53}Mn(p, 3n)]; measured E_γ, I_γ, γ-γ coin, E_{β^+}, I_{β^+}, γ-β^+ coin; calculated logft; ^{53}Fe, ^{53}Mn deduced levels J^π; calculated shell-model wave functions, γ transition probabilities.]

I. PREAMBLE

^{53}Fe, an 8.5-min nuclide, which decays primarily by β^+ emission but with some electron capture (ϵ), was first produced in 1936 by an (α, n) reaction on naturally occurring chromium.[1] However, the γ-ray activity associated with the decay of ^{53}Fe was not reported until 1953.[2] Other than the work of Juliano *et al.*[3] in 1959, very little has been done to ascertain the states in ^{53}Mn populated by the decay of ^{53}Fe. The bulk of the available knowledge concerning the states in ^{53}Mn has been obtained via in-beam γ-ray and transfer-reaction studies. Many different groups have performed such studies, but a representative sampling should include recent work on ^{52}Cr(p, γ),[4,5] ^{53}Cr(p, $n\gamma$),[6,7] ^{50}Cr(α, $p\gamma$),[8] ^{53}Cr(p, n),[9] ^{56}Fe(p, α),[10] ^{52}Cr(τ, d),[11] and ^{52}Cr(α, t)[12] reactions—in these papers one can find references to other and older work.

Knowledge of the ^{53}Mn level scheme is important not just for its own sake, but because it promises to be a good test of the validity of simple shell-model calculations. The $N=28$ closed shell is particularly stable and is less subject to configuration mixing than $N=20$.[13] Thus, the ^{53}Mn nucleus with 28 neutrons and 25 protons provides an excellent example for study of the simple $(1f_{7/2})^{-3}$ proton configuration.

During the course of this investigation, a shorter-lived species was observed and subsequently attributed to a metastable isomer in ^{53}Fe.[14] This isomer has a half-life of 2.5 min and an excitation energy of 3040.6 keV.[14-17] It has been interpreted, primarily through isomer preparation ratios[15] and the reduced transition probability of the isomeric transition (apparently of $E4$ multipolarity), as having a spin and parity of $\frac{19}{2}^-$. This corresponds to the highest spin state that can result from the three-quasiparticle configuration $[(\pi f_{7/2})^{-2}]_{6^+}(\nu f_{7/2})^{-1}$

In this work we report the results of our γ and β^+ studies on these isomers. With the aid of Ge(Li) detectors in various singles and coincidence configurations and with repeated bombardments, many new weak γ rays have been observed. Careful examination of the γ rays deexciting the $\frac{19}{2}^-$ metastable state has resulted in the direct observation of transitions of $E6$ and $M5$ multipolarities.

The measured strengths of these transitions yield an interesting test of simple shell-model assumptions because of the presumed purity of the wave function of the $\frac{19}{2}^-$ state. In a complementary vein, the observed rates constitute a major portion of the little experimental knowledge that is available for such high-multipolarity electromagnetic transitions.

II. SOURCE PREPARATION

$^{53}Fe^m$ and $^{53}Fe^g$ sources were prepared by the ^{55}Mn(p, 3n)^{53}Fe reaction, a clean and relatively

PHYSICAL REVIEW C VOLUME 11, NUMBER 4 APRIL 1975

High-resolution study of ^{40}Ca via inelastic proton scattering at 35 MeV*

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Spectra of inelastic proton scattering on ^{40}Ca have been obtained with 4.5 keV resolution at a bombarding energy of 35 MeV. Cross sections for the excitation of several previously unresolved particle-hole states have been measured. Nearly all known energy levels plus nine new levels have been observed up to an excitation energy of 9.3 MeV, slightly above the proton separation energy, and accurate excitation energies have been determined for these states.

[NUCLEAR REACTIONS ^{40}Ca(p,p'), $E=35.2$ MeV; measured $\sigma(15°, E_p)$, $\sigma(30°, E_p)$; deduced excitation energies; resolution 4.5 keV.]

I. INTRODUCTION

The states in ^{40}Ca which contain large components of the $f_{7/2}-d_{3/2}^{-1}$ shell model particle-hole configuration have been previously identified in $(^3$He$,d)$,[1] (d,n),[2] and $(^3$He$,\alpha)$[3] reaction studies. The observation of these same states via inelastic proton scattering is of particular interest because these cross sections provide a good test of the effective interaction used in the microscopic model for this reaction.

A previous study of the ^{40}Ca(p,p') reaction by Gruhn *et al.*[4] was the subject of such a microscopic analysis by Petrovich *et al.*[5] That analysis was very promising but there were significant uncertainties because several of the states of interest were unresolved from nearby levels. For example, the 30 keV resolution of Ref. 4 was inadequate to resolve the first 4^- particle-hole state which is a member of a 16 keV doublet. Also all four of the $T=1$ states were either unresolved or incompletely resolved.

In the (p,p') study of Gruhn *et al.*[4] complete angular distributions were measured at four different beam energies from 25 to 40 MeV. The goal of the present experiment was to supplement this comprehensive study with high-resolution spectra (4.5 keV resolution) at one of the same bombarding energies. In this way even without complete angular distributions relative yields within the previously unresolved doublets were obtained, thereby allowing a more detailed test of the microscopic inelastic scattering theory.

A by-product of the present experiment is the determination of very accurate excitation energies for almost all of the levels of ^{40}Ca up to over 9 MeV. The uncertainties assigned to these excitation energies are 0.3–1.2 keV thereby allowing unambiguous comparison of levels seen in this study with previous γ ray measurements.

II. EXPERIMENTAL METHOD

This experiment used a 35.2 MeV proton beam from the Michigan State University cyclotron (references in Ref. 4). The high-resolution spectra were recorded on Kodak NTB 25 μm nuclear track plates in the focal plane of an Enge split-pole magnetic spectrograph.[6] Two exposures were made for an integrated charge of 3000 μC each at laboratory scattering angles of 15.0 and 30.0°.

The experimental resolution of 4.5 keV full width at half-maximum (FWHM) was obtained by using the spectrometer in the energy loss or dispersion matching mode[7] with a solid angle of 0.3 msr. Spectrograph aberrations limit the ultimate resolution if larger solid angles are used. The resolution was measured and optimized using the on-line tuning procedure described in Ref. 7. The linewidth of the energy levels recorded on the nuclear emulsions was 0.15 mm FWHM. This necessitated scanning the plates in 0.05 mm steps, which was very time consuming. The resulting spectra were very clean, however, with an average background of about 2 counts per channel in a spectrum which had an elastic peak with a height of about 2×10^6 counts.

A 40 μg/cm^2 target of metallic Ca enriched to 99.9% in ^{40}Ca was prepared by vacuum evaporation onto a 25 μg/cm^2 backing consisting of a thin carbon foil plus two layers of Formvar. A mixture of 5 mg $CaCO_3$ and Zr powder was heated under vacuum in a Ta tube. The tube was crimped at both ends and had a small hole drilled in its side. First CO_2 was driven off by passing current through the tube to heat it to a dull red color and then the resulting CaO was reduced by the Zr with Ca metal simultaneously evaporating through the hole at a much higher temperature. The target was transferred from the evaporator to a vacuum

Microscopic interpretation of inelastic proton scattering from ^{138}Ba and ^{144}Sm†

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Microscopic DWBA calculations for the (p,p') reaction at $E_p = 30$ MeV have been performed for 2^+, 4^+, and 6^+ states in ^{138}Ba and ^{144}Sm. Large-basis shell-model wave functions were used to describe the nuclear states. The effective two-body interaction mediating the inelastic scattering was obtained from a recent survey of inelastic scattering analyses. Polarization charges for the nucleons were extracted using a scheme based on the model of Atkinson and Madsen. Two sets of shell-model wave functions were employed for the ^{138}Ba calculation, and it was found that comparison of the inelastic proton scattering calculations with experiment clearly distinguished between the two sets. For the better wave functions, the polarization charges were essentially independent of state and multipole.

[NUCLEAR REACTIONS ^{138}Ba(p,p'), ^{144}Sm(p,p'), 30 MeV; calculated $\sigma(\theta)$; deduced polarization charges.]

I. INTRODUCTION

The nuclei which concern us in this paper are ^{138}Ba and ^{144}Sm. These are so-called "$N=82$" nuclei, consisting of 6 and 12 valence protons, respectively, outside an assumed closed $N=82$, $Z=50$ core. We have measured the angular distributions for inelastic scattering of 30 MeV protons to about 15 low-lying states in each of these nuclei. The results of that experiment, along with a discussion of other properties of these nuclei, are found in Ref. 1. In this paper we analyze the inelastic scattering to the first and second 2^+, 4^+, and 6^+ states in ^{138}Ba and ^{144}Sm using shell-model wave functions to describe the states and a realistic effective two-body force, taken from a recent survey[2] of inelastic scattering data, to describe the interaction between the incident proton and the valence protons in the target. The knock-on exchange term is included exactly, an important point since recent microscopic analyses of inelastic nuclear scattering data[3-6] have shown that inclusion of the knock-on exchange amplitude removes many of the inconsistencies found in earlier comparisons of experiment and theory.[7]

Most previous microscopic distorted-wave–Born approximation (DWBA) calculations for inelastic scattering have been restricted to regions of the Periodic Table where particle-hole[8,9] or simple shell-model wave functions[5,7] could be assumed for the description of the nuclear states. One purpose of the present work was to determine whether large-basis shell-model wave functions could account for the results of (p,p') measurements on nuclei with several valence nucleons. A second purpose was the extraction of polarization charges for the valence protons which could account for core-polarization effects. Using a model for calculating inelastic scattering enhancement factors developed by Atkinson and Madsen[4] and discussed by McManus,[10] we determined polarization charges appropriate to large-basis shell-model calculations in this mass region. Finally, we considered the information on the structure of the wave functions which can be obtained from a study of the shell-model transition densities. A preliminary report of this work has been published elsewhere.[11]

II. SHELL-MODEL WAVE FUNCTIONS

The shell-model basis space for the wave functions used in the present study consisted of the $1g_{7/2}$ and $2d_{5/2}$ orbits, plus one-proton excitations from this subspace into the $3s_{1/2}$ or $2d_{3/2}$ orbits. The two-body interaction between the valence nucleons was parametrized in terms of a modified surface δ interaction (MSDI), with the four single-particle energies and the two MSDI parameters fixed by making a least-squares fit of model eigenvalues to experimental energies of levels of known J^π in $N=82$ nuclei.

Two Hamiltonians were investigated. The MSDI parameters for the first[12] were obtained by fitting to levels of known J^π from ^{136}Xe through ^{145}Eu ($A=136-145$), and those for the second[13] by fitting to levels from ^{136}Xe through ^{140}Ce ($A=136-140$). The "$A=136-145$" interaction was used to calculate wave functions for both ^{138}Ba and ^{144}Sm, while the "$A=136-140$" interaction was designed for the lower mass $N=82$ isotones, and hence was used only for ^{138}Ba. Table I lists the single-particle energies and MSDI parameters for both Hamiltonians. The basic difference between them is the $1g_{7/2}$-$2d_{5/2}$ single-particle-energy splitting, which was about 500 keV for the $A=136-145$ interaction and

Study of the $^{64}Ni(p,t)^{62}Ni$ reaction*

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Energy levels in ^{62}Ni up to an excitation energy of 6.4 MeV have been studied by the $^{64}Ni(p,t)^{62}Ni$ reaction at 40 MeV bombarding energy with an over-all resolution of 12 keV full width at half maximum. Spins and parities are assigned to levels which were excited with characteristic angular distributions. These include 0^+ states at 2.05, 2.89, 4.23, 4.62, and 5.45 MeV. A distorted-wave analysis based on shell-model wave functions was performed and compared to the experimental differential cross sections.

[NUCLEAR REACTIONS $^{64}Ni(p,t)$, $E=40$ MeV; measured $\sigma(E_t,\theta)$; enriched target. ^{62}Ni deduced levels, L, J, π.]

I. INTRODUCTION

The excitations and the level structure of the Ni isotopes are of considerable interest for nuclear structure calculations. The closure of the $1f_{7/2}$ shell at ^{56}Ni leads to a description of the low-lying states with the proton shells completely inert and the valence neutrons in the $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, and $1g_{9/2}$ shells. Several detailed shell-model calculations have been performed by Auerbach,[1] Cohen *et al.*,[2] and Glaudemans, DeVoigt, and Stephens[3] within the $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$ neutron configuration space.

Considerable experimental information exists of the levels of ^{62}Ni up to an excitation energy of 6 MeV. Information prior to January 1974 is summarized in the compilation of Verheul.[4] Among the recent works, a great deal of new information concerning spin and parity values of many ^{62}Ni states has been provided using the $^{60}Ni(t,p)$,[5] $^{64}Ni(p,t)$,[6] $^{62}Ni(p,p'\gamma)$,[7] $^{61}Ni(p,p')$,[8] and $^{62}Ni(n,\gamma)$[9] reactions and the β decay of ^{62}Co (Ref. 10) and ^{62}Cu (Ref. 11).

The present $^{64}Ni(p,t)^{62}Ni$ experiment forms part of a systematic and high resolution study of the (p,t) reaction on the Ni isotopes with the aim of determining the excitation energies, spins, and parities of levels of the Ni isotopes. Angular distributions were obtained from 6° to 54° for approximately 55 resolved levels in ^{62}Ni up to an excitation energy of 6.4 MeV. The characteristic features of the L transfer in the angular distributions are used to make several new spin-parity assignments.

For both the initial and final nuclei, new shell-model calculations have been performed considering an inert ^{56}Ni core and valence nucleons in the $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, and $1g_{9/2}$ shells where the number of the particles in the $1g_{9/2}$ orbit is limited to be not more than 2. The modified surface δ interaction (MSDI) was used as the effective two-body interaction in the calculations. The interaction strengths A and B as well as the single particle energy of the $1g_{9/2}$ orbit were adjusted to fit experimental ground state binding energies and level spacings. Details of calculations will be presented elsewhere.[12] Based on these, in the following referred to as the MSDI4 wave functions and the shell-model wave functions of Glaudemans *et al.*[3] (in the following referred to as MSDI3 wave functions), microscopic distorted-wave Born approximation (DWBA) calculations have been carried out and compared to the experimental data.

II. EXPERIMENTAL PROCEDURE

The present experiment was performed with a 40 MeV proton beam from the Michigan State University Cyclotron in two different configurations. In one case, the reaction products were detected in a position sensitive wire-counter plastic-scintillator combination in the focal plane of the Enge split-pole magnetic spectrograph. The target used in this arrangement was a 0.38 mg/cm² thick, self-supporting ^{64}Ni foil (isotopic enrichment ≥99%). The energy resolution obtained was about 50 keV full width at half-maximum (FWHM). This configuration of detector and target allowed acquisition of very accurate angular distributions for a number of strong transitions and the tracing out of the deep minima of the $L=0$ angular distributions.

In the other experimental configuration the tritons were detected in Kodak NTB-25 photographic emulsions. Here the target was a 0.25 mg/cm² thick, self-supporting ^{64}Ni foil (isotopic enrichment ≈98%). The resolution of the system was optimized by adjusting the dispersion of the beam across the target while monitoring the resolution

Experimental studies of the neutron-deficient gadolinium isotopes: $^{145}Gd^{m_1}$ and $^{145}Gd^{m_2}$

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An isomer in ^{145}Gd at 27.3 keV is reported with a half-life of 11.5 ± 0.3 nsec and an internal conversion coefficient $\alpha_L = 16.9 \pm 1.4$. This state is described as substantially the $\nu d_{3/2}$ single-neutron state which is fed by the $^{145}Gd^{m_2}$ $\nu h_{11/2}$ isomer and which deexcites through the $\nu s_{1/2}$ ground state. The isomeric transition from $^{145}Gd^{m_1}$ is found to be 99.2 ± 0.2% $M1$ + 0.8 ± 0.2% $E2$, indicating a hindrance factor of 100 in the $M1$ and an enhancement factor of 40 in the $E2$ over the single-particle estimates. Recent information on the $N = 81$ $\frac{11}{2}^-$ isomers is presented for ^{133}Te through ^{147}Dy showing the systematic changes in experimental energies and $M4$ matrix elements.

[RADIOACTIVITY $^{145}Gd^{m_1}$; measured $T_{1/2}$, E_γ, ICC, $\gamma\gamma$ coin; deduced $B(M1)$, $B(E2)$. Ge(Li) detector, 550 eV at 127 keV; Ge(Li) detector, 2.0 keV at 1332 keV. $^{133}Te^{m_1}$, $^{135}Xe^{m_2}$, $^{137}Ba^{m_2}$, $^{139}Ce^{m_2}$, $^{141}Nd^{m_2}$, $^{143}Sm^{m_2}$, $^{145}Gd^{m_2}$, $^{147}Dy^{m_2}$; deduced $B(M4)$.]

In their early work on $^{145}Gd^{m_2}$ decay,[1] Eppley, McHarris, and Kelly (hereafter EMK) reported a weak β-decay branch and a 721.4-keV $M4$ isomeric transition to a state of indeterminate energy. This state lay at low energy in the ^{145}Gd level scheme, and the transition out of it was unobserved at that time. The $M4$ nature of the transition into the first excited state was verified by measuring the conversion coefficients α_K and α_K/α_L. The 85-sec half-life of $^{145}Gd^{m_2}$ made the study of this isomer difficult in the early experiments, but it was established to be the $h_{11/2}$ single-neutron (hole) orbit. The first excited state was then presumed to be a $d_{3/2}$ single neutron (hole), while the ground state was suggested to be the $s_{1/2}$ neutron (hole).[2] This was later verified by atomic beam studies.[3]

In the present work, the $^{145}Gd^{m_1}$ state was found by x-γ coincidence techniques to lie at 27.3 ± 0.1 keV excitation. The conversion coefficient α_L was measured, as was the half-life. This extends the systematic information about the $h_{11/2}$ single-neutron states to a seventh $N=81$ odd-A isotone.

Subsequent to the completion of these experiments, information on the eighth $N=81$ odd-A isotone, $^{147}Dy^{m_2}$, was reported by Rainis, Toth, Newman, Bingham, Carter, and Schmidt-Ott.[4] These authors also determined the energy of the 27.3-keV state in ^{145}Gd. We have extracted the radial matrix element $|M|^2$ for the $M4$ transition in ^{147}Dy and compared this with the other $N=81$ $M4$ transitions. The turnover in the $|M|^2$ vs A curve for this matrix element predicted by EMK at this isotope is clearly substantiated.

A standard fast-slow megachannel coincidence experiment[5] was performed with a planar high-resolution Ge(Li) detector gating on the 3–50-keV energy range and a coaxial 18% efficient (relative to a 7.6-×7.6-cm NaI) Ge(Li) detector gating on the energy region above 500 keV. Pairs of coincidence events were gathered on magnetic tape along with information about the time between the events. The coincidence time resolution on prompt events was ≈10 nsec full width at half-maximum. Sources of $^{145}Gd^{g+m}$ were prepared from $^{148}Sm(\tau, 6n)^{145}Gd$ reaction recoils transported by a He-jet thermalizer system[6] and collected on a programmable moving tape surface which brought the source in front of the detector.

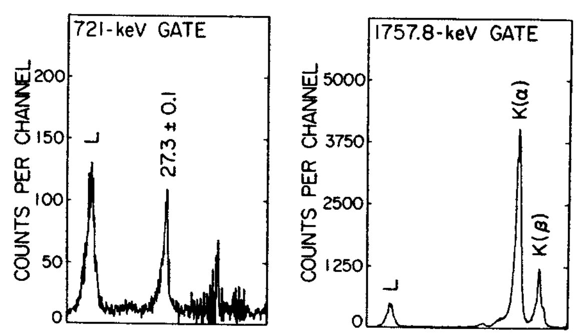

FIG. 1. Spectrum of the 27.3-keV γ ray in coincidence with the 721.4-keV transition from $^{145}Gd^{m_2}$ (left). The L x rays arise from internal conversion. A calibration spectrum (right) is also shown for $K+L$ x rays in coincidence with the 1757.8-keV γ ray from $^{145}Gd^{g}$ decay.

Mass of ^{9}Li†

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New precise determinations of the ^{9}Li mass excess by observation of the ^{10}Be(d, ^{3}He)^{9}Li reaction and by analysis of ^{7}Li(t, p)^{9}Li data have yielded a value of 24.9554 ± 0.0020 MeV. This value, which is 10 keV lower than previous results, makes a significant reduction in the cubic coefficient of the isobaric multiplet mass equation for the $A = 9$ ground state quartet. The new value of d, 5.8 ± 1.5 keV, is considerably closer to theoretical estimates.

[NUCLEAR REACTIONS ^{10}Be(d, ^{3}He) and ^{7}Li(t, p). Measured ^{9}Li mass. Deduced coefficients of IMME for $A = 9$ quartets.]

INTRODUCTION

Precise mass determinations have played an important role in studies of nuclear systematics and decay phenomena. In the case of $A = 9$, the ^{9}Li ground state is the fourth member of a $T = \frac{3}{2}$ isospin quartet which includes ^{9}C in its ground state, and ^{9}Be and ^{9}B in their lowest $T = \frac{3}{2}$ excited levels. The isobaric multiplet mass equation (IMME)

$$M(T_z) = a + bT_z + cT_z^2 \qquad (1)$$

which was proposed by Wigner in 1957,[1] has had a remarkable success in fitting the masses of a large number of $T = \frac{3}{2}$ quartets, and only in the lowest $A = 9$ quartet have the experimental data shown a deviation sufficiently significant to require the addition of a cubic term, dT_z^3, to Eq. (1). Recent experiments have reduced the experimental uncertainties in the masses of the other members of the quartet,[2,3] so that in the latest determination, a value of $d = 7.6 \pm 1.7$ keV is found.[3] A recent investigation of the $T = \frac{3}{2}$ quartet of states based on the first excited state of ^{9}Li ($E_x = 2.691$ MeV, $J^\pi = \frac{1}{2}^-$, $T = \frac{3}{2}$) indicates a d coefficient of 4.2 ± 3.1 keV, which is neither as large nor as significant as for the lower quartet.[4]

Previous determinations of the ^{9}Li mass have been made by the ^{7}Li(t, p)^{9}Li reaction where a value of 24 966 ± 15 keV was obtained for the mass excess[5] and also via the ^{18}O(^{7}Li, ^{9}Li)^{16}O reaction where a value of 24 965.4 ± 5 keV was determined.[6] The availability of a target of the radioactive isotope ^{10}Be ($t_{1/2} = 1.6 \times 10^6$ y) and of the ^{7}Li(t, p)^{9}Li plates exposed recently at Los Alamos by Ajzenberg-Selove and collaborators,[7] who have made them available to us for analysis, as well as the improved accuracy in the other $T = \frac{3}{2}$ members, provided the incentive for the present redetermination of the ^{9}Li mass.

TABLE I. Analysis of (t, p) plates. The asterisk (*) indicates states used as calibrations.

θ_{lab}	Mass Excess of ^{9}Li (keV)	E_x ^{14}C(6) (keV)	E_x ^{14}C(7) (keV)	E_x ^{18}O(15) (keV)
15°	24 956.9	7341.1*	8318.6*	7113.3
10°	24 955.2	7341.4	8318.1*	7114.5*
5.5°	24 954.3	···	8318.0*	7113.9*
Ave.	24 955.5 ± 3.0	7341.2	8318.2	7113.9
Prev. Result	24 965.5 ± 4.7 [a]	7341.4 ± 3.4 [b]	8318 ± 5 [b]	7114 ± 2 [b]

[a] References 5 and 6. [b] Reference 10.

Spectroscopy of ^{52}Mn from the ^{54}Fe(p, ^{3}He) reaction at 40.2 MeV

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The ^{54}Fe(p, ^{3}He) reaction has been studied at 40.2 MeV between 6° and 60°. Assignments of L transfers have been made with distorted-wave Born approximation calculations. These results are compared with other two-nucleon transfer data and theoretical shell-model calculations.

[NUCLEAR REACTIONS ^{54}Fe(p, ^{3}He), E_p = 40.2 MeV; measured $\sigma(E_{^3\text{He}}, \theta)$; enriched target. Deduced energies, L values of ^{52}Mn levels.]

I. INTRODUCTION

Spectroscopic studies with two-nucleon transfer reactions on the $f_{7/2}$ shell nuclei have been quite extensively performed during recent years. Nevertheless, information obtained on these nuclei through (p, ^{3}He) reactions is rather scarce. There are several reasons for such a situation. Firstly, these nuclei have a rather high level density and need to be studied with good energy resolution. Secondly, the cross sections of such reactions are usually low (< 20 μb/sr). These two statements imply the use of thin targets and high beam intensities. The Michigan State University cyclotron is able to deliver 1–2 μA on the target, and at the same time good over-all energy resolution can be obtained using a spectrograph with live focal plane detectors. Live detectors are required because it is almost impossible to separate the low yield ^{3}He particles from other particle types when photographic emulsions are employed. Now that live detectors with spatial resolution better than 1 mm are available it is possible to start studies on $f_{7/2}$ shell nuclei with (p, ^{3}He) reactions. In this work we report results on the reaction ^{54}Fe(p, ^{3}He)^{52}Mn. The nucleus ^{52}Mn can be reached only by a charge exchange reaction[1] or a multinucleon transfer reaction. It has already been studied by the two-nucleon transfer reaction: (d, α) at 15,[2,3] 17,[4] and 28 MeV,[5] (^{3}He,p) at 16[6] and 35 MeV,[7] and (α, d) at 30 MeV.[8] Results obtained with these reactions are rather contradictory for some of the levels observed, and it is of interest to complete the present available data with the (p, ^{3}He) reaction. This reaction is less restrictive than (d, α) since it can proceed either by $S=0$ or $S=1$ neutron-proton pair transfer. Therefore it should permit the observation and spin parity assignment for even J levels reached by $(j)^2$ transfer which is forbidden in (d, α) reactions.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with a 40.2 MeV proton beam from the Michigan State University cyclotron. The target of ^{54}Fe was isotopically enriched (96.8%), and its thickness was 70 μg/cm². It was obtained by vacuum evaporation on an enriched carbon-12 backing of 30 μg/cm². The outgoing ^{3}He particles were detected in a single wire charge-division gas proportional counter placed in the focal plane of an Enge split-pole spectrograph. The wire counter was mounted in front of a plastic scintillator the signal of which was used to gate it, allowing good particle identification. A resolution of 25 keV was obtained as can be seen in the spectrum observed at 16° in Fig. 1. Angular distributions have been taken from 6° to 60° with 4° steps in general. The opening angle of the spectrograph in the reaction plane was 1° for angles below 12° and 2° at all other angles. The angular distributions obtained are displayed in Fig. 2. Only statistical uncertainties are included in the error bars. The accuracy of the absolute cross section is estimated to be about 20%.

III. DISTORTED-WAVE ANALYSIS

Distorted-wave Born approximation (DWBA) calculations were performed using the two-nucleon transfer option of the code DWUCK.[10] In this option the two-particle form factor is calculated by taking the individual motions of the nucleons into account and projecting out the relative angular momentum zero part according to the method described by Bayman and Kallio.[11] The cross section for the (p, ^{3}He) reaction is given by[9]

$$\frac{d\sigma}{d\theta} = D_0^2 \sum_{LSJT} b_{ST}^2 (T_B T | T_A)^2 |(D(S,T)|^2 \sigma_{LSJT}^{\text{DWBA}}(\theta) ,$$

where $\sigma_{LSJT}^{\text{DWBA}}$ is the calculated cross section for

Masses of $T_z = -1/2$ nuclei in the $1f_{7/2}$ shell*

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The $(p, ^6He)$ reaction was used to observe and measure the masses of the proton-rich nuclei ^{45}V, ^{49}Mn, and ^{53}Co, thus completing all mirror pairs in the $f_{7/2}$ shell. New measurements of the masses of ^{43}Ti, ^{47}Cr, ^{51}Fe, and ^{55}Ni were made using the $(^3He, ^6He)$ reaction. Coulomb energy differences of the $T = 1/2$ mirror pairs are extracted, and the new masses are used to predict the masses of proton-rich nuclei with $23 \le Z \le 28$.

NUCLEAR REACTIONS ^{27}Al, ^{50}Cr, ^{54}Fe, $^{58}Ni(p, ^6He)$, $E_p = 46$ MeV, ^{27}Al, ^{46}Ti, ^{50}Cr, ^{54}Fe, $^{58}Ni(^3He, ^6He)$, $E_{^3He} = 70$ MeV, measured Q, deduced mass excess of ^{43}Ti, ^{45}V, ^{47}Cr, ^{49}Mn, ^{51}Fe, ^{53}Co, ^{55}Ni, predicted masses of proton-rich nuclei with $21 \le Z \le 28$.

I. INTRODUCTION

This paper presents the results of the measurements of the ground state masses of the nuclei ^{45}V, ^{49}Mn, and ^{53}Co, and remeasurements of the masses of ^{43}Ti, ^{47}Cr, ^{51}Fe, and ^{55}Ni.[1] The nucleus ^{45}V is observed for the first time, whereas ^{53}Co has been detected previously in a proton-emitting isomeric state,[2] and ^{49}Mn was observed in the $^{40}Ca(^{12}C, t)^{49}Mn$ reaction.[3] The Q value of this heavy ion reaction was consistent with the prediction for the mass of ^{49}Mn under the assumption of equal population of ground and first excited states which were unresolved. The present precision mass measurements employed the $(p, ^6He)$ and $(^3He, ^6He)$ reactions on relatively thin targets. The new measurements complete the series of $T = \frac{1}{2}$ mirror nuclei in the $f_{7/2}$ shell and allow comparison of Coulomb energies throughout an entire nuclear subshell to a shell-model prediction.[4] The results of the present measurement also permit the prediction of the masses of proton-rich nuclei far from the $N = Z$ line by means of the symmetric mass relation of Kelson and Garvey.[5]

II. EXPERIMENTAL METHOD

The determination of the new masses was made by comparing the ^6He particles from the $(p, ^6He)$ reaction on ^{50}Cr, ^{54}Fe, and ^{58}Ni targets to the ^6He particles from the calibration reaction $^{27}Al(p, ^6He)$-^{22}Mg in a magnetic spectrograph. The remeasurements of masses of ^{43}Ti, ^{47}Cr, ^{51}Fe, and ^{55}Ni were made by comparing the ^6He particles from the $(^3He, ^6He)$ reaction on ^{46}Ti, ^{50}Cr, ^{54}Fe, and ^{58}Ni targets to the ^6He particles from the $^{27}Al(^3He, ^6He)$-^{24}Al reaction. Beams of 46 MeV protons and 70 MeV ^3He particles from the Michigan State University cyclotron were used. The detection system consisted of a resistive wire proportional counter with an entrance window of 0.0013 cm aluminized Kapton. After passing through the window and gas of the counter, the particles enter directly into an aluminized plastic scintillator which serves as the back of the wire counter. The elimination of a window between gas and scintillator facilitated the detection in the scintillator of the low energy ^6He particles from the $(p, ^6He)$ reactions. The method and electronics have been previously described.[6] In the $(p, ^6He)$ measurements, the long flight time of the ^6He particles, which exceeded two cyclotron rf periods caused them to overlap with higher velocity particles from later beam bursts. A pulsing system was employed to allow only one-in-three cyclotron beam bursts to reach the target. This removed the ambiguity in mass identification in the time-of-flight spectrum. The measurements were made at lab angles of 8.0 to 10.6° with a solid angle of 1.2×10^{-3} sr. The targets were foils 85 to 325 $\mu g/cm^2$ in thickness which were measured by means of energy loss of ^{241}Am α particles.

III. RESULTS

Figure 1 shows the spectra obtained in the $(p, ^6He)$ reactions. A single state dominates each spectrum and is identified by comparison to the mirror nuclei as the lowest $J^\pi = \frac{7}{2}^-$ level. In ^{49}Mn the $\frac{7}{2}^-$ level is not the ground state but an excited state at 0.26 MeV. The ground state is expected to have $J^\pi = \frac{5}{2}^-$ which is the J^π value of its mirror ^{49}Cr. This seniority-3 state is very weakly excited relative to the $\frac{7}{2}^-$ level with a cross section of only 8 nb/sr. Table I lists the mass excesses from both the present and previous measure-

Unnatural parity transitions in $^{22}Ne(p, t)^{20}Ne$†

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New measurements have been made with the $^{22}Ne(p,t)$ reaction to excite the $K^\pi = 2^-$ rotational band in ^{20}Ne. Coupled-channel Born approximation calculations fail to account for the angular distribution of the transition to the 4^- member of this band, although they describe well that for the transition to the 2^- member. Particularly significant is the failure of the cross section for the 4^- transition to decrease at forward angles. This behavior is in disagreement with that expected for unnatural parity transitions in (p,t) reactions which proceed through multistep processes involving inelastic excitations. The implications of these results for the reaction mechanism are discussed.

[NUCLEAR REACTIONS $^{22}Ne(p, t)$, $E = 40$ MeV; measured $\sigma(\theta)$ for $E_{exc} = 4.97$ (2^-), 5.63 (3^-), and 7.01 (4^-) MeV. Compared to CCBA calculations.]

In view of the current interest in understanding the effects of higher-order (multistep) processes in nuclear transfer reactions, a class of transitions which are particularly important to study are those for which the first-order processes are forbidden or strongly unfavored. For these transitions comparisons between different higher-order reaction theories can be more easily made, since interference from the first-order processes is eliminated. One example of such "forbidden" reactions is a (p, t) transition from a 0^+ initial to an unnatural-parity final state. This transition is allowed in the first-order distorted-wave Born approximation (DWBA) if the full finite-range theory is used or if the usual restriction is removed that the nucleons in the triton be in zero relative-angular-momentum states. However, such effects have been shown to yield negligible contributions.[1] Thus, if compound-nuclear contributions are neglected, the reaction must proceed almost entirely via multistep processes. There are two main types of multistep processes normally considered: those that involve inelastic scattering intermediate steps[2] and those involving successive particle transfer.[3,4]

A particularly interesting case is that of $^{22}Ne(p, t)$ to the $K^\pi = 2^-$ band in ^{20}Ne, for which the unnatural-parity transition to the 2^- bandhead at 4.97 MeV has been observed previously.[2,5,6] Because of the highly collective nature of the nuclei involved, the multistep processes involving inelastic intermediate steps are particularly strong. Olsen *et al.*[2] have shown, using the coupled-channel Born approximation (CCBA), that these effects account very well for the magnitude and shape of their experimental angular distribution for the 2^- transition. In addition, however, Udagawa and Olsen[3] have calculated the $(p\text{-}d\text{-}t)$ successive single-nucleon pickup contribution using the coupled-reaction-channel (CRC) formalism, and have found it to be of similar strength to that of the CCBA contribution. The principal difference between the two calculations is that the CCBA contribution drops rapidly at forward angles, whereas the CRC contribution rises. Udagawa and Olsen[3] showed that this result is a fundamental characteristic of the two processes (as long as contributions from the spin-orbit term of the optical-model potentials are negligible) and follows from the fact that the former proceeds mainly via a spin transfer $S = 0$, whereas the latter proceeds mainly via $S = 1$. There is some question as to the absolute normalization of the CRC calculations because the nonorthogonality of the basis functions used in the various channels is ignored.[3,7] Thus, it was suggested[3] that a measurement of the forward-angle cross section of the 2^- transition would distinguish which process is dominant and thus give some insight into the nonorthogonality correction required in the CRC formalism. Vourvopoulos *et al.*[5] have recently observed the 2^- transition at three angles more forward than the Olsen *et al.*[2] measurements. These data showed a significant decrease in the forward-angle cross section, an effect which was interpreted as unequivocally establishing the dominance of inelastic multistep processes for this transition.

In this note, we would like to report new measurements which show that the mechanism of the $^{22}Ne(p, t)$ reaction to the $K^\pi = 2^-$ band may be more complicated than suggested by Vourvopoulos *et al.*[5] An important test for the multistep calculations is

PHYSICAL REVIEW C VOLUME 12, NUMBER 2 AUGUST 1975

$^{17}O(\alpha,d)^{19}F$ to the $\frac{7}{2}^+$ and $\frac{11}{2}^+$ states*

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The pertinence of the observed features of the $^{17}O(\alpha,d)^{19}F$ transitions to the first two $\frac{7}{2}^+$ and first two $\frac{11}{2}^+$ states in ^{19}F to rotational-model and shell-model descriptions of this nucleus is outlined.

[NUCLEAR REACTIONS $^{17}O(\alpha,d)$, $E=47.5$ MeV; measured $\sigma(E_d,\theta)$ for $\frac{7}{2}^+$ and $\frac{11}{2}^+$ states; DWBA analysis with $(sd)^3$ microscopic wave functions.]

The $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{9}{2}^+$, and $\frac{13}{2}^+$ states of ^{19}F at excitation energies of 0.0, 1.554, 0.197, 2.780, and 4.648 MeV, respectively, can be interpreted in terms of a decoupled $K^\pi=\frac{1}{2}^+$ rotational band. It has been realized for some time that a microscopic treatment in an $(sd)^3$ shell-model space can yield equivalent structural features for these states and that the most accurate description of these states is one obtained from a mixed-configuration shell-model calculation.[1] The $\frac{7}{2}^+$ and $\frac{11}{2}^+$ states that should lie within this same rotational scheme cannot be so clearly identified in the experimental spectrum. The lowest $\frac{7}{2}^+$ state, at 4.378 MeV, is apparently better characterized as $(d_{5/2})^3{}_{J=7/2}$ rather than as the $\frac{7}{2}^+$ member of the rotational sequence, while the state at 5.47 MeV appears[2] to better meet the criteria normally expected for the rotational $\frac{7}{2}^+$ state. The $(d_{5/2})^3$ character of the 4.378-MeV state is evident in the strong β decay[3] to it from the ground state of ^{19}O. The remaining band member to be identified is the state with $J^\pi=\frac{11}{2}^+$. We have attempted to study the character of the two $\frac{11}{2}^+$ states known[4] to occur at 6.499 and 7.935 MeV by populating them with the (α,d) reaction on ^{17}O. For np transfer on ^{17}O leading to an $\frac{11}{2}^+$ state in ^{19}F, the selection rules allow (in an

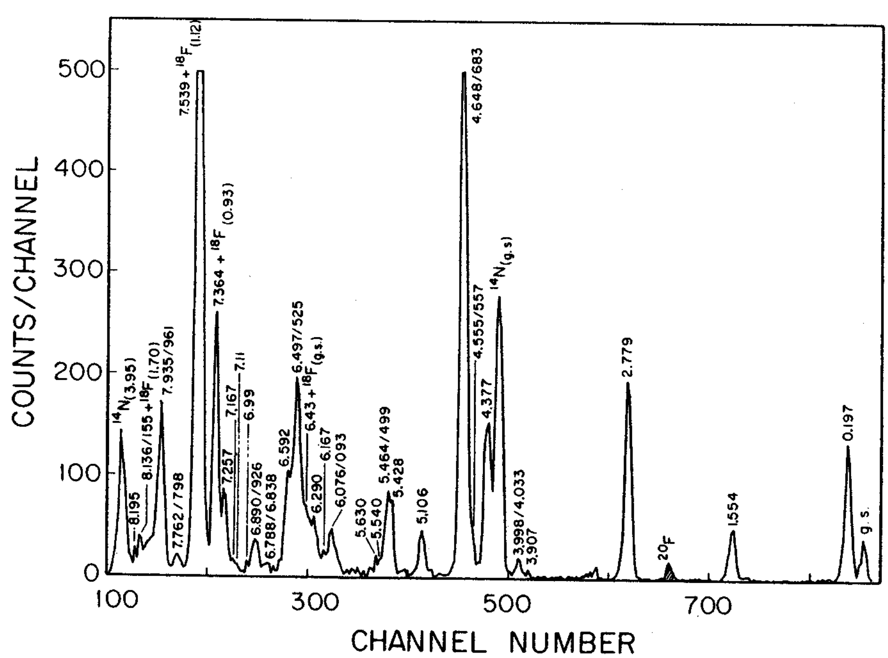

FIG. 1. Spectrum from the $^{17}O(\alpha,d)^{19}F$ reaction at 47.5 MeV and 10°.

PHYSICAL REVIEW C VOLUME 12, NUMBER 2 AUGUST 1975

Microscopic description of isobaric-analog-state transitions induced by 25-, 35-, and 45-MeV protons*

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Differential cross sections have been measured for (p,n) reactions to the isobaric analogs of the targets ^{48}Ca, ^{90}Zr, ^{120}Sn, and ^{208}Pb at proton bombarding energies of 25, 35, and 45 MeV. The isospin-flip strength of a phenomenological nucleon-nucleon force has been determined with microscopic distorted-wave calculations including the "knock-on" exchange amplitude. A realistic G-matrix effective interaction also provides a reasonable account of the observed cross sections, particularly at the higher proton energies.

NUCLEAR REACTIONS ^{48}Ca, ^{90}Zr, ^{120}Sn, $^{208}Pb(p,n)$, $E=25$, 35, 45 MeV; measured IAS $\sigma(\theta)$; compared with microscopic direct-reaction model; deduced effective nucleon-nucleon interaction. Included knockon exchange amplitude.

I. INTRODUCTION

Many nuclear-reaction cross sections have been adequately reproduced with simple one-body potential models of the projectile-target interaction. Nevertheless, a more detailed understanding of nuclear processes requires the calculation of scattering in terms of realistic forces between the individual nucleons. Unfortunately, the nuclear many-body problem cannot be solved exactly with presently available mathematical techniques. Furthermore, realistic nucleon-nucleon potentials are generally too strong for direct perturbation expansions to converge rapidly, if at all. However, approximations based on the multiple-scattering formalism[1] have been employed with reasonable success in both bound-state[2] and scattering[3] calculations.

The multiple-scattering approach to nuclear reactions allows the potential between the projectile and ith target nucleon (v_{ip}) to be replaced with an effective two-body scattering operator which is less pathological. This is accomplished through a rearrangement of the Born series for the scattering amplitude so that the basic interaction includes multiple scattering by a particular target nucleon as the projectile propagates under the average influence of the remainder of the target (the "core"), as represented by a one-body "optical" potential. Such an effective scattering operator may be defined by

$$t_{ip}=v_{ip}+v_{ip}\frac{1}{e^{(+)}}t_{ip}\,, \tag{1}$$

where

$$e^{(\pm)}=E-H_T-k_p-U_{(i)}\pm i\epsilon\,,$$

$$U_{(i)}=\sum_{j(\neq i)=1}^{A}U_j\,,$$

$$(H_T+k_p)\psi=E\psi\,,$$

H_T is the Hamiltonian for the A target nucleons, k_p is the kinetic-energy operator for the projectile, U_j is the contribution of the jth target nucleon to the optical potential, and it is understood that all matrix elements are ultimately evaluated in the limit $\epsilon\to 0$. To first order in t_{ip}, the direct amplitude for inelastic scattering is given by[4]

$$T_{FI}^{(1)}=\sum_{i=1}^{A}\langle\chi_{F(i)}^{(-)}|t_{ip}|\chi_{I(i)}^{(+)}\rangle\,, \tag{2}$$

where

$$\chi_J^{(\pm)}=\psi_J+\frac{1}{e^{(\pm)}}U_{(i)}\psi_J\,,\quad J=I \text{ or } F$$

with initial and final states labeled by I and F, respectively.

Equation (2) has been designated the single inelastic scattering approximation[5] (SISA), since it neglects virtual excitation of the core in intermediate states. Disregarding such processes is an essential feature of the usual microscopic direct-interaction concept of nuclear reactions.[6] However, core excitations are obviously important for a reaction known to proceed through a metastable compound nucleus. Thus, the SISA may only be expected to give a reasonable account of reactions induced by projectiles which bring sufficient energy into the compound nucleus so that the probability of its decay to any particular final state is small compared to that for the competing direct-reaction process. For nucleon-nucleus

PHYSICAL REVIEW C VOLUME 12, NUMBER 3 SEPTEMBER 1975

High-resolution study of ^{208}Pb with 35-MeV protons*

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The inelastic scattering of 35-MeV protons by ^{208}Pb was measured with a resolution of 5–8 keV. Angular distributions of states up to an excitation energy of about 8 MeV were obtained. Collective model calculations enabled the l transfers of many states to be identified. The possibility of excitation of 1^+ states is discussed. Microscopic model calculations were made with both phenomenological and theoretical information. The large number of observed unnatural parity states permitted the role of noncentral forces in these transitions to be investigated.

[NUCLEAR REACTIONS ^{208}Pb(p,p), $E=35$ MeV; measured $\sigma(\theta)$, $\theta=10-100°$. Deduced L, $\beta_L{}^2$. Microscopic DWBA analysis.]

I. INTRODUCTION

Nuclei in the mass region about ^{208}Pb have been extensively studied both experimentally and theoretically. Inelastic scattering[1-6] and Coulomb excitation[7] have given information about the strongly populated states of many of these nuclei Decay studies and transfer reactions[8-11] together with isobaric analog resonance experiments[12-14] have provided information about the microscopic structure of many of the low-lying states. The level properties and the microscopic configurations have been intensively studied in nuclear structure calculations. Also, recent improvements[15] in the theoretical treatment of inelastic proton scattering, primarily use of realistic interactions and explicit inclusion of knock-on exchange effects, have led to successful calculations for cases in which wave functions or transition densities were well known. ^{208}Pb thus is an attractive subject for a high resolution (p,p') experimental study coupled with a microscopic theoretical analysis.

A relatively high resolution ^{208}Pb(p,p') experiment[1] was reported at 24.5 MeV bombarding energy with energy resolution of ≈25 keV full width at half-maximum (FWHM). Spin and parity assignments for the most strongly excited states up to 4.7 MeV of excitation energy were made. Lately, analysis[2] of the (p,p') reaction at 54 MeV has extended l transfer assignments to states up to about 7 MeV of excitation, where ^{208}Pb becomes particle unstable. The resolution was about 35–40 keV FWHM. In both studies, experimental angular distributions were compared primarily with the collective model predictions. To date, these represent the most extensive and highest resolution (p,p') studies of ^{208}Pb. Recently, experiments with charged particle reactions at energies of 30 to 50 MeV and resolution better than 10 keV have become possible. This permits the extraction of cross sections and excitation energies for weakly excited states which can be reliably compared with theoretical predictions.

This paper reports a high resolution study of ^{208}Pb(p,p') performed at 35 MeV with energy resolution on the order of 1 part in 5000. Angular distributions at this bombarding energy have more distinguishing features than those at lower energies yet are not so forward-angle peaked as to make identification of small l transfers difficult. About 150 states with excitation energies up to 7.5 MeV have been experimentally resolved and their angular distributions are presented. Determinations of l assignments and deformation parameters as well as comparison with previous measurements are made. Microscopic model inelastic scattering predictions are compared with the data for normal and nonnormal parity excitations. The existence of magnetic dipole states is also discussed.

II. EXPERIMENTAL PROCEDURE

The experiment used the 35 MeV proton beam from the Michigan State University sector-focused cyclotron, and the scattered protons were detected using the Enge split-pole spectrometer. The high resolution data was recorded on Kodak NTB 25 μm nuclear emulsions in the spectrometer focal plane. A thin stainless steel absorber between 0.25 and 0.38 mm thick immediately before the emulsion stopped all particles other than protons. The absorber decreased the particle

Study of ^{48}V with the ^{50}Cr(p,^{3}He) reaction at 44.7 MeV†

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The ^{50}Cr(p,^{3}He)^{48}V reaction has been studied at 44.7 MeV for levels with an excitation energy up to 3.7 MeV. A distorted-wave Born approximation analysis permitted several L assignments. A comparison with available information on ^{48}V is made.

[NUCLEAR REACTION ^{50}Cr(p,^{3}He), E_p = 44.7 MeV; measured $\sigma(E_{^3\mathrm{He}}, \theta)$; enriched target. Deduced energies, L values of ^{48}V levels.]

I. INTRODUCTION

Studies of the ^{48}V nucleus have been quite extensively performed during the last few years by means of the single nucleon transfer reaction ^{47}Ti(^{3}He, d)[1] and the two-nucleon transfer reactions (d, α)[2,3] and (^{3}He, p).[2,4] In the ^{47}Ti(^{3}He, d) reaction l_p values and spectroscopic factors were extracted. The ^{50}Cr(d, α) reaction was performed by Dorenbusch, Belote, and Rapaport[2] at 7 MeV bombarding energy. Only excitation energies were obtained in this work, whereas several L transfers for levels below 2.0 MeV were obtained by Bachner, Vander Giet, and Lance[3] in a (d, α) experiment at 15 MeV bombarding energy. The two-nucleon stripping experiment (^{3}He, p) has been performed by Dorenbusch *et al.*[2] at 12.0 MeV and by Smith *et al.*[4] at 17 MeV. In the latter case, the emphasis was on 1$^+$ states. The ^{48}V level scheme has also been investigated by means of the charge exchange reaction (^{3}He, t).[5,6] Studies involving γ rays have been performed mainly by three groups: Huber *et al.*,[7] Taras, Haas, and Vaillancourt,[8] and Samuelson *et al.*[9] They have been able to give several spin-parity assignments, and some high-spin states have been reported. Moreover, an odd-parity rotational band constructed on a low-lying 1$^-$ level at 519 keV has been reported by Haas and Taras.[10] Recently, a second rotational band built on a 4$^-$ state at 1099 keV has been proposed by Samuelson *et al.*[9] This latter state was identified by Taras *et al.* as a 5$^+$. Since other discrepancies exist besides this one in the information available on ^{48}V, it was felt to be of interest to add information from a study of the ^{50}Cr(p, ^{3}He) reaction. Moreover, due to the special features associated with this type of reaction, there is unique information to obtain. Theoretical studies[11,12] of the ^{48}V nucleus have employed the shell-model framework with only $f_{7/2}$ particles. No theoretical studies of the rotational bands have yet been made.

II. EXPERIMENTAL PROCEDURE

A 44.7 MeV proton beam of the Michigan State University Cyclotron bombarded a ^{50}Cr target enriched to 96.8%. Its thickness was ~80 μg/cm^2, and it was prepared by vacuum evaporation on a carbon backing of 30 μg/cm^2. The outgoing ^{3}He were momentum-analyzed in an Enge split-pole spectrograph. They were detected and identified by a wire counter and plastic scintillator combination placed in the focal plane.[13] The angular aperture of the spectrograph in the reaction plane was 2° except for angles below 16°, where it was 1°. A typical energy spectrum is shown in Fig. 1. The resolution ranged from 30 to 35 keV. For some regions of the spectra, it was necessary to use the peak fitting program SAMPO[14] in order to determine the area of unresolved peaks. The angular distributions were measured between 6° and 58°; they are displayed in Fig. 2. Only statistical uncertainties are included in the error bars. The absolute cross-section determination was made by reference to the elastic scattering using an identical experimental configuration. The elastic scattering of protons on ^{50}Cr was measured between 20–50°, and the cross sections were then computed from the parameters of Bechetti and

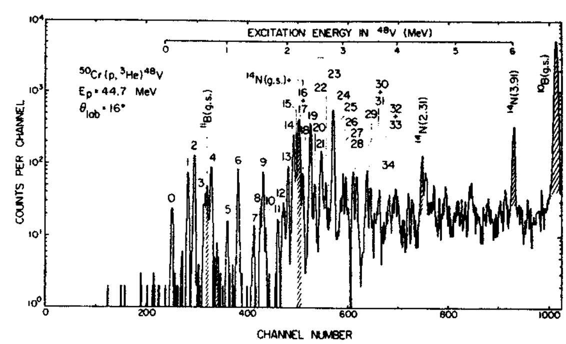

FIG. 1. Energy spectrum of the ^{50}Cr(p, ^{3}He) reaction at 16°.

PHYSICAL REVIEW C VOLUME 12, NUMBER 3 SEPTEMBER 1975

Discrepancies between formation and decay of isobaric analog states of Pb and Bi†

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For nuclei near $A=208$, comparisons have been made between formation of isobaric analog states by the (p,n) reaction and their decay by proton emission. The discrepancy in cross sections is removed if the isobaric analog state formed in the (p,n) reaction is taken to have a Lorentzian rather than Gaussian line shape, and if the background of evaporation and pre-equilibrium protons is subtracted from the proton spectra. The latter procedure should also resolve the width anomaly.

[NUCLEAR REACTIONS ^{208}Pb(p,n) and ^{208}Pb$(p,n\tilde{p})$, $E_p=21$–35 MeV measured σ.]

In a recent letter,[1] an explanation was offered to account for the discrepancies in the lead region between (p,n) reactions populating analog states and $(p,n\tilde{p})$ reactions, i.e., reactions in which analog states are formed by (p,n) and then decay by proton $(\tilde{p})$ emission. The discrepancies noted in that paper are: (1) the larger total widths of the analog states observed in the $(p,n\tilde{p})$ reaction than in the direct (p,n) process on ^{208}Pb and ^{209}Bi, and (2) the much larger cross section measured from $\tilde{p}$ decay than from the direct (p,n) reaction on ^{209}Bi to its isobaric analog in ^{209}Po. The first of these problems has been emphasized previously,[2] where an even larger discrepancy was observed for ^{207}Pb. However, the (p,n) and $(p,n\tilde{p})$ reactions on ^{206}Pb give similar total widths.

The letter by Grimes *et al.* attempts to account for these discrepancies in terms of the excitation of excited analog states and their subsequent decay. We wish to suggest that the explanation offered for (1) above does not apply, and in any case, with improvements in analysis of the data, both width and cross section discrepancies disappear.

In a previous publication,[2] Crawley and Miller examined and ruled out the possibility that population of an excited analog state in the ^{208}Pb$(p,n\tilde{p})$ reaction produces the width anomaly by running at bombarding energies above and below the threshold (21.53 MeV) for excitation of the first excited analog state in ^{208}Bi. The large width was still observed in the decay at 21.15 MeV, thus ruling out this explanation. Grimes *et al.* also suggest that a more isotropic angular distribution near threshold could give additional broadening due to kinematic effects. However, in the analysis of previous data, the broadening from kinematic effects was taken into account explicitly in extracting the width of the analog state.[2,3] In particular, three different shapes were assumed for the (p,n) angular distribution, including an isotropic distribution. We have repeated these calculations at 21.15 MeV and found no great change in the line shape previously computed at 25 MeV.[2,3] For an isotropic distribution the full width at half-maximum kinematic contribution is 0.1 MeV. The conclusion is that kinematic effects cannot explain the anomalous width of about 320 keV observed for ^{208}Pb.

These measurements on ^{208}Pb$(p,n\tilde{p})$[2] do not absolutely rule out the same explanation given by Grimes *et al.* for the case of ^{209}Bi$(p,n\tilde{p})$, since there are two excited $T_>$ states in ^{209}Po, analog of the 0.91-MeV $(\frac{7}{2}^-)$ and 1.61-MeV $(\frac{13}{2}^+)$ states in ^{209}Bi, which could in principle be excited by the (p,n) reaction at the bombarding energy of 21.15 MeV used in Ref. 2. However, two arguments make this explanation unlikely in the case of ^{209}Bi. First, no excited analog states have been observed in (p,n) reactions on these heavy nuclei, and an upper limit of 1 to 2 mb has been placed on their total cross sections.[1] For ^{208}Pb(p,n) at 35 MeV, there may be evidence of excitation to the first excited analog state, but not more than 0.5 to 1 mb.[4] Microscopic calculations for the (p,n) reaction to the 0.91-MeV analog state $(J^\pi=\frac{7}{2}^-)$, using the code DWBA 70[5] and including exchange effects, suggest a total cross section of less than 0.1 mb. A similar result is expected for the 1.61-MeV $(\frac{13}{2}^+)$ analog state. Second order processes may enhance these cross sections but, since these states are not collective, the inelastic scattering to them is small. Therefore, second order processes involving inelastic excitation of the parent states[6] will probably not increase the cross section for the (p,n) reaction by more than a factor of 2 or 3. Such small total cross sections suggest that decays from these states are unlikely to contribute significantly to the total width observed.

In addition, all other aspects of the (p,n) and $(p,n\tilde{p})$ process for ^{208}Pb and ^{209}Bi appear very

PHYSICAL REVIEW C VOLUME 12, NUMBER 4 OCTOBER 1975

$^{37}Cl(p, {}^3He)^{35}S$ reaction*

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Angular distributions of the $^{37}Cl(p, {}^3He)^{35}S$ reaction at 40.2 MeV bombarding energy have been measured for states in ^{35}S up to 9.16 MeV energy excitation. These data have been analyzed with the distorted-wave Born approximation, and values of the angular momentum L transferred to several states have been deduced. A shell-model analysis of the transitions to the low-lying levels has been performed, and the new information gained about the structure of ^{35}S is discussed.

[NUCLEAR REACTIONS $^{37}Cl(p, {}^3He)$, E_p=40.2 MeV; measured ($E_{^3He}, \theta$); enriched target. ^{35}S deduced levels, L values.]

I. INTRODUCTION

Information[1-7] on ^{35}S is rather scarce. Excitation energies of levels up to 7.022 MeV have been determined by Moss[1] via the $^{34}S(d,p)$ reaction. Values of the single-neutron angular momentum transfer l_n to a few levels have been deduced from study of the same reaction by van der Baan and Leighton.[2] Measurements of particle-γ angular correlations from the $^{34}S(d,p\gamma)$ reaction[3] have yielded a few spin assignments or spin limits.

Shell-model calculations have been performed by several authors on this nucleus. The negative-parity states have been studied first by Erne[8] and more recently by Maripuu and Hokken.[9] The latter authors assume a ^{32}S core and $d_{3/2}{}^2f_{7/2}$ and $d_{3/2}{}^22p_{3/2}$ configurations, while only the $d_{3/2}{}^2f_{7/2}$ configuration was assumed by Erne. Positive-parity states have been calculated by Glaudemans, Wiechers, and Brussaard[10] and Wildenthal *et al.*[11] A full s-d vector space is assumed in the calculations of Wildenthal *et al*. together with several different effective Hamiltonians.

The present $^{37}Cl(p, {}^3He)$ experiment was undertaken with the aim of augmenting the existing experimental information on ^{35}S. Determination of the two-nucleon angular momentum L transferred to a level will determine the parity and limit the possible values of the spin assignments for levels about which nothing was previously known beyond the excitation energy. Moreover, to the extent that the reaction mechanism is understood, the validity of the shell-model wave functions for the low-lying levels can be investigated via comparison of the shapes and magnitudes of theoretical angular distributions to the observed data. The only previously existing $^{37}Cl(p, {}^3He)^{35}S$ data consisted of the angular distribution of the transition to the ground state, reported by Vignon *et al.*[12]

II. EXPERIMENTAL PROCEDURE

The experiment was performed with 40.2 MeV protons from the Michigan State University cyclotron. The target of NaCl was isotopically enriched in ^{37}Cl(97%), and the thickness of ^{37}Cl was ~55 $\mu g/cm^2$. It was fabricated by evaporation of the salt onto a carbon backing (30 $\mu g/cm^2$). The reaction products were detected with a wire-counter plastic-scintillator combination placed in the focal plane of an Enge split-pole spectrograph. With this arrangement, good particle identification and an energy resolution of about 30 keV was obtained. A typical spectrum, obtained at 15°, is presented in Fig. 1; levels up to 9.16 MeV have been observed.

Angular distributions measured for various residual levels, taken between 4 and 50°, are displayed in Figs. 2 and 3. Error bars reflect only statistical uncertainties. The $(p, {}^3He)$ cross sections were determined by reference to the elastic scattering of protons, measured between 27 and 49°. The observed elastic scattering cross sections were assumed to be equal in magnitude to those computed from the parameters of Greenlees and Pyle.[13] The observed and calculated *shapes* of the elastic scattering do match each other. The relative rates of the (p,p) and $(p, {}^3He)$ reactions, measured under essentially identical experimental conditions, were then used to establish the cross section scale for the $(p, {}^3He)$ data. We estimate such a procedure to be accurate to 20%.

III. DISTORTED-WAVE ANALYSIS

The theoretical cross sections for the $^{37}Cl(p, {}^3He)^{35}S$ reaction have been calculated with the code DWUCK.[14] The two-nucleon form factor is computed according to the Bayman-Kallio method.[15]

$(f_{7/2})^2{}_{7,0}d_{3/2}{}^{-1}$ configuration states in ^{41}Ca strongly populated by the ^{39}K(α, d) reaction*

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Angular distributions of levels in ^{41}Ca strongly populated in the ^{39}K(α, d) reaction have been measured at E_α = 40 MeV. Levels which have components corresponding to the coupling of the captured proton-neutron pair in the $(f_{7/2})^2{}_{7,0}$ configuration to the ground state of ^{39}K have been identified by means of their characteristic L = 6 angular distributions. Evidence for the $[(f_{7/2})^2{}_{7,0}\ d_{3/2}{}^{-1}]$ 2p-1h character of the states in ^{41}Ca at 3.37, 3.83, 3.92, 3.97, 4.52, 5.22, and 5.35 MeV is discussed.

[NUCLEAR REACTION ^{39}K(α, d), E_α = 40 MeV, measured $\sigma(E_d, \theta)$; natural target; deduced L transfer.]

I. INTRODUCTION

It has been shown previously[1-3] that in the (α, d) reaction the proton-neutron pair is preferentially transferred in a completely aligned configuration. Furthermore, high values of the transferred orbital angular momentum are kinematically favored due to momentum mismatch. Hence, levels corresponding to a $[J_i + (j_p j_n)J_{max}]J_f$ configuration should be populated strongly. Here J_i is the angular momentum of the target nucleus, j_p and j_n are the total angular momenta of the shell-model states into which the transferred proton-neutron pair is captured, coupled to the maximum allowed angular mementum J_{max}, and J_f is the angular momentum of the final state formed by vector coupling of J_i and J_{max}. For odd-A target nuclei where $J_i \neq 0$, $J_i \leq J_{max}$, one expects a multiplicity of $(2J_i + 1)$ high-spin states to be populated. We have studied the ^{39}K(α, d) reaction in order to locate high-spin states with $\frac{11}{2}^+ \leq J \leq \frac{17}{2}^+$ of the $[(f_{7/2})^2{}_{7,0}d_{3/2}{}^{-1}]$ 2p-1h configuration in ^{41}Ca. This configuration is excited by an orbital angular momentum transfer of $L = 6$.

High-spin levels in ^{41}Ca have been studied by Gorodetzky *et al.*[4] and Lieb *et al.*[5] via γ-ray spectroscopy of heavy-ion induced reactions, but these experiments presumably yielded only information about possible spin and parity values for states along the yrast line. The present ^{39}K(α, d) experiment was undertaken to determine the possible configurations of these high-spin states and beyond that to get information about the high-spin states away from the yrast line.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experiment was performed using a 40 MeV α-particle beam from the Michigan State University cyclotron. The target was made by evaporating natural potassium metal onto a thin carbon backing and was kept under vacuum at all times. The target thickness (about 60 μg/cm^2) was determined by measuring the differential cross sections of the elastically scattered 40 MeV α particles and normalizing these data to calculations made with standard optical-model parameters. The re-

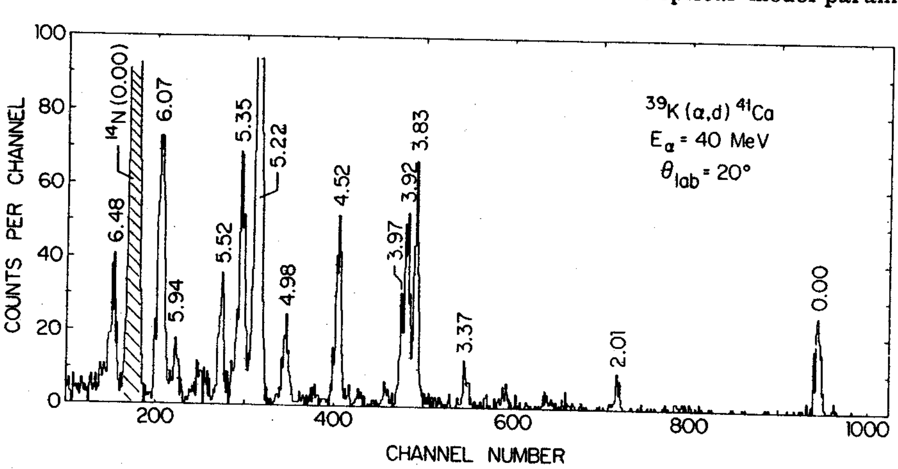

FIG. 1. Deuteron spectrum from the ^{39}K$(\alpha, d)^{41}$Ca reaction taken at θ_{lab} = 20°. The contaminant ground state transition of the ^{12}C$(\alpha, d)^{14}$N reaction is cross hatched.

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Level structure of ^{54}Mn from the ^{56}Fe(p,^{3}He) reaction at 40.2 MeV†

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The ^{56}Fe(p,^{3}He)^{54}Mn reaction has been studied at an incident energy of 40.2 MeV. Levels up to 6.16 MeV of excitation have been observed with an energy resolution of 25 keV. The experimental angular distributions have been analyzed with the distorted-wave Born approximation. Several L assignments have been made which, when compared to other experimental data, permitted new spin assignments. A comparison with theoretical calculations is also presented.

[NUCLEAR REACTIONS ^{56}Fe(p, ^{3}He), E_p = 40.2 MeV; measured $\sigma(E_{^3\mathrm{He}}, \theta)$; enriched target. Deduced energies, L values of ^{54}Mn levels.]

I. INTRODUCTION

Nuclei with $N = 29$ have been the subject of a number of theoretical studies[1–4] in the framework of the shell model. A common feature of all these studies is that the valence neutrons are allowed to occupy $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ shells whereas protons are constrained to remain in the $1f_{7/2}$ shell. The calculations differ in the manner with which they take into account n-n and n-p effective interactions. The $N = 29$ nucleus ^{54}Mn, which has been quite extensively studied during the last past years, can be reached by one- and two-nucleon transfer reactions. Among the one-nucleon transfer reaction works available the (^{3}He, d) experiment of Lynn *et al.*[5] is the most complete; other information obtained through reactions such as ^{53}Cr(d,n)[6] and ^{55}Mn(p,d)[7] is quite limited. The ^{52}Cr(^{3}He,p) reaction has been performed by Lynn *et al.*[5] at 11 MeV incident energy and by Betts, Hansen, and Pullen[8] at 15 and 16.5 MeV. The latter were able to observe the level scheme up to 7 MeV excitation energy. Recently, Kawa, Okada, and Yamagata[9] studied the ^{52}Cr(α,d) reaction at E_α = 24 MeV with a limited energy resolution of about 80 keV emphasizing the excitation of possible high spin states. (d,α) studies have been carried out by Bjerregaard *et al.*[10] (only the level scheme up to 3.2 MeV excitation energy was reported), by Hjorth[11] at 15 MeV incident energy with a limited energy resolution (60 keV), and more recently by Majumder, Sen Gupta, and Guichard.[12] The latter experiment was performed at 12 MeV with 25 keV energy resolution and several L assignments were

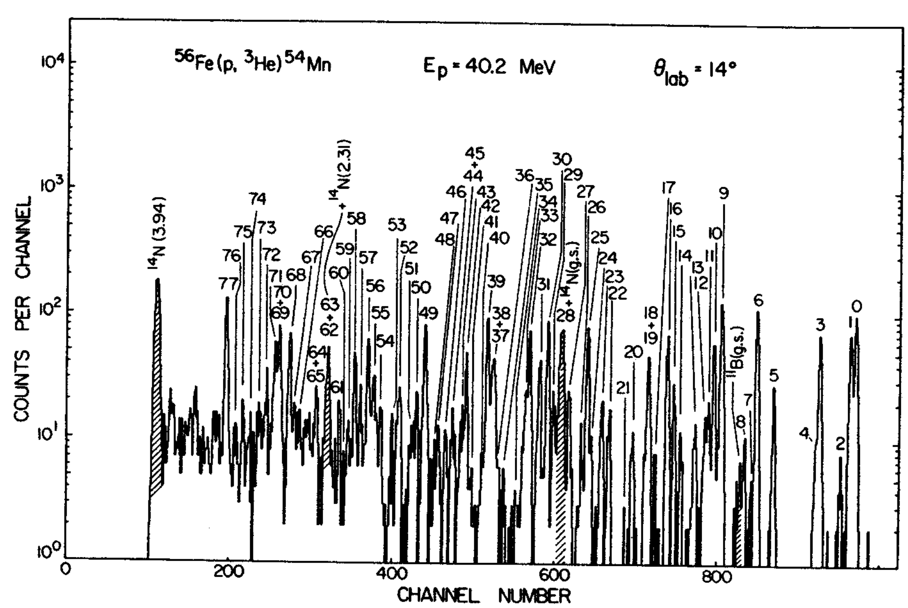

FIG. 1. Energy spectrum of the ^{56}Fe(p, ^{3}He) reaction at 14°.

$^{52}Cr(p, {}^3He)^{50}V$ reaction

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The energy levels in ^{50}V have been observed up to 3.9 MeV with the $^{52}Cr(p, {}^3He)$ reaction at 40.2 MeV incident energy. Forty-five levels have been seen, and a distorted wave analysis permitted L assignments for most of them. These results are compared to existing information and to $f_{7/2}{}^n$ shell-model calculations.

[NUCLEAR REACTION $^{52}Cr(p, {}^3He)$, E_p=40.2 MeV; measured $\sigma(E_{^3He}, \theta)$; enriched target. Deduced energies, L values of ^{50}V levels.]

I. INTRODUCTION

The present work on ^{50}V is part of an investigation of the nuclear structure of some fp shell nuclei via the $(p, {}^3He)$ reaction. The nucleus ^{50}V has been quite thoroughly investigated during the last few years. A great amount of data have been collected through inelastic scattering (p, p')[1] and (d, d')[2] as well as by one- and two-nucleon transfer and charge exchange reactions. Among recent one-nucleon experiments, the (d, t) work of Del-Vecchio *et al.*[3] which was performed with 9 keV resolution, permitted the observation of levels below 3.2 MeV and assigning of l values for most of them. In addition, these authors also reported results on a (d, α) experiment which yielded some spin assignments. The $({}^3He, \alpha)$ pickup reaction has been investigated by Smith *et al.*[4] and Majumder *et al.*[5] These latter authors have explored the ^{50}V spectrum up to 9.3 MeV and have observed five analog states of ^{50}Ti. The one-nucleon stripping reaction $({}^3He, d)$ has been reported by Smith *et al.*,[4] Sourkes, Ohnuma, and Hintz,[6] and Bishop, Pullen, and Rosner.[7] In addition, Smith *et al.*[4] have also performed the $({}^3He, p)$ and $({}^3He, p\gamma)$ experiments, mainly for the determination of 0^+ and 1^+ levels. A more detailed investigation of the $({}^3He, p)$ reaction has been made by Caldwell, Hansen, and Pullen.[8] In this experiment a resolution of 24 keV permitted the observation of 97 states up to 7.5 MeV. Preliminary results on the $^{50}Cr({}^3He, t)$ experiment have been given by Manthuruthil, Poirier, and Meyer-Schützmeister.[9] Studies of the γ-ray deexcitation of ^{50}V by Blasi *et al.*[10] and more recently by Tomita and Tanaka[11] and by Rickel *et al.*[12] have permitted spin assignments for some of the low-lying levels. These experiments reveal that the ^{50}V spectrum is quite complicated and that additional information is needed. The $^{50}Cr(p, {}^3He)$ reaction has never been investigated and, due to the selection rules associated with two-nucleon transfer reactions, should be an interesting way of adding to the present information on ^{50}V.

II. EXPERIMENTAL PROCEDURE

The $^{52}Cr(p, {}^3He)^{50}V$ reaction was investigated with a 40.2 MeV proton beam from the Michigan State University cyclotron. The ^{52}Cr target (isotopically enriched to 99.87%) had a thickness of 115 $\mu g/cm^2$ and was obtained by evaporation on a carbon backing (~30 $\mu g/cm^2$). Reaction products were analyzed by a proportional counter and plastic scintillator combination placed in the focal plane of an Enge split-pole spectrograph. The proportional counter, designed in this laboratory,[13] was of a new slanted cathode construction with delay line readout and permitted good spatial resolution (~0.5 mm). An energy spectrum obtained at 30° is shown in Fig. 1. The over-all energy resolution is 20 keV and is mainly due to energy loss in the target. The spectra have been analyzed with the peak fitting program AUTOFIT,[14] which was necessary for the determination of areas of overlapping peaks. The angular distributions, which were taken between 6° and 54° with 4° steps in general, are displayed in Figs. 2 and 3. Error bars indicate statistical uncertainties only. The uncertainty in the absolute cross section is estimated to be about 20%.

III. DISTORTED WAVE ANALYSIS

Angular distributions were analyzed, as in our previous experiments,[15] by the zero range distorted wave code DWUCK72,[16] in which the two-particle form factor is evaluated according to the Bayman and Kallio[17] method. Optical model parameters are the same as those used in Ref. 15. As can be seen in Figs. 2 and 3 the agreement between calculated and experimental angular distri-

$^{37}Cl(^3He,\alpha\gamma)^{36}Cl$ reaction: γ decay of the two lowest lying $T=2$ states

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The $^{37}Cl(^3He, \alpha\gamma)^{36}Cl$ reaction was studied at 18 MeV, using an enriched $CaCl_2$ target. The γ rays coincident with the α particles emitted at forward angle were detected by two Ge(Li) detectors located at $\theta=90°$ and 125°. Forty-two levels were observed in ^{36}Cl, essentially those seen in the (p,d) reaction. The γ-decay schemes of the two lowest lying $T=2$ levels of ^{36}Cl (analogs of the first two levels of ^{36}S, $J^\pi=0^+$ and 2^+, respectively) have been determined. The lowest $T=2$ level at $E_x=4299.5\pm1.1$ keV, feeds three levels: $E_x=1165$ keV ($J^\pi=1^+$, $65\pm8\%$), $E_x=1601$ keV ($J^\pi=1^+$, $28\pm5\%$), and $E_x=2677$ keV ($J^\pi=1^+$, $7\pm3\%$). The second one at $E_x=7564\pm4$ keV feeds the levels at $E_x=1601$ keV ($42\pm6\%$), $E_x=1960$ keV ($J^\pi=2^+$, $40\pm6\%$), and $E_x=2491$ keV ($J^\pi=2^+$, $18\pm4\%$). These decay schemes are compared with shell model predictions. Some other levels of ^{36}Cl are also discussed.

[NUCLEAR REACTIONS $^{37}Cl(^3He, \alpha\gamma)$, $E=18$ MeV; measured $\sigma(\theta=0°)$; γ-decay schemes of the two first $T=2$ ^{36}Cl states deduced; Ge(Li) detectors; enriched target.]

I. INTRODUCTION

The first $(J^\pi, T)=(0^+, 2)$ levels in the $A=4n$ and $T_z=0$ and $+1$ s-d shell nuclei have been located in a simultaneous study[1] of the (p,t) and $(p, ^3He)$ reactions. Data on the electromagnetic decay mode of some of these states have been obtained[2,3] in the $T_z=+1$ nuclei ^{24}Na, ^{28}Al, and ^{32}P, by studying the γ rays in coincidence with the proton group feeding the first $T=2$ level populated in the $(^3He, p)$ reaction. In the $T_z=0$ nuclei ^{20}Ne, ^{24}Mg, ^{28}Si, and ^{32}S, data have been obtained[4-7] by detecting the γ rays emitted after the formation of the first $T=2$ level as an isospin forbidden resonance in proton or α-capture reactions.

Our aim has been to extend this study of the γ decay of the $T=2$ levels to the $A=36$ and $T_z=0$ and $+1$ nuclei. The results summarized in the present paper concern the $T_z=+1$ nucleus ^{36}Cl and have been obtained using the $^{37}Cl(^3He, \alpha\gamma)^{36}Cl$ reaction which, starting from a $T=\frac{3}{2}$ target, permits feeding of $T=2$ levels. The first $T=2$ level (analog of the $J^\pi=0^+$ ground state of ^{36}S) has been previously observed in several reactions: $^{38}Ar(p, ^3He)^{36}Cl$,[1] $^{37}Cl(^3He, \alpha)^{36}Cl$,[8,9] and $^{37}Cl(p, d)^{36}Cl$.[10,11] The most precise value for the excitation energy of this state $E_x=4299\pm3$ keV has been obtained very recently[11] in a high resolution study of the (p,d) reaction which used a split-pole magnetic spectrograph. In the same study, the second $T=2$ level (analog of the $J^\pi=2^+$ first excited state of ^{36}S) has been identified at $E_x=7557\pm6$ keV. This level had also been observed[9] using the $(^3He, \alpha)$ reaction, as well as two other levels around 8.9 MeV for which a $T=2$ assignment was also proposed. In these one-nucleon transfer reactions the attribution of $T=2$ isospin is based upon excitation energy, transferred orbital momentum, and spectroscopic factor. No experimental data were available as yet concerning the γ decay of these $T=2$ levels.

Additional information about the levels of ^{36}Cl can be found in a recent review article[12] by Endt and van der Leun. Results have been obtained with the transfer reactions already referred to, with other transfer reactions such as (d,p)[13,14] and (p,d),[15] with thermal neutron radiative capture reactions,[16-18] and with the $^{35}Cl(d, p\gamma)^{36}Cl$ reaction.[19]

II. EXPERIMENTAL ARRANGEMENT

The $^{37}Cl(^3He, \alpha)^{36}Cl$ reaction has been studied using an 18-MeV ^3He beam from the Orsay MP tandem. The target (180 ± 25 $\mu g/cm^2$) was prepared by vacuum evaporation of $CaCl_2$ (enriched to 96% in ^{37}Cl) onto a 20-$\mu g/cm^2$ carbon backing.

The γ rays were detected by two Ge(Li) detectors, 42 and 76 cm^3, located in the horizontal plane at $\theta=90°$ and 125° with respect to the direction of the beam. In order to avoid undue loss of resolution, the counting rates were limited to 50 000 counts/sec by setting the detectors 10 cm from the target and reducing the beam intensity to 300 nA. The resolution was measured with a strong

$^{48}Ti(p,{}^3He)^{46}Sc$ reaction*

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The reaction $^{48}Ti(p,{}^3He)^{46}Sc$ has been studied at an incident energy of 40.2 MeV with an energy resolution of 17 keV. Sixty levels have been observed below 3.7 MeV. A distorted-wave Born approximation analysis permitted L assignments for most of them. A comparison with the other information on ^{46}Sc is made.

[NUCLEAR REACTION $^{48}Ti(p,{}^3He)$, $E_p=40.2$ MeV; measured $\sigma(E_{^3He},\theta)$; enriched target. Deduced energies, L values of ^{46}Sc levels.]

I. INTRODUCTION

The nucleus ^{46}Sc has been the subject of detailed studies during the few past years by means of particle transfer reactions and γ-ray experiments. Rapaport, Sperduto, and Buechner[1] have performed a $^{45}Sc(d,p)$ experiment at 7 MeV incident energy with a 12 keV energy resolution and have assigned orbital angular momenta l_n for most of the levels observed. The low-lying levels of ^{46}Sc (up to 1.7 MeV) have been investigated with a $^{47}Ti(d,{}^3He)$ reaction by Lewis,[2] and l_p values were deduced. The $(^3He,p)$ reaction has been studied by Schlegel *et al.*[3] at only a few angles, and only $L=0$ orbital angular momenta were extracted. A $^{48}Ti(d,\alpha)$ experiment has been conducted by Lewis[4] at $E_d=17$ MeV with an energy resolution of 15 keV and by Guichard *et al.*[5] at $E_d=26.7$ MeV with an energy resolution of 90 keV. In both studies, angular momenta were extracted. The $(^3He,t)$ experiment of Yntema[6] has given spin limits for some of the observed levels. Accurate excitation energies together with spin assignments have been made through (n,γ)[7,8] or $(n,\gamma\gamma)$[9] experiments. Lifetimes of low-lying levels have been measured by Fossan, C. Chasman, and K. W. Jones[10] and Dracoulis, Durell, and Gelletly.[11]

These studies have thus permitted a quite complete investigation of the low-lying part of the ^{46}Sc spectrum and have revealed a quite complicated level scheme. However, information on levels above 1 MeV is not sufficient to give a good characterization of most of the levels. Therefore, we have undertaken the $^{48}Ti(p,{}^3He)^{46}Sc$ experiment in order to augment the present experimental information on ^{46}Sc. Comparison of the angular distributions with distorted-wave theory allows in most cases the extraction of the transferred orbital angular momentum L and, together with other results, may lead to spin or limits on spin values for the observed levels.

This study is part of a systematic investigation of some fp shell nuclei through $(p,{}^3He)$ reactions.[12]

II. EXPERIMENTAL PROCEDURE

The experiment was carried out at the Michigan State University Cyclotron with a 40.2 MeV proton beam. The ^{48}Ti target was isotopically enriched (99.1%) and its thickness was $\approx 50\ \mu g/cm^2$. An Enge split-pole spectrograph momentum analyzed the reaction products, which were detected in the focal plane by a proportional counter using delay line readout backed by a plastic scintillator. The proportional counter was designed in this laboratory[13] and has a good spatial resolution. A spectrum obtained at 30° is shown in Fig. 1. The energy resolution is 17 keV and is limited by target thickness, uncompensated beam energy spread, spectrograph abberations, and detector resolution (≈ 0.3 mm or ≈ 9 keV). The data were analyzed with the peak fitting program AUTOFIT.[14] Angular distributions have been measured from 6° to 54° with a 4° step. They are displayed in Figs. 2 and 3. The error bars represent only statistical uncertainties. The absolute cross section has been determined by reference to the proton elastic cross sections. The proton elastic yield has been measured under the same experimental condition, and the cross sections were computed from the parameters of Becchetti and Greenlees[15] (with $r_R=1.17$ fm). Such a procedure is estimated to be accurate to 20%.

III. DISTORTED WAVE ANALYSIS

The zero range distorted wave code DWUCK72[16] was used to compute the theoretical angular distributions. The two-nucleon form factor was evaluated according to the method of Bayman and Kallio.[17] The optical potential parameters are the

Measurement of the mass of ^{8}C by the ^{14}N(^{3}He,^{9}Li) reaction*

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The mass of the particle-unstable $T_z = -2$ nuclide ^{8}C has been measured by means of the ^{14}N(^{3}He, ^{9}Li) reaction, which has an observed cross section of about 5 nb sr^{-1} at 76 MeV. The mass excess found is 35.06 ± 0.05 MeV, and the width of the ^{8}C ground state is 290 ± 80 keV. The result for the mass excess is more precise than that obtained in a previous (α, ^{8}He) experiment and confirms that significant higher-order terms must be added to the isobaric multiplet mass equation to describe the mass-8 isobaric quintet.

[NUCLEAR REACTIONS ^{14}N(^{3}He, ^{9}Li), $E = 76$ MeV; measured Q, $\sigma(\theta)$. ^{8}C obtained mass, Γ. Deduced a, b, c, d, e coefficients in IMME.]

INTRODUCTION

The recent completion of the mass-8 isobaric quintet, consisting of the ground states of ^{8}C and ^{8}He, and the lowest $T = 2$ states in ^{8}B, ^{8}Be, and ^{8}Li, provided a test of the three-parameter isobaric multiplet mass equation (IMME) in a five-member multiplet.[1] The result was that a quadratic IMME

$$M(T_z) = a + bT_z + cT_z^2$$

described the five masses remarkably well, but that there were definite indications of the need for a term eT_z^4, with $e = 4 \pm 2$ keV. The presence of a significant cubic term dT_z^3 could not, moreover, be ruled out.

The largest single contribution to the uncertainties in these conclusions came from the most proton-rich member of the quintet, ^{8}C, whose mass was known only to ±170 keV. That measurement was made by the ^{12}C(α, ^{8}He) reaction,[2] which has a Q value of −64 MeV. Not only is this reaction inaccessible to the Michigan State University (MSU) cyclotron, but also it introduces an undesirable correlation between the masses of ^{8}C and ^{8}He, which are both members of the multiplet, reducing the precision with which the d and e coefficients can be derived. By using instead the ^{14}N(^{3}He, ^{9}Li)^{8}C reaction, one can eliminate that correlation, and take advantage of the accurately known properties of the MSU cyclotron-spectrograph system. No previous observation of the (^{3}He, ^{9}Li) reaction has been reported, and it is thus of interest not only in the ^{8}C mass measurement but also as a possible route to a large number of very proton-rich nuclei.

EXPERIMENTAL METHOD

In view of the very low cross section expected for the (^{3}He, ^{9}Li) reaction, every effort was made to reduce background and to provide tightly controlled and redundant identification of ^{9}Li particles. An additional problem was the need for a nitrogen target, and the experiments described here have made use of solid Melamine ($C_3N_6H_6$) targets and gaseous N_2 in a gas cell.

Beams of 76-MeV ^{3}He ions from the MSU cyclotron were brought to a focus in the target chamber of an Enge split-pole spectrograph. Reaction products were detected in the focal plane by a triple detector system consisting of two single-wire proportional counters backed by a large Si detector, 5 cm long, 1 cm high, and 1500 μm deep. Use of the Si detector in place of the usual plastic scintillator gave high-resolution total energy signals, and improved discrimination against neutron and γ-ray background. Good resolution (limited by the 2-msr entrance aperture of the spectrograph) was also obtained in the time-of-flight spectrum, in which the transit time of particles through the spectrograph is measured relative to the cyclotron rf period.

The first section of the dual proportional counter provided energy-loss information, and the second both energy-loss and position information. The anode of the second section was of 10-μm nichrome wire, and the position was obtained by the

$^{34}S(p,t)^{32}S$ reaction

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Angular distributions of the $^{34}S(p,t)^{32}S$ reaction at E_p=40 MeV have been measured for states in ^{32}S up to an excitation energy of 11 MeV. Assignments of the L transfers on the basis of the characteristic shapes of the angular distributions yield several new spin and parity assignments for states in ^{32}S. Transitions to several unnatural parity states in ^{32}S were observed with a cross section of about 5 μb/sr. For transitions to the natural parity states distorted-wave analyses based on current shell-model wave functions were performed and compared with the experimental differential cross sections.

[NUCLEAR REACTIONS $^{34}S(p,t)$, E_p=40 MeV; measured $\sigma(E_t,\theta)$; enriched target. ^{32}S deduced levels, L, J, π.]

I. INTRODUCTION

In the simplest shell model, the $2s_{1/2}$ subshell is filled at ^{32}S. The one-particle, one-hole aspects of the ^{32}S level structure can be studied by means of the single-nucleon transfer reactions on the adjacent nuclei ^{31}P and ^{33}S. Since one starts from nonzero spin ground states, the spin values in the final nucleus ^{32}S cannot be determined unambiguously. The two-nucleon transfer reactions on the even target nuclei ^{30}Si and ^{34}S, however, allow unique spin and parity assignments. They also provide information about the two-particle, two-hole character of the ^{32}S levels.

Among the single-nucleon transfer reactions only the $^{31}P(d,n)^{32}S$ (see Ref. 1) and $^{31}P(^3He,d)^{32}S$ (see Refs. 2 and 3) have been studied. The two-nucleon transfer reaction $^{34}S(p,t)^{32}S$ was used[4] to locate the lowest 0^+, $T=2$ state in ^{32}S, but no angular distributions were measured. In the $^{30}Si(^3He,n)^{32}S$ reaction only the ground state transition has been studied so far.[5]

The present investigation of the $^{34}S(p,t)^{32}S$ reaction has two aims. One is to extend the present spectroscopic information about the levels of ^{32}S. The assignment of spins and parities to previously unassigned levels furthers the realm of testing nuclear structure calculations simply on the basis of their predicted energy level spectra. The other aim is to test available shell-model wave functions. The comparison of experimental differential cross sections with the results of microscopic distorted-wave Born approximation (DWBA) calculations based upon matrix elements of the coupled two-particle creation (or annihilation) operator can provide a sensitive test of the wave functions of the initial and final states.

Shell-model wave functions for states of both the target and final nucleus have been calculated by Wildenthal *et al.*[6,7] Older calculations[6] were carried out by diagonalizing a Hamiltonian consisting of a combination of free and surface δ two-body matrix elements in a truncated $(1d_{5/2})^{n_1}(2s_{1/2})^{n_2}(1d_{3/2})^{n_3}$ basis space with $n_1 \geq 10$. In the following we refer to these wave functions as FPSDI wave functions. In more recent calculations,[7] the constraints on the configuration space were removed and the two-body matrix elements were treated as independent free parameters in an empirically adjustment to best fit experimental ground state binding energies and level spacings. We refer to these wave functions as DSD wave functions.

Spectroscopic amplitudes calculated from these two sets of wave functions were used with DWBA to predict relative cross sections of transitions tc states in ^{32}S. The consistency of the ratio of the measured to calculated cross sections then gives measure of the goodness of the theoretical wave functions.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The present experiment was carried out with a 40 MeV proton beam from the Michigan State University cyclotron. The reaction products were detected in a position sensitive wire-counter plastic-scintillator combination on the focal plane of an Enge split-pole magnetic spectrograph. The target consisted of two layers of enriched ^{34}S (9.6% ^{32}S, 0.4% ^{33}S, and 90.0% ^{34}S), sandwiched between layers of Formvar and carbon foils in

^{61,62}Ni(p, d) reactions

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The ^{61,62}Ni(p, d) reactions were studied at 40 MeV. A very pronounced j-dependence effect was observed for the $l=3$ transitions. Spins and parities are assigned to levels of ^{61}Ni which include two $\frac{1}{2}^+$ states. Spectroscopic factors extracted from distorted-wave Born-approximation analysis are compared to shell-model predictions.

[NUCLEAR REACTIONS ^{61,62}Ni(p,d), E=40 MeV; measured $\sigma(E_d, \theta)$; enriched targets. Extracted spectroscopic factors. ^{61}Ni deduced levels, L, J, π.]

I. INTRODUCTION

The nickel isotopes occupy a privileged position in the framework of the shell model since the neighboring doubly-closed ^{56}Ni nucleus can play the role of an inert core in the description of the low-lying states of these isotopes. The excitations and the level structures of ^{60,61}Ni as well as the other nickel isotopes have been quite extensively studied.[1-9] The existing one-neutron pickup data are available from the study of (d, t) reaction by Fulmer and Daehnick.[4] The isobaric analog states have been investigated by Sherr *et al.*[5] with the (p, d) reaction at 28 MeV and the (τ, α) reaction has been studied by Rundquist.[6] The present work concerns an investigation of ^{61,62}Ni(p, d) reactions at 40 MeV. A very pronounced j-dependence effect is observed for the $l=3$ transitions. Spins and parities were assigned to levels of ^{60,61}Ni which include two previously unreported $\frac{1}{2}^+$ states. The spectroscopic factors of strongly excited states were extracted and are compared with results of shell-model calculations.

II. EXPERIMENTAL PROCEDURES

The ^{61,62}Ni(p, d) reactions were investigated using the 40 MeV proton beam from the Michigan State University cyclotron. The beam intensity on target was between 300 and 700 nA. The deuterons were analyzed in the focal plane of a split-pole magnetic spectrograph with a position sensitive single wire proportional counter for both reactions and also with Kodak NTB 25 nuclear emulsions for the ^{61}Ni(p, d) reaction. In the latter case, the dispersion matching and the other techniques described by Blosser *et al.*[10] were used. The energy resolutions were, respectively, 45 and 12 keV full width at half maximum (FWHM). The ^{61,62}Ni targets were self-supporting foils of about 250 μg/cm^2 and were enriched isotopically to 93% and 99%, respectively.

A typical spectrum, as recorded with nuclear emulsion, is shown in Fig. 1. The angular distributions, measured from 4° to 54° are shown in Figs. 2, 3(a), and 3(b). The uncertainty in the absolute cross section obtained in measuring the target thickness, the spectrograph solid angle, and the collected charge is estimated to be about 15%.

III. ANALYSIS OF EXPERIMENTAL ANGULAR DISTRIBUTIONS

For the ^{62}Ni(p, d) reaction, the value of the orbital angular momentum l for each transition is unique, and thus can be determined directly from comparison with the angular distribution of low-lying states with known spin and parity. The distorted-wave Born approximation (DWBA) calculations, made with the DWUCK 72 code,[11] provide the spectroscopic factors s_{lj} according to the formula

$$\frac{\sigma(\theta)_{\text{exp}}}{\sigma_{lj}(\theta)_{\text{DWUCK}}} = \frac{2.29}{2j+1} C^2 S_{lj} ,$$

where C^2 is an isospin coupling coefficient and is equal to unity for all cases considered here. For the ^{61}Ni(p, d) reaction, the spin and parity selection rules are less restrictive, and in most cases two values of l can contribute to the same transition (Table I). A least-squares fitting procedure was thus necessary to determine the relative reduced strength of each l value involved. This method was also applied for nonresolved transitions in the ^{62}Ni(p, d) reaction. Since the DWBA calculations do not reproduce exactly the experimental angular distributions for pure transitions, the values of the spectroscopic factors obtained with the latter procedure were thus less certain.

Mass of ^{35}K†

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The ^{40}Ca(^{3}He, ^{8}Li)^{35}K reaction at 73.7 and 75.8 MeV was employed to make the first observation of ^{35}K and to measure its mass. The Q value for the reaction was found to be -29.693 ± 0.020 MeV and the mass excess to be -11.170 ± 0.020 MeV. Excited states of ^{35}K were found at 1.56 and 2.69 MeV.

[NUCLEAR REACTIONS ^{40}Ca(^{3}He, ^{8}Li), $E=75.8$, 73.7 MeV, measured $\sigma(8°)$ Q value.]

I. INTRODUCTION

In this paper we discuss the first observation of ^{35}K and a measurement of its mass excess. This nucleus is one for which an accurate measurement of the mass is required to complete the ground state isobaric mass quartets in the *sd* shell. ^{35}K and the other $T_z = -\frac{3}{2}$, $A = 4n+3$ nuclei can be reached with either the (p; ^{6}He) or (^{3}He, ^{8}Li) reaction on $A = 4n$, $T_z = 0$ targets. In a recent experiment[1] the (^{3}He, ^{8}Li) reaction was employed for the first time and shown to have some advantages over (p, ^{6}He). The main source of these advantages results from the somewhat less negative Q values and the capability of modern sector focused cyclotrons to produce ^{3}He beam energies 50% higher than proton beam energies.

II. EXPERIMENTAL

The ^{40}Ca(^{3}He, ^{8}Li)^{35}K reaction was induced with 73.7 and 75.8 MeV ^{3}He particles from the Michigan State University cyclotron. The ^{8}Li particles were detected on the focal plane of the Enge split pole spectrograph in the manner described previously.[2] One addition to the scintillator-proportional counter detector system was a second proportional counter which provided redundant energy-loss information. This has proven to be very valuable in reducing background due to occasional events from lighter particles which have energy losses considerably larger than the mean value. Time-of-flight measurements eliminate the vast majority of these events, but the random arrival of a γ ray in the scintillator at the required time for a ^{8}Li could then simulate a ^{8}Li ion.

The targets consisted of 370 and 190 μg/cm^2 of enriched ^{40}Ca on a 20 μg/cm^2 natural carbon backing. The 1% ^{13}C in the backing proved to be the major source of background in this experiment since the (^{3}He, ^{8}Li) reactions on ^{13}C and ^{40}Ca have similar Q values. The energy loss in the ^{40}Ca targets, about 150 and 80 keV, was the determining factor in the resolution and also added to the error of the Q-value determination. Even with the thick target, long runs (≈ 1 day) were required, but the ^{13}C peak present in the spectrum provided a check on drifts. Calibration runs made before and after the data runs showed only a few kilovolts of drift. The final error (20 keV) of the mass includes contributions mainly from centroid determination but also from beam energy and angle determination.

The spectrum of ^{40}Ca(^{3}He, ^{8}Li)^{35}K shown in Fig. 1 was taken at 8° and 73.8 MeV. The cross section for the ^{13}C(^{3}He, ^{8}Li) reaction leading to the ground state of ^{8}B is about 60 times greater than that for the ^{35}K ground state. An enriched ^{12}C backing would have improved the appearance of the data substantially, because much of the background between peaks is due to the ^{13}C(^{3}He, ^{8}Li) reaction to unbound states, but it would not have affected the error of the Q-value measurement. One can also see in Fig. 1 excited states of ^{35}K at 1.56 ± 0.04 and 2.69 ± 0.05 MeV, which correspond to the $\frac{1}{2}^+$ and $(\frac{5}{2}^+)$ levels in the mirror nucleus ^{35}S at almost the same energies.[3] The resolution of the spectrum is about 90 keV which permits an observation of the approximately 200 keV broadening of the ^{35}K(g.s.) + ^{8}Li(0.98 MeV) peak due to the recoil after γ emission by the ^{8}Li. The equivalent companion peak for the 1.56 MeV state is apparently too weak to be observed.

The Q value for the ^{40}Ca(^{3}He, ^{8}He)^{35}K reaction was determined by means of a comparison to the ^{40}Ca(^{3}He, ^{6}Li)^{37}K, ^{40}Ca(^{3}He, ^{7}Li)^{36}K, ^{24}Mg(^{3}He, ^{8}Li)-^{19}Na, and ^{13}C(^{3}He, ^{8}Li) reactions. A list of the cross sections at 8° and 73.8 MeV for these reactions is given in Table I. An average value of these calibrations was used, and a contribution to

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Measurement of the excitation energy of the 7.654 MeV state of ^{12}C and the rate of the 3α reaction*

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The excitation energy of the second excited state of ^{12}C has been measured to be 7654.00 ± 0.20 keV. Combining this result with the recent precise measurement of the atomic mass of ^4He by Smith and Wapstra, the Q value for the reaction $3\alpha \rightarrow {}^{12}C(7654.00)$ is determined to be 379.31 ± 0.21 keV. This result implies a change of +9%, at a stellar temperature of 10^8 K, in the 3α reaction rate quoted in the recent compilation of Fowler, Caughlan, and Zimmerman.

[NUCLEAR REACTIONS ^{12}C, ^{15}N, $^{16}O(p,p')$, $E=34.75$ MeV; magnetic spectrograph; measured excitation energies of $^{12}C(7.65$ MeV), $^{15}N(7.56$ MeV), and $^{16}O(6.13$ MeV) states with 200 eV uncertainties. Measurement related to astrophysical helium burning (3α) rate.]

I. INTRODUCTION

In helium burning stars ^4He is converted into ^{12}C and ^{16}O by the successive reactions

$$3\alpha \rightarrow {}^{12}C \quad (3\alpha \text{ reaction}),$$

$$^{12}C(\alpha,\gamma)^{16}O$$

with reaction rates $P_{3\alpha}$ and $P_{\alpha 12}$, respectively.[1] Since the ratio of ^{12}C to ^{16}O at the completion of helium burning depends strongly on the relative values of the two reaction rates, they must be known accurately if one wishes to determine the initial conditions for calculations of subsequent stages of stellar evolution. Such calculations are presently an active research area in astrophysics.

The rate of the 3α reaction depends on the nuclear parameters according to

$$P_{3\alpha} \propto \Gamma_{rad} e^{-Q/kT}, \tag{1}$$

$$Q = (M_{12}c^2 + E_x) - 3M_\alpha c^2, \tag{2}$$

where k is Boltzmann's constant, c is the velocity of light, T is the temperature, M_{12} and M_α are the atomic mass excesses of ^{12}C and ^4He, and Γ_{rad} is the radiative width of the 7.65 MeV, $J^\pi = 0^+$ state of ^{12}C. The exponential dependence of $P_{3\alpha}$ on the excitation energy E_x of the 7.65 MeV state, coupled with the fact that $kT \simeq 10$ keV in helium burning stars means that E_x must be known rather well if one wishes to predict $P_{3\alpha}$ accurately.

The more recent measurements of E_x are all in good agreement,[2-5] the most precise of them having an uncertainty of 1.1 keV, and the weighted average an uncertainty of perhaps 0.8 keV, depending somewhat on the extent to which the various measurements are regarded as uncorrelated. Adding E_x to $-3M_\alpha c^2$, which was known to within ± 0.75 keV,[6] one obtained Q with an uncertainty of 1.1 keV. This yielded an uncertainty of 14% in $P_{3\alpha}$ at $T = 10^8$ K.

There had been little incentive to measure E_x with more precision because of the limiting uncertainty in M_α. A direct measurement of the breakup energy avoids this problem, but it appears that it would be difficult to achieve an accuracy better than the ± 2.0 keV obtained by Barnes and Nichols.[7] Recently, however, the situation has changed. There has been a measurement of M_α with an accuracy of 15 eV[8] and techniques for the measurement of excitation energies have evolved,[9] so that it is now possible to determine Q with a standard deviation of 200 eV, essentially eliminating the contribution of the uncertainty in Q to that in $P_{3\alpha}$. The results of such a determination are described in this paper.

II. EXPERIMENTAL METHOD

The excitation energy of the 7.65 MeV state was measured by using a magnetic spectrograph to compare the momentum of protons inelastically scattered from this state with the calibration momenta of protons scattered from states of accurately known mass. Sufficient known lines were recorded *simultaneously* with the unknown to permit the determination from a single exposure of the beam energy, the scattering angle, and the spectrograph calibration parameters.[9] Such a procedure eliminates many of the uncertainties (such as beam energy and scattering angle variations from run to run) which limit the accuracy of *sequential* calibration-measurement techniques.

High-spin level structure of ^{190}Pt and ^{192}Pt†

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The level structures of the shape transitional nuclei ^{190}Pt and ^{192}Pt have been studied by $(\alpha, xn\gamma)$ reactions on enriched Os targets. The measurements included γ-ray singles, prompt and delayed γ-γ coincidences, half-life determinations in the range 1–500 ns, and γ-ray angular distributions. Detailed level schemes for ^{190}Pt and ^{192}Pt, incorporating much new spectroscopic information, are reported. Acute backbending observed at about spin 10 in the positive parity yrast sequences of the two nuclei is attributed to intersection of the ground bands by rotation aligned bands of both $(\nu i_{13/2}^{-2})$ and $(\pi h_{11/2}^{-2})$ character. A description of well-developed 5^- bands observed in both nuclei as semidecoupled $(\nu i_{13/2}, \nu j)$ bands is briefly discussed. 10^- isomers with half-lives of 47 ± 6 ns in ^{190}Pt and 250 ± 30 ns in ^{192}Pt are reported. The nature of these isomers is discussed in light of our related finding that the neighboring nuclei ^{189,191,193}Pt have triaxial shapes ($\gamma \sim 30°$), and it is concluded that the 10^- states are predominantly of $(\nu i_{13/2}, \nu h_{9/2})$ two-quasiparticle composition.

[NUCLEAR REACTIONS ^{190,192}Os$(\alpha, 4n\gamma)$, ^{188,190}Os$(\alpha, 2n\gamma)$, $E = 28-50$ MeV; measured E_γ, $I_\gamma(\theta)$, γ-γ coin, γ-t relationships; ^{190,192}Pt deduced level schemes, J, π, $T_{1/2}$.]

I. INTRODUCTION

In an extensive series of experiments, the level structures of the nine Pt nuclei in the mass range $A = 186-194$ have been studied by $(\alpha, xn\gamma)$ in-beam spectroscopy. These investigations were stimulated by the evidence for backbending behavior in the ground bands of even Os nuclei,[1] by the discovery of the systematic occurrence of $5^-, 7^-, 9^-, \ldots$ "bands" in Pt and Hg nuclei,[2] and by Berkeley[3] and Jülich[4] results for odd and even mass Hg nuclei which can be satisfactorily understood in terms of rotation-alignment coupling.[5] The fact that the Pt nuclei span a region in which the prolate to oblate nuclear shape transition is believed to occur[6] has lent added interest to the present studies.

We have recently reported briefly on the dominant systematic features of the high-spin level spectra of the nine Pt nuclei.[7] Here the detailed results for the ^{190}Pt and ^{192}Pt nuclei are given. In discussing the implications of the findings, occasional reference will also be made to our results for the other Pt nuclei, which will be fully described in future publications. Concurrently with the present investigation, the ^{190}Pt and ^{192}Pt level structures have also been studied by Funke *et al.*[8]; generally, their results and ours are in excellent agreement.

II. EXPERIMENTAL PROCEDURES AND ANALYSIS

Targets approximately 10 mg/cm² thick of isotopically enriched ^{188}Os (87%), ^{190}Os (95%), and ^{192}Os (98%) imbedded in thin polystyrene films were prepared as described earlier.[2] These targets were bombarded with 1–5-nA beams of 30–50-MeV α particles from the Michigan State University sector-focused cyclotron and γ-ray data were acquired using several calibrated Ge(Li) spectrometers.

The γ-ray singles measurements were performed with a 10% Ge(Li) detector at 55° and a low energy photon Ge(Li) spectrometer (LEPS) at 125° to the beam direction. The resolution of the 10% spectrometer was 2.1 keV full width at half maximum (FWHM) for 1332-keV γ rays and that of the LEPS was 650 eV FWHM for 122-keV γ

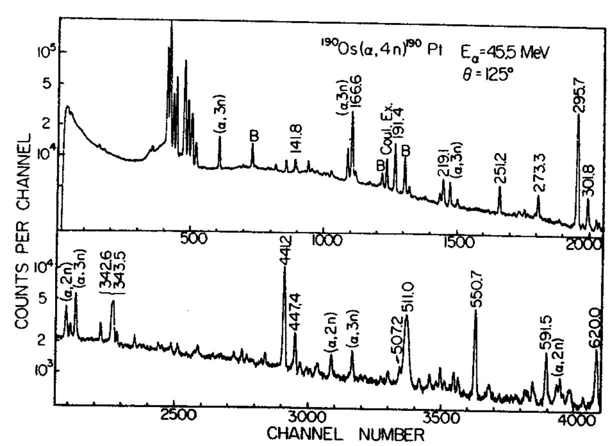

FIG. 1. A γ-ray singles spectrum measured with the LEPS spectrometer for 45.5-MeV α particles incident on the ^{190}Os target.

$\nu i_{13/2}$ and $\nu h_{9/2}$ isomers in odd-A Pt nuclei*

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$\frac{13}{2}^+$ isomers with half-lives of 311±15, 143±5, and 95± 5 μs in ^{187}Pt, ^{189}Pt, and ^{191}Pt, respectively, have been observed in $(\alpha, 3n\gamma)$ reactions on isotopically enriched Os targets. Isomeric decay schemes based on the present measurements and on ^{189}Au and ^{191}Au decay data are presented. It is proposed that the ^{187,189,191}Pt $\frac{13}{2}^+$ isomers deexcite by $M2$ transitions to $\frac{9}{2}^-$ intrinsic states of $\nu h_{9/2}$ character. In $A \geq 193$ Pt nuclei the corresponding $\frac{9}{2}^-$ states must lie above the known $\nu i_{13/2}$ isomers, which have much longer half-lives.

[NUCLEAR REACTIONS ^{186,188,190,192}Os$(\alpha, 3n\gamma)$, E=30–50 MeV, enriched targets; measured $\sigma(E)$, E_γ, I_γ, γ-γ coin, $\sigma(\theta)\gamma$, $T_{1/2}$, deduced ^{187}Pt, ^{189}Pt, ^{191}Pt isomeric decay schemes, J, π.]

I. INTRODUCTION

In a recent study[1] of the high-spin level systematics of $^{186-194}$Pt by $(\alpha, xn\gamma)$ reactions on isotopically enriched Os targets, we identified decoupled $\nu i_{13/2}$ bands in the four odd-A nuclei ^{187}Pt, ^{189}Pt, ^{191}Pt, and ^{193}Pt. The $\frac{13}{2}^+$ bandheads which were observed to be very strongly populated in the $(\alpha, 3n)$ reactions are low-lying isomers and not the ground states of these nuclei. The present paper describes the properties and modes of deexcitation of these $\frac{13}{2}^+$ isomers. Very recently, the ground state spins of ^{187}Pt, ^{189}Pt, and ^{191}Pt have been determined to be $\frac{3}{2}$ by the atomic beam magnetic resonance method.[2]

In ^{193}Pt and ^{195}Pt, $\frac{13}{2}^+$ $M4$ isomers with half-lives of 4.3 and 4.2 days, respectively, have been known for several years.[3] No isomers with comparable half-lives have been found in the lighter odd-A Pt nuclei, but there have been reports of shorter lived isomers which are pertinent to the present investigation. In the Ir$(p, 2n)$ reaction, Conlon[4] identified a 107-μs ^{191}Pt isomer deexciting by a 91-keV $E2$ transition. In similar proton bombardments of natural iridium, Fraser and Moore[5] observed γ rays of 167 and 90 keV decaying with half-lives of 145 and 95 μs, respectively, and tentatively assigned them to new ^{190}Pt and ^{192}Pt isomers. These assignments are shown on the most recent Chart of the Nuclides.[6] In studies of the radioactive decay of high-spin ^{189}Au^m, the ISOLDE collaboration[7] identified a ^{189}Pt isomer decaying by a 167-keV $E2$ transition with a half-life of 464 ns.

II. EXPERIMENTAL PROCEDURE AND ANALYSIS

The experimental methods used were very similar to those described in the preceding paper.[8] Targets of isotopically enriched ^{186}Os(62%), ^{188}Os(87%), ^{190}Os(95%), and ^{192}Os(98%) were bombarded with 30–50 MeV α particles from the Michigan State University cyclotron and γ-ray singles, γ-γ coincidence, angular distribution, and lifetime measurements were performed. Isotopic assignments of individual γ rays to ^{187}Pt, ^{189}Pt, ^{191}Pt, and ^{193}Pt were based primarily on excitation function determinations. When the γ-γ coincidence data for all four nuclei had been completely analyzed, no strong γ rays of ^{193}Pt remained unplaced in the level scheme. However, intense γ rays of 91.1, 166.7, and 117.3 keV which the excitation function measurements quite clearly showed to be due to ^{191}Pt, ^{189}Pt, and ^{187}Pt, respectively, remained unplaced. These γ rays did not appear in the prompt coincidence spectra, their angular distributions were isotropic and, in beam-sweeping lifetime measurements, no decay of the lines was detectable during a 500-ns period. Therefore longer lifetime measurements were undertaken using a beam pulsing system which greatly extended the range of measurable lifetimes. For the isomers under study here, it was found suitable to allow beam on target every millisecond for 200 μs, followed by an 800-μs beam-off period. In Fig. 1, the decay data obtained and the half-lives determined for the three isomers are shown.

It is clear from these results that the 145- and

2.L

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A STUDY OF THE NUCLEAR CONTINUUM IN ^{16}O BY INELASTIC ^{3}He SCATTERING [†]

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Abstract: Inelastic scattering of 71 MeV ^{3}He particles from ^{16}O shows an enhancement and structure of the continuum consistent with the assumption of a giant quadrupole resonance. Completely microscopic model calculations indicate that the excitation of $1^-(T=1)$ and $0^+(T=0)$ states may account for only about 10 % of the total cross sections of the excitation region 17–27 MeV.

E | NUCLEAR REACTION ^{16}O(^{3}He, ^{3}He′), $E = 71$ MeV; measured $\sigma(E_{^3\text{He}'}, \theta)$ ^{16}O resonances deduced E2 strength.

1. Introduction

Inelastic scattering of ^{3}He particles shows strong excitation of the low-energy region of the nuclear continuum. In heavier nuclei [1]) ($A > 60$) this manifests itself as a 3–5 MeV broad peak several MeV below the giant dipole resonance (GDR). The cross section exhausts the E2 sum strength and this fact [along with a host of other information summarized in ref. [1])] has led to its interpretation as a giant quadrupole resonance (GQR). In the lighter nuclei the spectra exhibit a structure similar in character to that observed in the GDR, i.e. there are usually several peaks spread over a 4–10 MeV range of energies. In this work we present results which are typical for light nuclei. The ^{16}O nucleus is a key one in nuclear structure studies and is the most thoroughly investigated in capture and photonuclear reactions. Much work, both theoretical [2]) and experimental [3-5]), has been devoted to the contention that a sizable E2 strength in the continuum region is required to account for the photonuclear data. Wang and Shakin [2]) proposed large E2 amplitudes to explain the (γ, n_0) excitation curve, angular distributions and polarization. They suggest that at the lower side of the GDR the E1 and E2 amplitudes are of comparable size. Recent polarized proton capture studies [3]) imply that 30 % of the Gell-Mann – Telegdi [6]) E2 sum is located in a broad peak at about 24.5 MeV.

In the present experiment inelastic scattering of 71 MeV ^{3}He particles is used to

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2.B:
2.G

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STUDY OF THE ^{30}Si(^{3}He, p)^{32}P REACTION

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Abstract: The ^{30}Si(^{3}He, p)^{32}P reaction was studied at an incident energy of 28 MeV, and angular distributions were measured for states in ^{32}P up to 3.00 MeV of excitation energy. Comparison of the experimental differential cross sections with two-nucleon transfer distorted-wave Born approximation (DWBA) calculations was made to test different sets of wave functions, which were calculated in the same configuration space but with different treatments of the effective residual interaction.

E | NUCLEAR REACTION ^{30}Si(^{3}He, p), E = 28 MeV; measured $\sigma(E_p, \theta)$. ^{32}P levels deduced S. Enriched target; DWBA analysis.

1. Introduction

As has been discussed in the literature [1–6]), the comparison of the results of two-nucleon transfer experiments with the predictions obtained from DWBA calculations which employ form factors derived from detailed nuclear structure calculations constitutes a potentially sensitive test of the theoretical wave functions employed. This report represents part of a systematic investigation of the two-nucleon transfer reaction (^{3}He, p) on sd shell nuclei, the aims of which are to delineate the extent to which the two-nucleon transfer data can provide a reliable critique of the structure theory predictions and, to the degree that this appears possible, to test presently available wave functions for states in this region.

In the case of the reaction under study here, ^{30}Si(^{3}He, p)^{32}P, wave functions for states of both the target and the final nucleus have been calculated in a shell-model study carried out by Wildenthal *et al.* [7]). These authors employed a truncated $1d_{5/2}$-$2s_{1/2}$-$1d_{3/2}$ basis space, in which the number of particles occupying the $1d_{5/2}$ orbit is limited to be greater than or equal to 10. Two different empirical Hamiltonians

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‡ Research supported in part by the US National Science Foundation.

2.G Nuclear Physics A239 (1975) 189—208;

A STUDY OF THE NUCLEAR STRUCTURE OF ^{36}Cl WITH THE (p, d) REACTION †

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Abstract: The ^{37}Cl(p, d)^{36}Cl reaction, at $E_p = 35$ MeV, was employed to study properties of the levels of ^{36}Cl. Excitation energies of levels up to 8.2 MeV were obtained by high-resolution magnetic analysis of the emitted deuterons. Angular distributions for the states observed in this span were measured over the angular range $\theta_L = 3°–55°$. These data were analyzed with the DWBA theory to obtain values of l_n and C^2S_l. The results are compared to the previously existent experimental picture for this nucleus and to current theoretical nuclear structure calculations.

E | NUCLEAR REACTIONS ^{37}Cl(p, d), $E = 35$ MeV; measured $\sigma(E_d, \theta)$. ^{36}Cl deduced excitation energies, J, π, l_n values and spectroscopic factors. Enriched target.

1. Introduction

The present work is part of a comprehensive study of doubly odd nuclei in the sd shell via the (p, d) reaction [1-4]. This study is motivated by the fact that current nuclear structure theories experience considerably more difficulty in accounting for the properties of the doubly odd nuclei in this region than for those of the doubly even or even-odd nuclei. The features of the low-lying energy levels of a nucleus which are revealed by single-nucleon transfer experiments are central to understanding the nuclear structure of the system. Our aim is to obtain complete and accurate sets of neutron-pickup spectroscopic factors so that unambiguous and definitive tests can be made of this aspect of current nuclear models. The present data for ^{36}Cl also provide a new and more accurate set of excitation energies for ^{36}Cl than previously existed and yield several new or revised assignments for l_n and π.

2. Experimental procedure

Targets for the present experiment were prepared by vacuum evaporation of NaCl, enriched to > 96.5 % in ^{37}Cl, on to 30 μg/cm^2 carbon foil backings. The targets were

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2.F

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THE $^{29}Si(^{3}He, p)^{31}P$ REACTION

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Abstract: Angular distributions of the $^{29}Si(^{3}He, p)^{31}P$ reaction at $E_{^3He} = 26$ MeV have been measured for states in ^{31}P up to an excitation energy of 5.7 MeV. These data were analyzed with distorted-wave Born approximation calculations based on current shell-model wave functions.

E | NUCLEAR REACTIONS $^{29}Si(^{3}He, p)$, $E = 26$ MeV; measured $\sigma(E, \theta_p)$. ^{31}P levels deduced L, S. Enriched target; DWBA analysis.

1. Introduction

The present investigation of the $^{29}Si(^{3}He, p)^{31}P$ reaction is part of a systematic study of two-nucleon transfer reactions on 2s-1d shell nuclei [1]. A major aim of this study is to provide a critique of existing nuclear structure theory from the standpoint of the matrix elements of the coupled two-particle creation operator. The comparison of experimental differential cross sections with the results of microscopic distorted-wave Born approximation (DWBA) calculations based upon the matrix elements $\langle\psi(A+2)|[a^{+}(n_1 l_1 j_1)a^{+}(n_2 l_2 j_2)]_{J,T}|\psi(A)\rangle$ can provide discriminating tests of the wave functions $\psi(A+2)$ and $\psi(A)$ [refs. [2,3])].

In this paper we present measured angular distributions for transitions to levels of ^{31}P in the region of excitation energy from 0 to 5.7 MeV. The experimental data for the states of well established spin and parity, J^{π}, are compared with DWBA calculations based on the shell-model wave functions of Wildenthal *et al.* [4,5]). These

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PREEQUILIBRIUM ANALYSIS OF (p, n) SPECTRA ON VARIOUS TARGETS AT PROTON ENERGIES OF 25 TO 45 MeV †

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Abstract: Thin target (p, n) spectra are reported for incident proton energies of 25, 35 and 45 MeV on ^{48}Ca, ^{90}Zr and ^{120}Sn, and at proton energies of 35 and 45 MeV on ^{208}Pb. Angle-integrated spectra are compared with predictions of the geometry-dependent hybrid model, the hybrid model, and the hybrid model with average state lifetime. The geometry-dependent hybrid model, when combined with evaporation components, gives an excellent prediction of the overall shapes and magnitudes of the experimental results. The simpler hybrid model fails in both respects, paralleling results of earlier comparisons of (p, p′) spectra with model calculations.

E | NUCLEAR REACTIONS ^{48}Ca, ^{90}Zr, ^{120}Sn, ^{208}Pb(p, n), $E = 25$, 35, 45 MeV; measured $\sigma(E_n, \theta)$ and $\int d\Omega\sigma(E_n, \theta)$. Enriched targets.

1. Introduction

The high-energy components of many particle spectra have been successfully interpreted in terms of preequilibrium decay models [1]). The model which has had broadest application and greatest success is the hybrid/geometry-dependent hybrid (GDH) model. These formulations have had success in reproducing many (α, p), (α, n), (^{3}He, p), (^{3}He, n) and (p, p′) spectra. Agreement has been found for a broad range of target masses and bombarding energies.

Relatively few comparisons have been performed for (p, n) spectra. Grimes *et al.* have applied the GDH model to the ^{51}V(p, n) reaction at proton energies between 16 and 26 MeV, with quite satisfactory results [2]). Agreement at higher energies remains to be demonstrated. Indeed it has been suggested that the model will predict incorrect spectral shapes and yields for (p, n) reactions, and that the good agreement found in reproducing (p, p′) spectra is fortuitous [3]). This work is

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AN ENERGY-DEPENDENT LANE-MODEL NUCLEON-NUCLEUS OPTICAL POTENTIAL†

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Abstract: An energy-dependent Lane-model nucleon-nucleus optical potential is presented. The isovector strength parameters of the potential have been determined by fitting (p, n) IAS angular-distribution data between 25 and 45 MeV for targets from ^{48}Ca to ^{208}Pb. The isoscalar strength parameters have been obtained by requiring that the Lane-model potential reproduce the Becchetti-Greenlees Coulomb-corrected proton potential. The energy associated with the proton in all energy-dependent parts of the potential is reduced by the average Coulomb potential inside the nucleus. The main result of the parameter search, other than determining the strength of the isovector energy dependence, is to redistribute the isovector strength found by Becchetti and Greenlees between the real-volume and imaginary-surface terms. The Lane-model optical potential so obtained is reasonably successful in reproducing (p, p), (p, n) IAS, and (n, n) scattering over a wide mass and energy range.

E | NUCLEAR REACTIONS ^{48}Ca, ^{90}Zr, ^{120}Sn, ^{208}Pb(p, n), $E = 25, 35, 45$ MeV; analyzed previously measured IAS $\sigma(\theta)$; deduced energy-dependent isovector parameters. ^{27}Al, Fe, Sn, ^{209}Bi(n, n), $E = 7.0, 14, 24$ MeV; calculated $\sigma(\theta)$.

1. Introduction

It has been pointed out by Lane [1]) that the nuclear optical potential may be written in a charge-independent form. Such a potential may be used not only to describe both proton and neutron elastic scattering from nuclei, but also the (p, n) reaction to the isobaric analog of the target ground state (IAS). The Lane-model optical potential may be written as

$$U = -U_0 + 4U_1 \, (\boldsymbol{t} \cdot \boldsymbol{T})/A, \tag{1}$$

where $\boldsymbol{t}$ and $\boldsymbol{T}$ are the nucleon and nucleus isospins, respectively, A is the mass number of the nucleus, and U_0 and U_1 are functions that do not depend upon isospin in the isospin-independent and isospin-dependent parts of the potential, respectively. The functions U_0 and U_1 should, in general, depend upon relative position and momentum [2-9]), and both may be complex [7-12]). If a sufficiently general parameterization of the Lane-model optical potential were available, one would be able to calculate

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A HIGH RESOLUTION STUDY OF ^{26}Al VIA THE (p, d) REACTION†

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Abstract: Excitation energies and angular distributions of ^{26}Al levels in the first 6 MeV of excitation have been measured with the ^{27}Al(p, d)^{26}Al reaction at E_p = 35 MeV. Deuteron spectra were analyzed with an Enge split-pole magnetic spectrograph and recorded on nuclear emulsions (experimental resolution ≈ 6 keV, FWHM); supplementary data were recorded with position-sensitive wire proportional counters. The angular distributions were analyzed with the DWBA to extract the *l*-values and associated spectroscopic factors of the neutron transfers. The results for excitation energies, *l*-values, spectroscopic factors, and values of J^{π}, T are discussed in terms of previous experimental and theoretical work and in the light of new shell-model calculations for this system.

E | NUCLEAR REACTION ^{27}Al(p, d), $E = 35$ MeV; measured $\sigma(E_d, \theta)$, ^{26}Al deduced levels, L, J, π, S. Magnetic spectrograph.

1. Introduction

The structure of the energy levels of ^{26}Al is enigmatic. In terms of the simplest shell model, based on an ^{16}O core, the active system consists of five protons and five neutrons, each in the $d_{\frac{5}{2}}$ orbit. In such a model, ^{26}Al could be treated as coupling of single neutron and proton holes in the $d_{\frac{5}{2}}$ orbit. However, there is no simple relationship between the lowest observed states of ^{26}Al and those of its particle conjugate in the $d_{\frac{5}{2}}^{n}$ model, ^{18}F [ref. [1])]. Simple rotational-model schemes [2]) fare no better than the simplest shell-model analysis and the addition of considerable complexity to the rotational model, by considering several bands and extensive band-mixing via Coriolis coupling, still fails to yield a viable explanation of this system [3]). Shell-model calculations which involve both the $d_{\frac{5}{2}}$ and $s_{\frac{1}{2}}$ orbits [4]) and which quantitatively explain many features of the A = 20–28 region still fail to give even a qualitative representation of the T = 0 part of the level structure of ^{26}Al. In doubly odd, self-conjugate nuclei such as ^{26}Al, T = 1 levels both occur in the first few MeV of excitation. The isobaric analogues of the T = 0 and T = 1 levels of ^{26}Al which occur in ^{26}Mg have been studied in some detail [5]), and while the A = 20–28 shell-model analysis of ref. [4]) can explain some features of this subset of levels, particularly the

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FAST CALIBRATION OF LARGE Si(Li) ELECTRON DETECTORS FROM 511.0 TO 4564.0 keV USING DOUBLE-ESCAPE PEAKS AND COMPTON EDGES FROM ^{66}Ga

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Double-escape peaks and Compton edges from the γ-rays of 9.5-h ^{66}Ga have been used to allow fast, precise calibration of Si(Li) electron detectors. They allow a direct calibration up to 4564.0 keV, and the calibration curve is linear enough that it can probably be extrapolated safely to even higher energies.

In order to use the larger Si(Li) detectors (5–10 mm active depth) for β and conversion-electron spectroscopy far from the region of β stability, it is desirable to have a means of rapid energy calibration over a broad energy range. Although conversion electrons and Compton edges can provide quick calibrations up to 2 MeV, the use of β endpoints to calibrate to higher energies is quite tedious. This occurs mainly because, in order to find a precise endpoint, one requires a knowledge of the spectrum shape as well as the efficiency for the detector.

The problem of having to use β endpoints for calibration to higher energies can be obviated by use of the double-escape spectrum of ^{66}Ga. ^{66}Ga is a well-known high-energy γ-ray standard[1,2]) with transitions up to 4806.6 keV. Double-escape events are therefore observed up to 3784.6 keV, and a Compton

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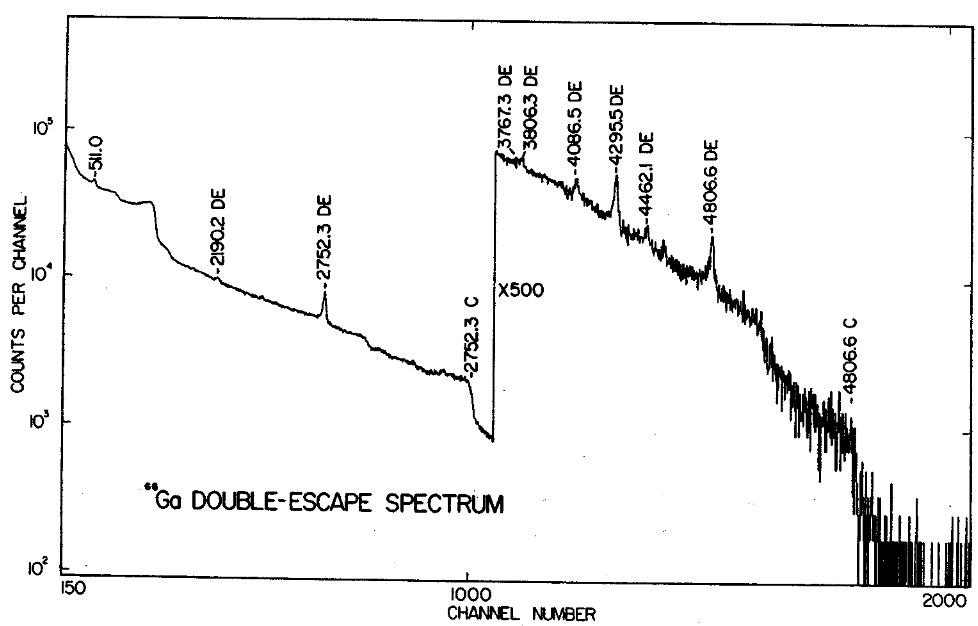

Fig. 1. γ-ray spectrum of ^{66}Ga taken with a 100-mm^2 × 10-mm deep Si(Li) electron detector. This spectrum shows clearly the double-escape peaks and Compton edges that are useful for calibration.

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BASIC ORBIT PROPERTIES OF IONS IN A MIGMA FUSION DEVICE*

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The "Migma Cell" designed by Maglich is aimed at producing useful fusion power by storing deuterons in precessing, self-colliding orbits in a suitable magnetic field[1]). We have undertaken a more thorough analysis of the basic orbit properties in such a device. Using equilibrium orbit and transfer matrix techniques, we have developed a computer code which calculates all the important properties of median plane orbits and of vertical focusing in the given magnetic field as a function of momentum. The results obtained for the same field as used by Maglich are presented, together with a discussion of their significance for beam injection and space-charge problems. In particular, our results show that inherent alternating-gradient effects increase the vertical focusing, but beyond a critical momentum value, the vertical oscillations become unstable because of overfocusing. Finally, some of the orbit data provided by Maglich are discussed and interpreted, along with his choice of magnetic field shape.

1. Introduction

In a recent article, Maglich has described the "Migma Cell", a potentially useful device for generating nuclear fusion power[1]). This device represents an extensive development of the "Migmatron", which is itself an outgrowth of the "Precetron"[2,3]). (These papers will hereafter be referred to collectively as Maglich et al.) The basic orbit properties of these devices, particularly the vertical focusing, have been treated rather casually using analytical methods based on the restrictive assumption of nearly circular orbits. A more rigorous treatment therefore seems desirable.

Precetron-Migma orbit properties can be accurately analysed using equilibrium orbits and transfer matrix techniques similar to those used in cyclic accelerators. The median-plane orbits execute a series of identical loops, going from r_{min} to r_{max} and back again to r_{min} in each loop. Although these orbits are generally not closed, the variation of the radius r is definitely periodic, and each orbit can therefore be viewed as an "equilibrium orbit" having a periodicity element equal to one loop. (The nonperiodicity of the azimuth θ is unimportant here since the field is axially symmetric.) With the equilibrium orbit thus defined, it becomes possible to calculate the transfer matrix for the vertical oscillations through one loop, and hence to determine the frequency ν_z and other properties of these oscillations.

We have developed a computer code which, for a given median plane field $B(r)$, calculates all of the important properties of the equilibrium orbits and of the vertical oscillations as a function of the momentum p. The output from this code should make it possible to evaluate rather quickly the advantages or disadvantages of a given field and operating condition. The structure of this code and some preliminary results are described in this paper.

In order to make the results as general as possible, we use a field unit B_0 and a length unit R_0, both of which are unspecified. All momenta are then expressed in terms of the unit:

$$p_0 = qB_0 R_0/c, \tag{1}$$

for an ion of charge q. All of the results are then independent of the choice of a particular ion and of the "scale" of the device.

2. Equilibrium orbit (EO)

We use the arc length $s = vt$ as the independent variable, so that time never occurs explicitly in the results. In terms of cartesian coordinates, the differential equations for the EO are then given by:

$$\mathrm{d}x/\mathrm{d}s = p_x/p, \qquad \mathrm{d}y/\mathrm{d}s = p_y/p, \tag{2a}$$

$$\mathrm{d}p_x/\mathrm{d}s = -(p_y/p)\,B(r), \quad \mathrm{d}p_y/\mathrm{d}s = (p_x/p)\,B(r), \tag{2b}$$

where $B(r) = -B_z(r, z=0)$, so that the ions rotate in the positive (counter-clockwise) sense.

The above equations are integrated numerically with the following initial conditions:

$$s = 0,\ \ x = 0,\ \ y = y_0,\ \ p_x = p,\ \ p_y = 0. \tag{3}$$

In addition to a given p, the orbit therefore has a specified value of $r_{min} = |y_0|$, and the sign of y_0 determines whether or not the orbit circles the origin. As the integration proceeds, the code calculates the

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AN ULTRA-THIN-WINDOW GAS CELL*

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A gas cell has been developed for which the total areal density encountered by outgoing reaction products can be as low as 50 μg/cm^2 at 25 torr gas pressure.

During a program of cross section measurements for the proton-induced spallation of ^{12}C, ^{14}N, ^{16}O, and ^{20}Ne[1,2]) gas targets were found necessary for all targets except ^{12}C. Usually the gas for such a target is confined in a cell by a thin foil or "window" through which the beam enters the cell and through which the reaction products leave to be detected outside the cell. For the relatively heavy low-energy reaction products one must detect in the spallation experiments, commonly used foils such as 13 μm thick Kapton (which stops 10 MeV ^{11}C ions) give large and unacceptable energy losses. For the gas cell described here, on the other hand, the areal densities encountered by the reaction products are typically less than 130 μg/cm^2, which corresponds to the range of a 210 keV ^{11}C ion.

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The gas cell is shown in figs. 1 and 2. Its unique feature is the moveable shell, the shell end closest to the beam serving both as the front-defining slit and as the exit-window support. The beam end of the shell is tapered to allow close approach to the beam at forward angles. In this design the counter is rigidly attached to the gas cell and both rotate together as the scattering angle is changed. Thus at different angles the beam passes through different parts of the entrance window. The geometry of the shell and its vacuum seal determine the accessible angular range, which for this cell is 10°–170°.

The entrance beam window was 13 μm thick Kapton bonded to the cell structure with epoxy Ciba Araldite 502. It could withstand differential pressures of about 200 torr and beam currents of about 1 μA. The exit window was made of Formvar. The slit end of the shell was buffed so the lips of the slit were rounded and no sharp edges remained. A 2% solution of Formvar in 1,2 dichloroethane was prepared and 1.4 μg/cm^2 thick films were produced by casting on

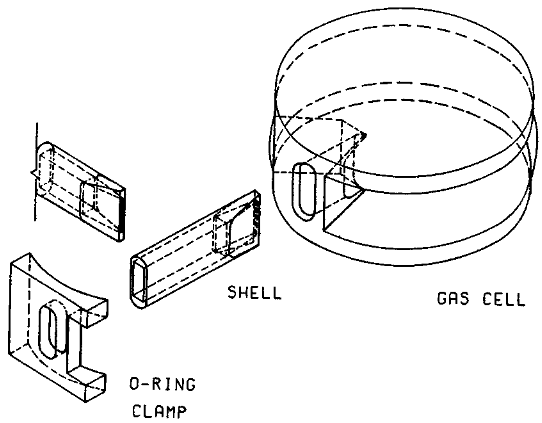

Fig. 1. The major components of the gas cell system are shown. An O-ring effects the shell-to-gas-cell seal.

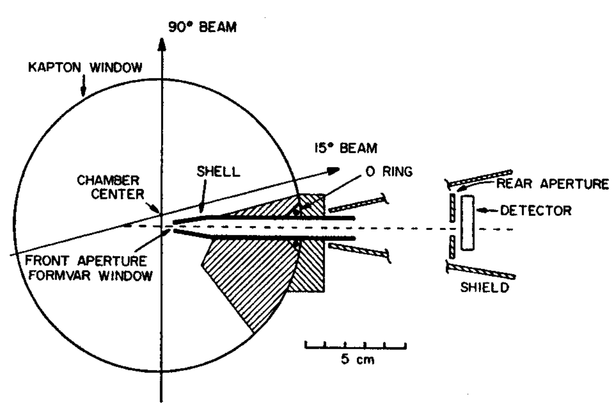

Fig. 2. Schematic diagram of the geometrical relationship between the slit system and the beam trajectory when one is observing particles produced at 15° and at 90°.

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ULTRA-FAST CHEMICAL SEPARATIONS ("PLASMA CHEMISTRY") WITH A HELIUM-JET RECOIL-TRANSPORT SYSTEM

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The transport efficiency through a long-capillary He-jet recoil-transport system can be changed for different elements by altering the nature and/or the concentration of the impurities in the He. Thus, it appears that a form of "plasma chemistry" is taking place in the formation of the "macromolecules" that transport the radioactive recoils through the system and the attachment of the recoils to chemically specific sites on these macromolecules. We describe some experimental results and point out the advantages of such a system; also, we note that it is possible to obtain information about the Z of a nuclide from these experiments.

1. Introduction

In the course of our recent work developing a helium-jet recoil-transport system (HeJRT)[1–4], we have made an interesting observation that may have important practical ramifications. It is generally accepted that the mechanism of transport of activities through long organically doped HeJRT systems (systems in which small amounts of benzene, methane, ethane, chloroform, or pump oil, etc. are added to the bulk helium supply) requires the combining of the activities with macromolecules generated from the organic material[5]). However, the nature of this combining or attachment is not generally understood.

We have some evidence that the chemical nature of both the recoil activity and the macromolecule are important, suggesting some form of chemical bond, as opposed to other mechanisms such as nucleation which do not reflect chemical specificity. We have further observed that this chemical specificity can be used to transport preferentially through the HeJRT system different components of a mixture of chemically differing recoil activities produced from the same target. In effect, in at least some cases, it is possible to achieve a partial chemical separation in the course of the thermalization and transportation process.

One possible explanation of this effect could be that the chemical natures of the recoil and macromolecule are effective in determining the macromolecule's ability to pick up and hold the recoil atoms. If this be the case, that component of a mixture of chemically different recoils which is preferentially picked up and held by macromolecules will, as a result, also be that component which is preferentially transported through the system. Those remaining components that are not readily picked up and held by the macromolecules will not have the benefit of the macromolecules' high transport efficiency through the system and will tend to become lost on the walls of the capillary leading to the counting area.

It is perhaps worth pointing out that, even if this explanation is in gross error, and the chemical nature of neither recoil nor macromolecule is the source of the effect, the effect is still real and can be used to achieve a preferential enhancement in the transport yield of chemically differing nuclear recoils in the HeJRT system. Even though only a partial chemical separation may be obtained, it can in many cases be used to determine the Z's of the nuclides being produced in a complex nuclear reaction. Coupling these effects with an on-line isotope separator following an HeJRT system[6,7]) could thus produce a powerful means of identification of both the Z and A of short-lived nuclei far from β stability without even having to resort to information from X-rays, etc. Also, since this "plasma chemistry" is ultra-fast, depending only on the transit time of the HeJRT system (in our present system ≈ 200 ms), one can use it with very short-lived nuclei.

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AN IMPROVED AND MODULAR HELIUM-JET RECOIL-TRANSPORT SYSTEM FOR THE STUDY OF SHORT-LIVED NUCLEI

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An improved, modular helium-jet recoil-transport system for the study of short-lived ($t_{1/2} \lesssim 0.2$ s) is described. Its target irradiation assembly consists of modular pieces, allowing the interchanging of different target holders, different recoil-thermalizing chambers, etc., for economical and convenient setting up of each experiment. A remote-control degrader package allows rapid control of accelerator beam energies. Improved target-preparation techniques are described, including compacting oxides onto foils with a hydraulic press. Auxiliary equipment such as gas supplies, capillaries, pumping equipment, and a stepping tape drive for the counting chamber are described. Different detector arrays and assemblies are used for different kinds of nuclear spectroscopy, and data are presented for some of these, including γ-ray, γ–γ megachannel (multiparameter) coincidence, and β-delayed proton spectroscopy.

1. Perspective

Since the advent of the helium-jet recoil-transport (HeJRT) method in 1962–63 [1,2]), it has undergone a myriad of variations and improvements at many different laboratories. From systems having a simple orifice feeding directly onto an α detector it has developed into complex and sophisticated systems having long capillaries that lead into low-background laboratories far from the target area[3,4]). It has even become possible to perform chemical separations and mass identifications on-line with HeJRT systems[5]). And although the detailed mechanisms of what makes HeJRT systems "work" still remain largely unknown, a fair body of empirical methodology has been developed from which we have gained some insight into the inner workings of these systems[6,7]). Suffice it to say that HeJRT systems have become extremely convenient if not quite essential for the study of nuclei far from stability, and with their recent couplings to on-line isotope separators[8,9]) they have become even more important.

For the past number of years we have been working on innovations and improvements in HeJRT systems in this laboratory, and, partly through systematics and the published results of others, partly by trial and error and serendipity, we have developed a very efficient and easy-to-use modular HeJRT system. In this paper we describe this system. Because much of the empirical systematics of HeJRT have already been published (e.g. ref. 6 and references therein), we limit ourselves to a discussion of the hardware of our particular system and to the salient points that make it work as it does. We then give some examples of its use in studying exotic nuclei far from β stability and its suitability for forming the first stage of an on-line isotope separator.

2. Target irradiation assembly

2.1. Modular target assembly

The target assembly for the HeJRT system is shown in fig. 1. It is of a modular design and is not enclosed in the customary larger container of helium. Each of the components is separate: beam window, collimator, absorbers, target holder, capillary exit flange, etc. All the components are of (local) standard design and are interchangeable. Accordingly, the assembly allows great flexibility in the design of an experiment, and changes are easily made during pauses in an experiment simply by loosening the two wing nuts and sliding in or out new or replacement components. This allows us to make radical changes in the assembly with a minimum of machine-shop time (by not duplicating

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PREPARATION OF A THICK ^{14}C TARGET*

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A high-temperature epoxy was mixed with ^{14}C powdered graphite and baked at 225 °C. The resulting wafer had a ^{14}C thickness of 3.5 mg/cm² and was used for $^{14}C(p, n)^{14}N$ measurements with micro-ampere beams from our isochronous cyclotron.

1. Introduction

Cracking of methyl iodide has been used for some time in the production of thin carbon targets[1]). Other carbon compounds have also been used, and when the carbon was deposited on thin nickel foils, subsequent etching left an unbacked region[2]). The technique has been improved by cracking onto a barium-chloride-coated surface from which the carbon film was then floated[3]). With this improvement, unbacked ^{14}C targets were made with 30% efficiency; they were 0.1–0.2 mg/cm² thick and were small – they were mounted on frames with a 7/32-inch opening[3]).

Targets such as these are too thin and too small for our purpose, which was to measure the angular distribution of the $^{14}C(p, n)^{14}N$ reaction to the three lowest states of ^{14}N with incident protons at several energies between 25 and 50 MeV.

Our neutron time-of-flight system[4]) has an unavoidably low efficiency of a few percent. With this efficiency and with many of the cross sections expected to be of order 10 μb/sr, we could not tolerate a target which was unnecessarily thin. In this case "unnecessarily thin" means "much less than the energy spacing of the final states". A 0.2 mg/cm² target is 2.5 keV thick to 35 MeV protons, whereas the relevant states of ^{14}N are at 0, 2.31, 3.95, and 4.91 MeV. Clearly, 0.2 mg/cm² is unnecessarily thin by a factor of about 100.

For reasons of counting rate, it is also desirable to use a beam of high intensity. Because neutrons lose no energy and are little attenuated in a target frame, the frame opening must be large enough to conveniently pass an entire beam of high intensity; otherwise a continuous background will result from proton interactions in the frame. A target backing, such as nickel, even ^{58}Ni, will result in neutron background when bombarded with 25–50 MeV protons, and is to be avoided.

The key to our solution of the problem is the very low Q-value, −18.1 MeV, of the (p, n) reaction on ^{12}C. This suggested that we embed elemental ^{14}C in some type of binder. Of the carbon in a binder, the 1.1% of ^{13}C, with its (p, n) Q-value of −3.00 MeV, would be the main source of background. For our purposes, ^{12}C, H, and ^{16}O [$Q(p, n) = -16.8$ MeV] would be completely inert.

2. Target preparation

Were it not for its low melting point, polystyrene would be an ideal binder in which to embed ^{14}C graphite powder. As it is, however, polystyrene flows at 75 °C. This would limit beam intensities to values below 0.1 μA. Instead we chose a high-temperature epoxy, one that begins to deform at approximately 350 °C, thus allowing a beam intensity about 20 times that allowed by polystyrene. In order to keep neutron background to a minimum, we chose an epoxy which is free of nitrogen. (Without this restriction, more suitable epoxies would be available.) It is a mixture of a cycloaliphatic epoxy, vinyl cyclohexene dioxide (VCD), and two rather obscure anhydrides, methyl nadic anhydride (MNA) and a pyromellitic dianhydride (PMDA).It is hard (Rockwell Hardness M 110–120), and brittle (rod impact ≅0.3 ft lbs.), and has a coefficient of thermal expansion $\cong 5\times10^{-5}$/°C. In units of molecular weights the epoxy mixture was VCD ($C_8H_{12}O_2$) 2 parts, MNA($C_{10}H_{10}O_3$) 1 part, and PMDA($C_{10}H_2O_6$) 1 part. The atomic percentages of

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A BATCH PROCESS FOR THE PRODUCTION OF ^{13}N-LABELED NITROGEN GAS

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A technique has been developed for generating $^{13}N^{14}N$ gas with specific activity ~20 mCi/ml. The ^{13}N is produced, nearly free of other radioactivities, in the $^{13}C(p,n)^{13}N$ reaction, using 17 mg amorphous carbon targets enriched to about 97% ^{13}C and a proton bombarding energy of 11 MeV. The irradiated material is converted to $^{13}N^{14}N$ gas by automated Dumas combustion and compressed into 1 ml vials, the entire procedure taking less than 15 min. A number of biological tests have shown that the $^{13}N^{14}N$ gas is essentially free of other labeled compounds of nitrogen. The advantages and disadvantages of other ^{13}N-producing nuclear reactions are discussed.

1. Introduction

Available techniques[1–7] for the production of ^{13}N-labeled nitrogen gas ($^{13}N^{14}N$ and $^{13}N^{13}N$) involve continuous-flow processes, in which the radioactivity is either produced in a flowing target gas[2] or is swept from a solid target by a carrier gas[3–6]. Such techniques have yielded labeled gases with rather low specific activities, typically less than 1 mCi/ml. Activities of this magnitude, or less, are satisfactory for many purposes. However, in some experiments (e.g. autoradiographic studies[8]) of the sites of fixed ^{13}N) the nature of the analytic procedure may limit the amount of biological material. In other experiments (e.g. studies[9]) of the early metabolism of fixed ^{13}N) the fixation time may be limited so as to study the time dependence of the process. Larger specific activities are often required to obtain usable amounts of fixed labeled nitrogen in such cases.

The batch process described in this paper was developed to satisfy our requirement of high-specific-activity, high-purity ^{13}N-labeled nitrogen gas, for use in studies of the fixation and metabolism of nitrogen by certain blue-green algae[8,9]. Briefly, the procedure is as follows. A ^{13}C target is bombarded with 11 MeV protons and ^{13}N is produced by the $^{13}C(p,n)^{13}N$ reaction. The irradiated material is removed from the sample holder, is subjected to automated Dumas combustion[10,11]), and the resulting gas is compressed into a 1 ml vial. The gas is found to be essentially free of radioactive constituents other than $^{13}N^{14}N$ or $^{13}N^{13}N$ and to have a total radioactivity of up to 20 mCi for a 1 μA bombarding current.

Activities of this magnitude have been obtained by one other technique[3]), but the procedure required very high beam power (60 μA of 14 MeV deuterons) and can therefore be carried out only at a few rather specialized installations. With the present technique, it is possible to achieve comparable activities in any laboratory where a proton accelerator with an energy

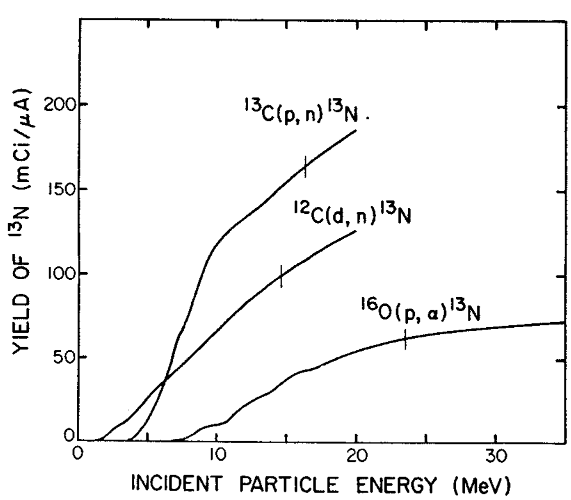

Fig. 1. Production of ^{13}N by several nuclear reactions. The thick sample is presumed to be bombarded for a time long compared to the ^{13}N halflife, so the saturation activity is attained; the activity is then obtained from the production rate by division by 3.7×10^7 disintegrations s^{-1} mCi^{-1}. The vertical bars on the curves mark the threshold energies for the production of ^{11}C.

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ORGANIC-SCINTILLATOR PULSE-SHAPE DISCRIMINATOR SIGNATURES ASSOCIATED WITH HIGH-ENERGY NEUTRONS*

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A two-dimensional system of pulse-shape discrimination (PSD) is described as applied to neutron time-of-flight experiments. When the detector is irradiated with neutrons and gamma rays from 40-MeV proton bombardment of ^{7}Li, five different PSD signatures are observed – one associated with gamma rays, four with neutrons. The origins of these groups are explained and their importance in neutron detection is discussed.

1. Introduction

In traversing matter, a charged particle produces an ionized track. The specific ionization density of this track is dependent upon the energy, charge, and mass of the particle. If the material traversed is an organic scintillator, the molecular modes excited are observed to depend upon the specific ionization[1]). The resultant de-excitation by scintillation can usually be described as the sum of two exponential decays whose relative intensities and decay time constants are dependent upon the charged particle[2]). Although additional decay components may be involved, their relative contribution is usually negligible[3]). Thus, two charged particles of different mass or charge will produce two different scintillation-light histories[4]). The exploitation of this dependence of the scintillation history on the specific ionization density in the track of the exciting particle is a method of discriminating amongst different particle types[5]). This experimental technique is commonly called pulse-shape discrimination (PSD).

A number of methods of PSD have been presented in the literature. These methods vary widely in resolution, complexity, and dynamic range[6]). Our use of PSD was for (p, n) time-of-flight (TOF) experiments[7]). These experiments required excellent particle resolution between neutron and gamma-ray events, excellent time resolution for neutron-energy determination by TOF computation, and wide dynamic pulse-height range for high efficiency. Because of the last requirement the zero-crossover method[8,9]) of PSD was chosen. To study the information obtained from each event, all three parameters: pulse height (PH), pulse shape (PS), and TOF were analyzed on-line. The PSD system was used to separate neutron from gamma-ray events. This combination of high-resolution PSD and TOF systems allowed identification of previously unnoticed PSD signatures.

2. The experimental systems

2.1. The cyclotron

The Michigan State University Isochronous Cyclotron is a variable-energy instrument capable of producing beams of protons with energies up to 50 MeV with a micro-burst time-width of less than 0.3 ns (fwhm)[10]). This feature has been vital in neutron TOF experiments because only a short flight path is available.

2.2. The PSD–TOF system

The detector is an NE 213 organic scintillator sealed

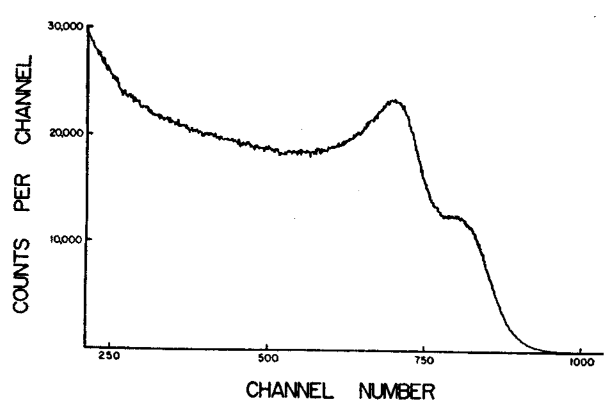

Fig. 1. Pulse-height spectrum of ^{60}Co gamma rays in the NE-213 scintillation detector.

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PHASE-SPACE DIAGRAMS FOR A MIGMA FUSION DEVICE*

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Results are presented from a systematic study of three-dimensional orbits in a Migma fusion device. As the vertical oscillation amplitude increases, the frequency of the oscillations decreases rapidly, so that a sequence of nonlinear coupling resonances is encountered. The periodic orbits and vortex boundaries associated with these resonances have been calculated, and the results are displayed in a series of phase-space diagrams, together with an explanation of their significance. The vertical confinement limit and its effect on these diagrams are also described. The problems of beam injection via self-ensnaring are examined, and a special injection orbit is proposed which should provide an exceptionally long confinement time together with a high central density. Finally, the effect of multiple scattering on the ion distribution in phase space is discussed, and arguments are presented in favor of a rather broad distribution under steady-state conditions.

1. Introduction

During the past few years, a group headed by B. C. Maglich has been working on the development of a practical fusion power source through the application of storage-ring and colliding-beam concepts[1]). A detailed report on this work was presented in a paper entitled "The Migma principle of controlled fusion", in which Maglich[2]) describes the theory and design of the "Migma Cell", a complete reactor unit having an estimated power output between 10 mW and 10 W. The power output is assumed to be limited by space-charge effects, and a subsequently proposed solution to this problem has led Maglich to conclude that a Migma Cell 40 cm in diameter might produce 0.1 MW[3,4]). These results are sufficiently impressive to stimulate a more widespread investigation and, at the same time, a more thorough analysis of Migma fusion devices.

Basically, the Migma Cell is a device for storing deuterons (or other ions) in precessing and self-colliding orbits, which loop through the center of an axially symmetric magnetic field. The design of such a device therefore requires, first of all, comprehensive information on the properties of these orbits. In a previous paper, we provided a systematic study of the orbit precession and vertical focusing for ions moving close to the median plane[5]). Here, we shall extend this treatment to the properties of orbits which execute large (nonlinear) vertical oscillations.

Ions moving in an axially symmetric magnetic field have a constant (generalized) angular momentum, $P_\theta = K$, as well as constant energy E. Since the corresponding cyclic coordinates, the azimuth θ and the time t, are not relevant to the properties of a Migma, the motion of the ions can be characterized by just four phase-space coordinates: K, E, and the vertical coordinates z and p_z. Under steady-state conditions the distribution of the ions in this four-dimensional space will completely specify all of the properties of the Migma.

Any ion which starts on the z-axis ($r = 0$) will have $K = 0$, and its precessing orbit will execute a sequence of loops each of which passes through the z-axis. An example of an orbit with $K = 0$ is shown in fig. 1. The

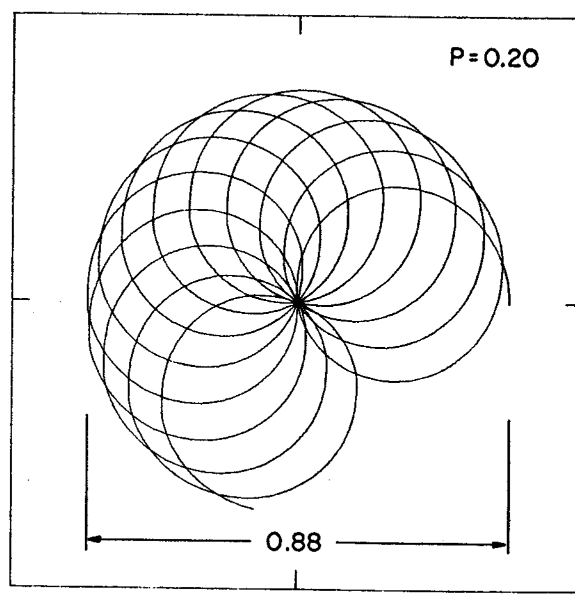

Fig. 1. XY-plot of the median-plane equilibrium orbit for $p = 0.20$. This precessing orbit repeatedly loops through the center of the axially symmetric magnetic field. For this and subsequent figures, we use the length unit R_0, and the momentum unit $p_0 = qB_0R_0/c$ defined by the field parameters in eq. (5).

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A PULSE HEIGHT RESOLUTION METER*

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An analog circuit has been constructed which measures the rms width of a pulse height distribution and provides a continuously updated meter display.

Most nuclear experiments involve the acquisition of pulse height distributions where the pulse height represents the magnitude of some measured quality (energy, time, position...). Often these pulse height distributions contain isolated peaks whose width reflects the quality of the experiment and is desired to be as small as possible. Unfortunately, the task of adjusting system parameters to minimize the width of a peak can be very tedious since it involves a search where one changes a parameter, accumulates a pulse height distribution, determines a peak width and tries again. This process can be greatly facilitated by having a continuous reading of the peak width. Then one can simply "tune" the system. We describe here a device which can isolate a region of a pulse height distribution and determine, in real time, the root-mean-square (rms) deviation of pulses about the mean. The result is displayed by a meter movement or other readout.

Instead of computing the mean pulse height and then the rms deviation of pulses about it, we have chosen to take the rms average of the difference between each pulse height and the height of the previous pulse. In this way, we minimize our sensitivity to changes in the mean. That this rms pulse difference is related to the rms deviation about the mean is easily shown. Let M be the result for N pulses of height X_i, then

$$M^2 = \frac{1}{N} \sum_{i=1}^{N-1} (X_{i+1} - X_i)^2$$

$$\approx \frac{1}{N} (2\sum X_i^2 - 2\sum X_{i+1} X_i)$$

$$\approx \frac{2}{N} \{\sum X_i^2 - \sum[\bar{X} - (\bar{X} - X_{i+1})]\,[\bar{X} - (\bar{X} - X_i)]\}$$

$$\approx \frac{2}{N} [N\overline{X^2} - N\bar{X}^2 + \bar{X} \sum(\bar{X} - X_{i+1}) +$$

$$+ \bar{X}\sum(\bar{X} - X_i) - \sum(\bar{X} - X_{i+1})\,(\bar{X} - X_i)]\,.$$

If N is sufficiently large and X_i and X_{i+1} are uncorrelated the sums above are zero leaving

$$M^2 = 2\overline{X^2} - 2\bar{X}^2 \equiv 2\sigma^2,$$

where σ is the rms deviation about the mean. In practice N will not be arbitrarily large because N is the number of pulses in the averaging period and this averaging period determines the response time of the instrument. At high data rates N can be quite large thus giving an error-free result, but at low rates one must compromise between short response time and high precision.

A simplified diagram of the device is shown in fig. 1. The basic functions can be divided into two parts: (1) selection of pulses whose height falls between two voltage levels defined by a level and a window setting; (2) determination and display of the width and centroid of the selected region of the pulse height distribution. The biased amplifier at the input of the circuit substracts a voltage defined by the level setting from the stretched input pulse and amplifies the difference ten times. This signal goes to two sample-and-hold (S/H) amplifiers that are controlled by the selection logic. This logic will cause the signal to be sampled if the top of the biased pulse falls within an adjustable window, fig. 2. A delay of about 500 ns is introduced from the start of the input pulse to the sampling time to allow for the rise time of the biased amplifier. For a selected pulse, the output voltage of S/H amplifier 2, after sampling, will be linearly related to the level of the input pulse; and S/H amplifier 1 will latch a voltage equal to the difference of the level of this pulse and the output of the delay line, which represents the level of the previous pulse held in S/H amplifier 2. The output of S/H amplifier 1, representing the variations $(X_{i+1} - X_i)$ of the input pulses, is amplified and submitted to the rms-to-dc converter (Analog Devices 440K)[1]) whose output then represents the width of the pulse height distribution. The variable gain of this

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HIGH RESOLUTION POSITION-SENSITIVE PROPORTIONAL COUNTER*

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A counter giving high resolution for lightly ionizing particles incident at 45° has been designed and placed in routine operation in an Enge split-pole magnetic spectrograph. Use of a lumped-constant delay line and inclined cathode pickup stripes results in a very compact unit with high transmission; the collection and readout geometry results in virtual elimination of straggling (energy-loss fluctuations) as a source of resolution degradation. Spectra with total line widths less than 0.25 mm fwhm have been observed with 35 MeV protons.

1. Introduction

There has been no completely satisfactory detector for use in the focal plane of the popular Enge split-pole spectrograph. Line widths less than 50 μm fwhm have been obtained[1]) in this spectrograph far in excess of the capabilities of most detection systems except for nuclear emulsions. The most widely used active detector is perhaps the resistive-anode proportional counter[2–4]) using either charge division or rise-time effects to locate the event. Although these detectors generally do not give submillimeter resolution, they are preferred because of their low cost, simplicity and ability to transmit the detected particles to backing detectors which serve to reduce background events and to improve the particle identification. Significantly better resolution has been obtained in detectors where the position is determined by relative timing of signals at the ends of a helically wound delay line which serves as the cathode of a proportional counter[5]). This device has good position resolution but is difficult to back with a second detector and is very bulky. A general feature of both types of counters is the steady deterioration of resolution as one goes to higher energy, lighter ions.

Thus, it has been our objective to design a counter which provides high resolution even for lightly ionizing particles, while retaining the virtues of the resistive anode devices. In section 2, we discuss some of the processes taking place in the detection and localization of a particle in a proportional counter. In later sections the design and performance of a detector which meets the desired objective will be described and theoretical limits for the position resolution will be presented and compared with the results obtained.

* Supported by the U.S. National Science Foundation.

2. Position resolution

2.1. Effects of energy-loss fluctuations

The resistive anode counters[2]) are capable of position resolution better than 0.3 mm for highly ionizing or normal incident particles; but in use where these conditions are not present, the resolution is generally worse than 1 mm. We feel that the explanation for this effect is that energy loss fluctuations can lead to position fluctuations for non-normal particles. In an early work, Miller et al.[4]) made an estimate of the seriousness of this effect based on the Bohr formula for the variance of the energy-loss distribution. It seems these calculations are in error and underestimate the severity of the problem. Braid et al.[6]) have since performed a Monte-Carlo calculation with a Vavilov[7]) distribution of energy loss, which is far more valid for particles with energies of interest.

We also have calculated the energy-loss fluctuation effects by integration of the Vavilov distributions for energy loss in the halves of the counter. We assume that the detected position is the center of gravity of the energy loss and is given by

$$X = \frac{E_1 X_1 - E_2 X_2}{E_1 + E_2}, \tag{1}$$

where $E_{1(2)}$ and $X_{1(2)}$ are the energy loss and its center of gravity for the first (second) half of the counter. It is assumed that X_1 and X_2 correspond to the geometrical centers of the particle trajectory in the first and second halves of the counter. The probability that X will have a particular value is then

$$P(X) \sim \int_0^\infty P_1(E_1)\, P_2(E_2)\, \mathrm{d}E_1, \tag{2}$$

where eq. (1) is used to solve for E_2 in terms of E_1 and

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AN ULTRA THIN ΔE–E COUNTER TELESCOPE WITH POSITION SENSITIVITY IN TWO DIMENSIONS*

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A thin-window proportional counter (ΔE)–Si surface barrier detector (E) telescope is described which has position sensitivity in two dimensions with a resolution of <0.40 mm fwhm (σ_{rms}< 0.17 mm). The counter is well suited for particles with $E/M = 0.2$–5 MeV/amu and is very easy to construct and to use.

1. Introduction

Counter telescopes consisting of a gas proportional counter for ΔE and a Si surface barrier detector for E are certainly not new; however, their full potential has seldom been exploited. Here we describe a compact version of such a detector with the following major characteristics: simple construction, spatial resolution of less than 0.4 mm fwhm in two dimensions, ΔE resolution of 7% plus straggling, energy and time resolution characteristic of a surface barrier detector and thin windows allowing detection of particles with energy as low as $E/M = 0.2$ MeV/amu. The performance of three common gases with respect to position resolution is investigated.

Two systems with somewhat similar characteristics have been reported recently. One of these is a proportional counter having two-dimensional position sensitivity with resolution <0.4 mm fwhm[1]). However the extensive use of field shaping wires makes this type of counter unusable as a ΔE detector in a telescope requiring good ΔE and E resolution. A position sensitive ionization chamber has also been reported[2]) which gives good ΔE and E resolution. This detector is, however, quite complex and gives relatively poor position and time resolution.

2. Construction

A schematic drawing and photograph of the counter are shown in figs. 1 and 2. The body of the detector is machined from aluminum and houses the surface barrier detector (Ortec 400 mm^2 heavy-ion type) and the proportional counter chamber. The surface barrier detector is held in place by its rear-mounted Microdot connector which is mated with a vacuum feedthrough. The front face of the surface barrier detector serves as the rear cathode of the proportional counter whose anode wire* is mounted (on wire extensions of standard BNC vacuum feedthroughs) just outside the active volume.

Two types of windows have been employed. The simplest were gold-coated mylar foils as thin as 300 μg/cm^2. Very much thinner windows have been made from multiple layers of formvar stretched over 25 μm diameter wolfram support wires. These windows are constructed on removable frames which fit on a special cover plate for the counter, as shown in figs. 1 and 2. The support wires are wound on a jig and are then epoxied in place. After the epoxy has set the excess wire is removed and successive layers of formvar

* Evanohm S, W. B. Driver Co., Newark, N. J., U.S.A.; 10 μm diam., 186 Ω/cm.

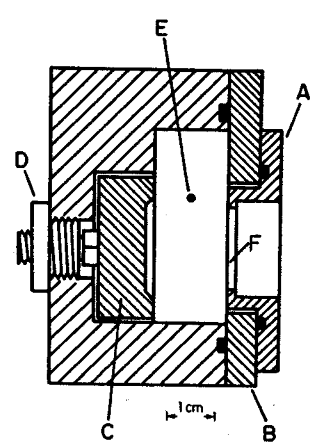

Fig. 1. Schematic cross section of the counter: (a) window frame, (b) front cover plate (c) surface barrier detector, (d) Microdot-to-Microdot bulkhead feedthrough, (e) anode wire, (f) window.

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NUKLEONIKA — VOL. 20 — No. 7-8/75

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EXOTIC NUCLEI WITH Z > N

The use of multinucleon transfer reactions to measure the mass and energy levels of nuclei far from β-stability is discussed. The results are compared to the predictions of the isobaric multiplet mass equation, Garvey-Kelson mass formulas and shell model calculations.

I. Introduction

In this lecture I will discuss the techniques, results and interpretation of a series of experiments performed over a period of five years in collaboration primarily with Prof. Edwin Kashy. The object of these experiments is to use two-body final state nuclear reactions to measure the masses and energy levels of exotic nuclei and in many cases to record their initial observation. An exotic nucleus has been defined as one at least three nucleons away from a stable nucleus. These nuclei, for example ^{9}C, are much more difficult to reach than non-exotic nuclei, and therefore special techniques are required. In the first part of the lecture I will discuss the particular technique we have employed, and then I will discuss the results and their interpretation.

Three transfer reactions which lead to exotic nuclei as final states are (^{3}He, ^{6}He), (p, ^{6}He) and (^{4}He, ^{8}He).

Table 1. Transfer Reactions Used to Study Exotic Proton-Rich Nuclei

Reaction	^{3}He, ^{6}He	p, ^{6}He	^{4}He, ^{8}He	^{3}He, ^{8}He
Typical Q-values (MeV)	−20 to −40	−25 to −50	−50 to −70	−50
Cross section μ/sr	0.05 to 4.0	0.005 to 0.100	0.020	< 0.004
Final nucleus T_z	−3/2 −1/2	−3/2 −1/2	−2 −3/2	−5/2 −2 −3/2

Typical parameters for these reactions are given in Table 1. The (^{3}He, ^{8}He) reaction has not been observed at the time of this lecture but is a very promising method of reaching very proton rich nuclei. The cross sections for all the reactions are very low and the Q-values

12*

Simple (Particle-Excitation) Nuclear Isomers and What They Can Teach Us

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What Are Nuclear Isomers?

In many ways the atomic nucleus is a most antisocial little thing. Atoms and molecules are forever interacting with the outside world, perturbing and being perturbed by their environments. Not so the nucleus. Locked deep within the atom, it is protected from most outside influences except for weak couplings such as the magnetic hyperfine interaction, and these are extremely weak compared with nuclear forces themselves.

The result of this is an almost iron-handed validity of selection rules for nuclear transitions. A "forbidden" (nondipole) transition usually does not "go" in an atomic or molecular system, for such a system most likely can be perturbed enough that an alternate "allowed" transition can proceed much faster than the forbidden one. When a seemingly forbidden transition does occur, it is usually because of perturbations through vibration, and the transition is usually quite slow. Now, forbidden transitions in nuclei have similarities to forbidden transitions in atoms and molecules, but they are much more common and are found with much higher degree of forbiddenness than in atoms and molecules. If the only direct way to get from state A to state B is *via* a many-times forbidden transition, then that many-times forbidden transition will most likely occur, although it may be very slow and state A may have a very long half-life.

When state A is an excited state in a nucleus and state B is a lower-lying state in the same nucleus, state A can deexcite to state B by γ-ray emission, the nuclear equivalent of X-ray emission. There is nothing intrinsically different between X-rays and γ rays except their point of origin and that γ rays are usually of higher energy than X-rays. (However, K X-rays of heavier elements have higher energies than γ-rays from low-energy transitions in nuclei, so there can be a considerable overlap in X-ray and γ-ray energies.)

If state A has a very different spin from state B, the γ transition will have to remove this difference in angular momentum—it is a "forbidden" transition, or, in nuclear parlance, a "high-multipolarity" transition. These high-multipolarity γ-ray transitions can be quite slow, meaning that state A can have quite a long half-life.

Wm. C. McHarris is Professor of Chemistry and Physics at Michigan State University, where his research centers around the MSU Sector-Focused Cyclotron and includes α-, β-, and γ-ray decay-scheme spectroscopy, in-beam particle-transfer reactions and γ-ray spectroscopy, and fast transfer techniques for short-lived nuclei, including development of a helium-jet on-line isotope separator. He is also working on weak-interaction and β-decay theory. He received his B.A. degree at Oberlin and the Ph.D at University of California, Berkeley, in 1965, following which he joined the faculty at Michigan State. He is an Alfred P. Sloan Fellow for 1972–1976.

This gives us the basis for defining the term "nuclear isomers." When two nuclear states have sufficiently different spins that each has an appreciable half-life of its own, the two states are said to be isomers, with a state that is not the ground state being called a "metastable" state. The metastable and ground states are symbolized by an m and a g in the mass-number superscript, *e.g.*, ^{53m}Fe (or ^{53}Fe^{m}) and ^{53g}Fe (or ^{53}Fe^{g}).

Deciding just when a half-life is "appreciable" gets to be rather arbitrary. As fast-timing electronics have become capable of probing the sub-nanosecond range, one sees more and more states with half-lives of a few nanoseconds being called metastable. For the purposes of this Account, we shall usually restrict ourselves to states with half-lives of seconds and longer.

Nuclear isomers can result for a number of reasons, including nucleons (protons or neutrons) occupying very different orbitals in states A and B ("particle-excitation" isomers), the nucleus having different shapes in states A and B ("shape" isomers), and selection rules on some of the more exotic quantum numbers in deformed nuclei. For the purposes of this introductory article, we shall restrict ourselves to particle-excitation isomers, which are the most straightforward to describe.

To get a semiquantitative idea of the half-lives involved in γ decay, one has to consider the process in more detail and perhaps invoke a nuclear model. The actual process is analogous to radiation by the motion of macroscopic charges (electric radiation) and currents (magnetic radiation). The electric or magnetic field is expressed in terms of a multipole expansion,[1] the terms in decreasing size then being called dipole (2^1-pole), quadrupole (2^2-pole), octupole (2^3-pole), hexadecapole (2^4-pole), and, in general, 2^l-pole radiation, where l is the (vector) amount of angular momentum that can be carried off by the transition. We call the electric transtions E1, E2, E3, E4, . . . , El and the magnetic ones M1, M2, M3, M4 . . . , Ml.

Detailed calculations of transition rates for individual nuclei quickly become cumbersome. Frequently a simplification called the Weisskopf single-particle estimate[1] is used. This considers that a γ transition results from a single nucleon's (proton or neutron) hopping from one simple harmonic-oscillator-type orbital to another. Even though it is a gross oversimplification, it gives answers that are in the correct ball park, and it is a simplistic but useful

(1) J. M. Blatt and V. F. Weisskopf, "Theoretical Nuclear Physics," Wiley, New York, N. Y., 1952, Chapter XII.

THE INITIAL ORGANIC PRODUCTS OF FIXATION OF ^{13}N-LABELED NITROGEN GAS BY THE BLUE-GREEN ALGA ANABAENA CYLINDRICA

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SUMMARY

Methods have been developed for the rapid isolation and characterization of the first organic products of fixation of ^{13}N-labeled N_2. In experiments with the blue-green alga, Anabaena cylindrica, glutamine is the first ^{13}N-labeled organic product observed, and glutamate is the second. The results indicate that the glutamine synthetase/glutamate synthase pathway is operative in this blue-green alga.

The primary products of biological nitrogen fixation have been investigated earlier, using N_2 labeled with the stable isotope ^{15}N, in nitrogen-fixing aerobic (1) and anaerobic (2) bacteria and in legume nodules (3, 4). Although products of fixation of ^{15}N-labeled N_2 ($[^{15}N]N_2$) were examined only after a minimum of 45 s of fixation (3, 4), these studies suggested that ammonia was the first nitrogenous product of fixation. However, the conclusion that glutamate was the first organic product of nitrogen fixation is now open to doubt. Recent evidence favors the operation of the glutamine synthetase/glutamine amide: 2-oxoglutarate amido transferase (glutamate synthase or GOGAT) pathway (5) in nitrogen-fixing microorganisms (6).

Both of the enzymatic activities required for this pathway have been measured in extracts of Anabaena cylindrica (7, 8). In other efforts to determine

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International Conference on Nuclei Far From Stability,
Corsica, May 1976

MASS MEASUREMENTS OF EXOTIC LIGHT NUCLEI*

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Abstract

Multinucleon-transfer reactions are used to measure the ground state masses of light nuclei far from beta stability. Techniques for particle identification and Q-value measurements in a magnetic spectrograph are discussed, and the results of the experiments are compared to various theoretical models.

1. Introduction

Transfer reactions can be used to measure nuclear masses with high precision, and the techniques which have evolved to make these measurements in a magnetic spectrograph are now being applied to nuclei far from beta stability in a number of laboratories. Besides providing a means of Q-value determination, the spectrograph has proven to be extremely valuable in the particle detection aspects of the problem. Of equal importance has been the advent of cyclotrons with well-defined, precise, high-energy beams. The cyclotron-spectrograph combination is capable of measuring masses to an accuracy in the kilovolt range in spite of the high particle energies involved which are in the range of 25-100 MeV. In this paper we will first discuss the techniques for particle identification and Q-value measurements. It will be evident that most of the physical effects we are discussing would not be visible if the accuracy of the measurements were not so high.

2. Method

A list of the transfer reactions which have been involved in studies of nuclei far from stability is given in Table I. The

TABLE I.--List of transfer reactions used to study nuclei far from beta stability.

ΔA	REACTION	ΔN	ΔP	ΔT_z	Q-values MeV	~dσ/dΩ* μb/sr
3	$(p,{}^4He)$	2	1	1/2	-7	50
	$({}^3He,{}^6Li)$	1	2	-1/2	-11	50
	$({}^3He,{}^6He)$	3	0	3/2	-27	1
4	$({}^3He,{}^7Be)$	2	2	0	-8	10
	$({}^3He,{}^7Li)$	3	1	1	-21	2
	$({}^4He,{}^8He)$	4	0	2	-60	0.01
5	$({}^3He,{}^8B)$	2	3	-1/2	-20	0.2
	$({}^3He,{}^8Li)$	4	1	3/2	-33	0.1
	$(p,{}^6He)$	4	1	3/2	-37	0.1
	$({}^3He,{}^8He)$	5	0	5/2	-52	0.0002
6	$({}^3He,{}^9Li)$	5	1	2	-51	0.005
	$({}^3He,{}^9C)$	2	4	-1	-30	<0.002

*75 MeV ^{3}He
45 MeV p

cross sections and Q-values given are typical ones for the particular reaction. The cross sections show a strong fall off with number of transferred particles and with transferred T_z. Not surprisingly, therefore, the farther from stability one wants to go, the lower the cross section. Extreme limits of nuclear stability can be reached by these reactions provided that nature has presented the appropriate targets. For example the two extremes of knowledge of the Cl isotopes, ^{31}Cl and ^{43}Cl, were both reached by five nucleon transfer reactions: $^{36}Ar(^3He,^8Li)^{31}Cl$ and $^{48}Ca(^3He,^8B)^{43}Cl$. The cross-sections for these reactions were approximately 10-25 nanobarns/sr. In all cases in which the cross section exceeded a few nanobarn/sr, a reasonable accurate mass has been obtained (<60 keV). The technique described here is responsible for the most accurate mass determinations of approximately 25 nuclei far from stability ranging from ^{8}C to ^{55}Ni and the first observation of about 15 of them.

In Fig. 1 we give an unusually complete view of the experimental apparatus used at Michigan State University. The maximum energy beams from the cyclotron are 76 MeV for ^{3}He's and 48 MeV for protons, and typical beam currents are 1 to 4 μA. At these currents the energy resolution of the cyclotron-spectrograph combination is less than the target thickness energy spread. The best energy resolution that has been obtained is 25 keV. In this case the beam, target and detector contributed about equally to the resolution. Good resolution is very important in both accurate Q-value measurements and in separating the peaks of interest from the background.

The detector is a triple telescope consisting of two wire counters and a plastic scintillator. The front wire counter measures the energy loss, ΔE', redundantly with the energy loss in the second counter, ΔE. In the present setup, a single channel analyser which is set on the ΔE' of the group of interest is one of the gate requirements for the other signals to reach the computer. By going from four to six ADC's we are planning to add the position information from this wire to the events recorded on tape. At present only the second wire gives position information (by resistive charge division). The spatial resolution is about 0.5 mm and usually contributes negligibly to the overall resolution. The principle of operation of a charge-division position sensitive detector is shown in Fig. 2. The computer constructs the energy loss by adding the signals to get ΔE and then taking the division $E_1/\Delta E$. Time of flight relative to the rf structure of the beam is also recorded as is the light output from the scintillator. This light signal is rather poor in quality and can not distinguish well between particle types. The plastic scintillator has another defect in that it is very gamma sensitive; keeping the raw counting rate in each detector to a minimum is crucial for suppressing background. For a plastic scintillator minimum volume is therefore important. We use 0.2 mm thick Pilot B scintillator, which is so thin that

International Conference on Nuclei Far From Stability, Corsica, May 1976

NUCLEAR SPECTROSCOPY WITH AN ON-LINE TIME-OF-FLIGHT MASS-IDENTIFICATION SYSTEM: HEAVY $T = \frac{1}{2}$ MIRROR NUCLEI*

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Abstract

The construction and use of an on-line He-jet fed time-of-flight mass-identification system are described. Using this system the $f_{7/2}$ $T = \frac{1}{2}$ nuclide ^{47}Cr has been produced and identified. We obtained a half-life for it of 460.0±1.5 msec, yielding a log*ft* of 3.63 for its superallowed decay to ^{47}V. We have also obtained a preliminary half-life of 219±6 msec for ^{55}Ni.

1. On-Line Time-of-Flight Mass Identification

Because the half-lives of nuclei get drastically shorter as one moves away from stability and the production of these nuclei also produces many impurities, it is obvious that a fast, on-line mass-identification system is a desirable tool for the study of such nuclei. Traditionally, two principle means have been used to make mass identifications -- magnetic separation and time-of-flight (TOF). A number of laboratories have constructed mass-identification systems based on the magnetic principle, but serious problems remain concerning the interface between the target and the magnet. Somehow the atoms must be taken from the target, ionized, and sent through the analyzing magnet. These difficulties, plus the expense of a magnetic system, made us decide to build a TOF system at Michigan State University. A TOF system had been constructed and was working at Texas A&M University[1]), and our instrument, called SIEGFRIED, is patterned after the one at Texas A&M.

In the TOF system, the decay (originally α decay was used, but any sort of decay producing a sufficient recoil energy should work -- our system is optimized for β-decay recoils) of the nuclei provides the ions that are accelerated down a flight tube. The interface between the target and SIEGFRIED is a He-jet recoil-transport system[2]). The explicit details of the chain of events follows below; refer to Fig. 1.

a. Atoms which have recoiled from an in-beam target are thermalized and brought to SIEGFRIED by a He-jet with a 0.4-mm×9-m capillary.

b. These "target recoils" are sprayed through a skimmer (to separate them from most of the He) and hit the collector. Presumably the target recoils are attached to some sort of large "molecules", often called clusters by He-jet enthusiasts. Many of these cluster-recoil combinations stick to the collector surface.

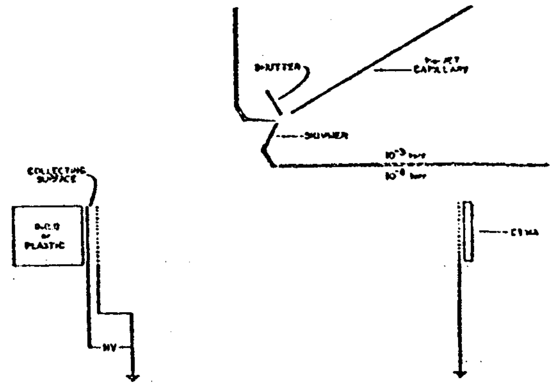

Fig. 1. Schematic diagram of SIEGFRIED on-line time-of-flight mass-identification system.

c. When one of the target recoils undergoes β decay, a number of events happen "simultaneously" in the time scale of interest. These simultaneous events, listed below, will be collectively referred to as a β event.

1) A β particle and ν are emitted.

2) The nucleus recoils. This recoil will be called the "β recoil".

3) Electron shake-off occurs, leaving the atom ionized.

4) If the β decay was to an excited state in the daughter, γ rays will be emitted. If the β particle was a β^+, 511-keV $\gamma^{\pm}$ quanta will be emitted.

d. If the β recoil is in the proper (forward) direction, the atom may leave the collecting surface. This produces an ion in the electric field maintained between the collector and the first grid. Any positive ions which appear in the electric field are accelerated down the flight tube and detected by the CEMA (Channel Electron Multiplier Array).

e. The time between detecting a β event and a CEMA event gives us the TOF and thus the mass.

A shutter is inserted between the He-jet capillary and the skimmer. This is necessary because the cyclotron produces a plasma in the He-jet chamber which is not yet relaxed when the helium-impurity mixture arrives at SIEGFRIED. The many ions produce a high count rate in the CEMA detector, which causes a very high chance-coincidence rate in the TOF spectrum. Therefore, SIEGFRIED is used in a pulsed mode in which the shutter opens, the He-jet deposits some activity, the shutter

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†Alfred P. Sloan Fellow, 1972-1976.

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HIGH-SPIN THREE-QUASIPARTICLE EXCITATIONS IN LIGHT ODD-A Pb NUCLEI*

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Abstract

The level structures of ^{199}Pb, ^{201}Pb and ^{203}Pb are being investigated by (α,3nγ) reactions on isotopically enriched Hg targets using 35-50 MeV α-particle beams from the Michigan State University cyclotron. Extensive yrast cascades have been observed in all three nuclei, which terminate in known $\nu i_{13/2}^{-1}$ isomeric states. The gross features of the high-spin level spectra in the odd-A Pb nuclei can be understood in terms of the coupling of known two quasiparticle states in the neighbouring even-A nuclei with the additional $\nu i_{13/2}$ hole. The present results make possible detailed and illuminating comparisons between the modes of excitation and the reduced transition probabilities in the odd- and even-A nuclei. Several new isomers have been identified in $^{199-203}$Pb, most of which arise from three-quasiparticle $21/2^-$, $25/2^-$ and $29/2^-$ states (related to 5^-, 7^- and 9^- states in even Pb nuclei). In ^{203}Pb, a $29/2^-$ ($\nu i_{13/2}^{-2}$, $\nu f_{5/2}^{-1}$) state at 2949 keV is the lowest-lying of the negative parity excitations; the half-life of this $29/2^-$ state is 0.48±0.04 sec and it de-excites by 153 keV E3 and 1027 keV M4 transitions to $23/2^+$ and $21/2^+$ states. The $21/2^-$ and $25/2^-$ states lie below the $29/2^-$ state in the other two nuclei and, consequently, the $29/2^-$ half-lives are much shorter — 11 μsec and 0.5 μsec in ^{199}Pb and ^{201}Pb, respectively. The detailed high-spin level schemes will be presented and discussed in terms of the shell model.

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Search for β-Delayed Proton Emitter ^{24}Si*

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The present results suggest that, at 62 MeV, production of ^{24}Si by the $^{24}Mg(^{3}He,3n)$ reaction is very weak relative to $^{24}Mg(^{3}He,2n)^{25}Si$. If the major branch of the proton decay of the 0^{+}, 2 state in ^{24}Al leads to the ground state of ^{23}Mg, then the cross section for the $(^{3}He,3n)$ process is no greater than 2% of the $(^{3}He,2n)$ reaction. Nevertheless, by further development of the recoil mass spectrometer described in this paper, a further reduction of at least a factor of 5 in this limit should be achievable.

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АКАДЕМИЯ НАУК СССР

НАУЧНЫЙ СОВЕТ ПО ПРОБЛЕМАМ УСКОРЕНИЯ ЗАРЯЖЕННЫХ ЧАСТИЦ

PROCEEDINGS FOR THE 4TH ALL RUSSIAN CONFERENCE ON ACCELERATORS OF CHARGED PARTICLES MOSCOW, NOVEMBER 1974

ТРУДЫ ЧЕТВЕРТОГО ВСЕСОЮЗНОГО СОВЕЩАНИЯ ПО УСКОРИТЕЛЯМ ЗАРЯЖЕННЫХ ЧАСТИЦ

(Москва, 18—20 ноября 1974 г.)

Том I

34. CHARACTERISTICS OF A 400(Q^2/A)MEV SUPERCONDUCTING CYCLOTRON*

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1. INTRODUCTION

High-field, superconducting coils as developed for bubble chambers have proved to be a major advance in low cost magnet technology. Coils for the NAL 15-foot Bubble Chamber,[1] for example, cost $2,000,000 and produce 3.0 tesla; this gives a field radius product corresponding to a cyclotron of energy 1100 (Q^2/A) MeV and the cost is less than half the cost of a conventional magnet with comparable bending capability. Noting the cost advantage of this coil technology, a group at Chalk River under Fraser suggested the adaptation of such coils to cyclotrons.[2] For isochronous cyclotrons the super-conducting, high-field coils are particularly matched to the requirements for acceleration of heavy ions, as has been noted previously.[3]

Considering energies of up to 10 MeV per nucleon for the very heaviest ions and up to perhaps 100 MeV per nucleon for lighter ions, the radial field increase needed to provide isochronism is moderate and the azimuthal variation required to provide adequate focusing can therefore be obtained from conventional sectored iron pole tips operating at room temperature. Thus, the low temperature part of the cyclotron is restricted to an anular cyrostat housing the main coil--all other components are at room temperature and can use existing technology as evolved and tested in the present generation of cyclotrons. The superconducting coils are also of course a tested technology--in bubble chambers such coils have proved to be unusually reliable. The probability of unforeseen technical difficulties in the total envisaged cyclotrons is therefore small, and the expected cost advantage is large.

In view of these factors a renewed study of such cyclotrons[4] was initiated at Michigan State in the Fall of 1973. This study has led to an attractive design for a 400(Q^2/A) MeV cyclotron. This paper reviews the basic characteristics of the planned cyclotron and presents results of performance calculations. The structure is an evolution from the earlier Chalk River study[2] and has a number of improved features.

2. CYCLOTRON GENERAL LAYOUT

Figure 1 shows the median plane layout of the cyclotron. The focusing is provided by four spiral sectors as indicated by the shaded "Hill" regions in the figure. The acceleration comes from four spiral dees located in the magnet valleys. Four rectangular yokes provide a path for the return flux. Figure 2 is a typical vertical section, the cut line (from left to right) following (a) the 45° line between yokes, (b) the center line of a dee, (c) the center line of a hill, and (d) the center line of a yoke. The cryostat shows clearly in Figure 2--an inner annular vessel contains the coil pancakes immersed in liquid helium. This inner vessel is mounted within a similar outer annular vessel which is at room temperature. The space between the helium vessel and the room temperature outer vessel contains a liquid nitrogen radiation shield, layers of super

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BEAM STABILIZATION BY EXTERNAL BEAM-PHASE FEEDBACK

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Abstract

The phase of the external beam with respect to the R.F. accelerating voltage of the Michigan State University Cyclotron is measured using a capacitive phase probe located in the beam line. The beam is stabilized with a feedback-circuit that reduces phase variations by adjusting the main magnetic field of the cyclotron. The damping factor of the system is about 20.

1. Introduction

The object of the phase-feedback system described below is to increase the stability of the external beam of the Michigan State University AVF variable energy cyclotron.

The phase of the external beam (with respect to the R.F. accelerating voltage) is continuously measured with a capacitive type beam probe, mounted in the beam-line, and a phase detector. When the cyclotron is in a proper operating condition and the operator activates the feedback circuit, the actual beam phase will be stored in a memory; deviations in phase from this value will then cause a corrective action by varying the magnitude of the main magnetic field of the cyclotron. Provisions are built in the feedback circuit to suspend operation in case the external beam disappears, which would occur with R.F. sparks, etc. The next paragraphs describe in more detail the various elements of the system and obtained results.

1.1 The beam probe

A magnetic- and a capacitive-induction type beam probe have been built and tested. Evaluation of both probes favored the capacitive type because of its superior signal to R.F. noise ratio, when mounted in the beam line. The probe (Fig. 1) consists of a short cylinder with length of 5 cm and a diameter of 2.8 cm, aligned in the center of the beam-line, so that the beam can pass through. The charged particles of the beam will induce a voltage, which is amplified by a preamplifier mounted on the housing of the probe. This amplified signal consists of a pulse-like voltage, representing the beam current, superimposed on a sinusoidal noise voltage, induced by the R.F. system. This signal is then routed through a variable frequency (14-25 MHz) notch filter, for attenuation of this R.F. noise, and another amplifier, both located in the cyclotron vault. The total amplification of this chain is typically 50 dB. The bandwith (3db) is about 100 MHz. The amplified signal is

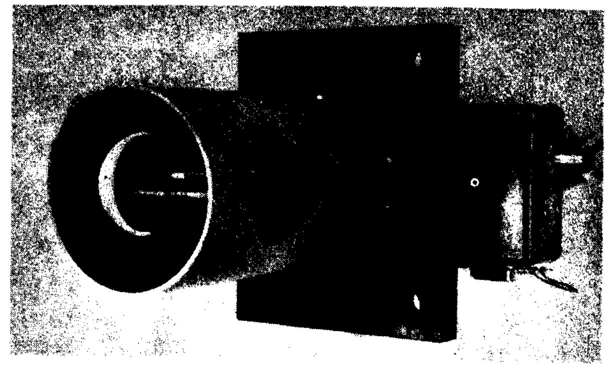

Fig. 1.--Capacitive phase-probe with preamplifier.

routed to the control room with a 50 Ω coaxial cable. A typical signal at this point is shown in Fig. 2.

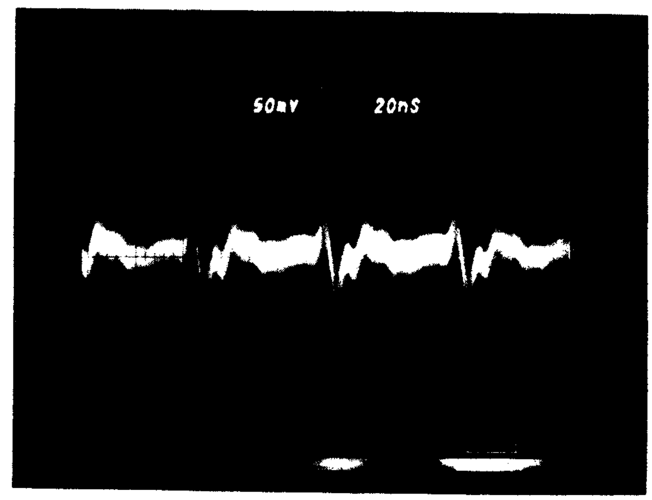

Fig. 2.--Typical signal from the phase-probe for a beam current of 0.6 A.

1.2 The phase detector

The phase detector (Fig. 3) is a combination of a zero-phase error detector and a R.F. phase-shifter network integrated in a feedback loop. The incoming signal V(t) is periodically sampled with gate S at time.

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IMPROVED ENERGY RESOLUTION WITH THE MSU CYCLOTRON

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Abstract

Recent measurements at MSU of inelastic proton scattering at 35 MeV using the Enge split-pole magnetic spectrograph have been made with energy resolution of E/ΔE= 23,000 (1.5 keV FWHM). The cyclotron-magnetic spectrograph system is operated in the dispersion matching mode, with the full cyclotron beam delivered to the target. Several phenomena which can limit the ultimate resolution have been observed. The narrowest lines recorded (50 μm FWHM in the spectrograph focal plane) imply as an absolute upper limit that 80% of the cyclotron's beam is contained within an incoherent radial emittance area of 0.4 mm-mr.

1. Introduction

The close relation between the ability to resolve nuclear levels and the ability to get information necessary to understand nuclei better is widely accepted. This fact has served as one strong motivation for the construction of several large magnetic spectrograph systems in various cyclotron laboratories, because the geometrical nature of the focusing process involved in particle detection in a spectrograph is uniquely adaptable for exploiting dispersion matching, which allows the resolution to approach the limit determined by the incoherent beam emittance area, even in the presence of large coherent energy fluctuations.

At the previous cyclotron conference calculations were presented[1] to indicate line width limits imposed in the MSU dispersion matching system by cyclotron emittance considerations. Since that time we have improved the resolution obtained in test runs by more than a factor of 2, from E/ΔE=10,000 to 23,000. This result sets a new upper limit on the cyclotron emittance, as discussed below.

Although the cyclotron ion source emittance sets the ultimate resolution limit of the system, other phenomena may determine the limit in actual practice. The effects of several such phenomena, which we have observed, are described below. Some of these parameters, such as target thickness, are often selected in actual experiments to increase the count rate rather than optimize resolution. The resolution of most experiments is limited by the aberrations and low dispersion of the Enge split-pole magnetic spectrograph,[2] which was not originally designed for use in such a high resolution system.

2. Recent Results

A brief description of the procedure used to tune the cyclotron and beam transport system will be given here. The object is to transport a beam to the target with an energy spread of ≲0.1% with the spatial correlations necessary for the spectrograph to operate in the dispersion matching or energy-loss mode, and to thereby obtain line widths with ΔE/E≲0.01% in the focal plane.

All cyclotron and beam transport system parameters are initially set at precalculated values. The beam transport quadrupole lenses are fine tuned to obtain good images visually at scintillator locations. Without further optimization this procedure normally yields energy resolution of 2000-4000 in the spectrograph.

The resolution is improved beyond this point via the on-line tuning procedure described previously.[3] With this method it has recently been possible under ideal conditions (very thin targets, very small spectrograph solid angle, etc.) to obtain an energy resolution of 23,000 or 1.5 keV FWHM with the 35 MeV proton beam scattered from carbon and nickel targets. In these runs all of the extracted cyclotron beam (~1μA) was transported to the target, and the runs were as long as one hour. The recent improvements came from a reduction of spectrograph solid angle and the elimination of excessive voltage ripple on the electrostatic deflector.

The results obtained from inelastic proton scattering from a 20 μg/cm^2 ^{58}Ni target are shown in Fig. 1a. The beam energy was 35 MeV, the scattering angle 15°, and the state indicated is the first excited state of ^{58}Ni recorded on a nuclear track plate in the focal plane of the spectrograph. The line width is 50 μm FWHM, and 82% of the area of the peak is contained within 100 μm. The spectrograph solid angle was limited to 0.06 msr for this exposure.

3. Resolution Limiting Phenomena

We have identified 6 important line-broadening phenomena, which we now discuss.

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ABSOLUTE CALIBRATION OF DEE VOLTAGE BY X-RAY ENDPOINT

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Abstract

We describe an X-ray technique for calibrating the rf voltmeters used to measure and stabilize the potentials of the dees in the M.S.U. cyclotron. The method is generally applicable and should be especially useful in cyclotrons which have multiple dees or which do not have separated turns.

1. Introduction

The Michigan State University Cyclotron has two weakly-coupled dees which can be operated either in phase or 180 degrees out of phase by adjusting the movable panels and the trimming capacitors to achieve a resonance in the desired mode. The modes are typically 200 kHz apart and about 8 kHz wide. The rf power is fed to the north dee only. The ratio of the amplitudes of the voltages on the north and south dees is varied by slightly detuning the south dee. Thus it is necessary to have a good measure of the relative dee voltage, and for this purpose we undertook to do a calibration of our dee voltmeters. In the X-ray technique described here the dee voltage is inferred from a measurement of the endpoint of the bremsstrahlung continuum, which corresponds to the peak dee voltage. It is possible to deduce the sum of the dee voltages from a measurement of the beam energy, the phase history and the number of turns. This will be shown to agree with the X-ray results.

2. Experiment

2.1 Detector Arrangement

Initially a Si(Li) X-ray detector (6 mm dia. Ortec model 7113-06275) was set up near a Plexiglass window (12 mm thick) in the cyclotron vacuum chamber. The X-ray continuum could be measured only at voltages above about 30 kV, mainly because signals became undectable in the background from room radioactivity at lower voltages. For this reason and also because of concern about distortion of the endpoint region of the spectrum from scattering, we inserted two 0.75 mm dia. thoriated tungsten filaments in the cyclotron, one under each dee, to provide controlled sources of electrons, as shown schematically in Fig. 1. A copper cap for the removable 6-inch steel plug in the lower yoke was modified to accept the filaments. One of the regular ion source filament leads was

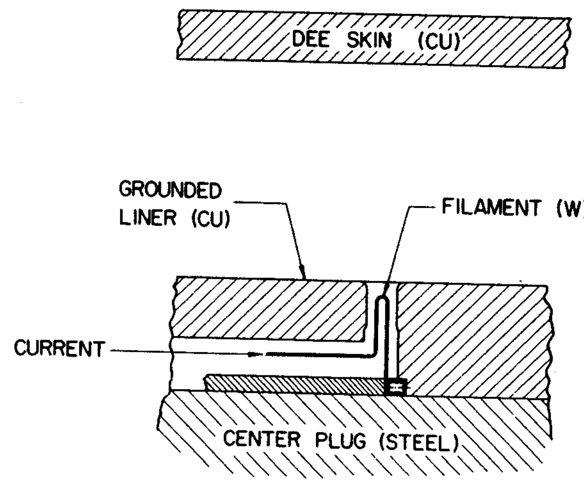

Fig. 1.--Layout of one electron source in the cyclotron. The support for the non-grounded side of the filament is not shown.

connected to each filament; the other end of each filament was grounded. This arrangement allowed remote switching from one filament to the other. The emission current could not be measured, however. In separate tests the filament emission was found to be about 2mA at a filament current of 40 A. Before the final data were taken the Plexiglass window was machined to a thickness of 2 mm in front of the detector.

At voltages above about 40 kV it was necessary to use a filter in front of the detector to prevent the counting rate from becoming excessive. The filters were mounted on a motor-driven wheel placed in front of the detector, which allowed selection of 7 different brass absorbers (from 0.13 mm to 1.70 mm thick), or no absorber, by remote control. The counting rate was always kept below 2kHz. Remote controls were not needed for radiation safety, but were used to speed up data collection.

2.2 Energy Calibration

Three typical spectra corresponding to different dee voltages are shown in Fig. 2. The energy scale was determined by measuring spectra from standard sources: ^{57}Co(6.4 keV, 14.39 keV, 122.19 keV, 136.31

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SUPERCONDUCTING CYCLOTRONS*

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Abstract

Superconducting cyclotrons are particularly appropriate for acceleration of heavy ions; this paper reviews design features of a superconducting cyclotron with energy 440 (Q^2/A) MeV. A strong magnetic field (4.6 tesla average) leads to small physical size (extraction radius 65 cm) and low construction costs. Operating costs are also low. The design is based on established technology (from present cyclotrons and from large bubble chambers). Two laboratories (in Chalk River, Canada and in East Lansing, Michigan) are proceeding with construction of full-scale prototype components for such cyclotrons.

1. Introduction

The idea of a superconducting cyclotron was explored at MSU in the early 60's[1)] but was laid aside due to unreliability of conductors then available. In 1973 a renewed study of superconducting cyclotrons was undertaken by a group at Chalk River under Fraser.[2)] After preliminary exploration Fraser's group concluded that the evolving superconducting coil technology was such that a cyclotron constructed using such a coil would be a major economic breakthru. MSU studies were reactivated in the fall of 1973[3)] and at the same time studies were in progress at the Lawrence Berkeley Laboratory.[4)] Both the Chalk River program and the Berkeley program are described in following contributed papers and so this paper will be devoted to discussion of results obtained in East Lansing.

Superconducting cyclotrons as presently planned combine a superconducting main coil with room temperature trim coils, rf system, vacuum tank, etc. Such a cyclotron is then fundamentally the same as present isochronous cyclotrons but with much higher magnetic fields (4-5 tesla). The superconducting main coil is similar in size and style to the coils used on a number of large bubble chambers. The oldest of these bubble chamber coils[5)] has now been in service since 1969 and has proved to be extremely reliable.

The relative absence of published literature on the superconducting cyclotron means that there is much to discuss; this is in conflict with the stringent page limit for the conference proceedings. Viewing this problem I have decided to use most of the alloted space for graphic materials, so that the paper is then dominantly a collection of figures and captions, intended to be concisely intelligible to the expert but probably difficult for the casual reader. Terminology and symbols are used without definition but in accord with normal cyclotron use (r, x, p_x, p_r, cyc. units, etc.). Proceedings of earlier cyclotron conferences are referred to for definitions.

The goals of the superconducting cyclotron program in East Lansing are at present rather general--we are trying to look at designs appropriate for a variety of different cyclotron applications, including both use as a stand-alone cyclotron and use as a post-accelerator. For the later we consider both large tandems and a preceeding cyclotron as possible first stage accelerators. In June 1975 we were authorized to proceed with construction of a full-scale prototype magnet for such a cyclotron.

2. Cyclotron Basic Structure

A coil, cryostat and refrigerator for the prototype magnet are being constructed by Argonne National Laboratory under Contract #31-109-38-3251L,[6)] and will be tested at Argonne at full field before being shipped to MSU. Figure 1 is a photograph of a conductor sample and conveys the compactness of the stabilized NbTi conductor. Conductor will be wound helically on a main coil bobbin; "picket fence" spacers between layers provide 50% face cooling of the conductor via direct emersion in liquid helium. The coil bobbin after winding is welded shut and becomes the helium vessel which is in turn installed in an annular cryostat as shown in Fig. 2. The total heat leak including both radiation loss and conduction losses thru leads and support members is estimated at 5 watts.[7)] Helium for the cryostat will be continuously supplied from a 500 liter storage dewar which will in turn be periodically replenished from an adjacent refrigerator (CTI Model 1400 with 2 compressors).

Two possible arrangements for the major mechanical features of the cyclotron are shown in Fig. 3 and 4. Many features of the two figures are independently interchangeable i.e., 3 sectors or 4 sectors, circular yoke or "cross" yoke, forgings or plates for the yoke, single dee stems or double dee stems, etc. The small insert in Fig. 3 shows a central region layout for a stand-alone cyclotron. For this configuration the central hole in the magnet is filled by iron plugs, the dees extend to the center and multiple ion sources, used one at a time, inject particles into one or the other of the 3 dees in the fashion of the Karlsruhe cyclotron.

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MEASUREMENTS OF NUCLEAR MASSES FAR FROM STABILITY*

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INTRODUCTION

Measurements of properties of nuclei far from nuclear stability provides a challenge to both the experimenter and theorist. To the first, it represents a new frontier in experimentation, and to the second a fertile source of data. There has been in recent years considerable effort on the neutron rich nuclei, and a smaller yet important attack in reaching the limits of particle stability on the proton rich side. Methods for measuring masses of nuclei far from nuclear stability are reviewed with emphasis placed on reaching proton-rich nuclei using particle transfer reactions such as $(p,{}^6He)$, $({}^3He,{}^8Li)$ and $({}^3He,{}^6He)$.

Neutron-Rich Nuclei: While it is the precise measurement of masses of proton rich nuclei with $A\leq 60$ which is the subject of this paper, we note briefly experiments where an accuracy of better than 100 keV has been obtained for masses of neutron rich nuclei. For example, Scott and collaborators[1] obtained $-10.75\pm.05$ MeV for the mass excess of ${}^{29}Mg$ using the three neutron transfer $({}^{11}B,{}^8B)$ and methods similar to those described here. Goosman and Alburger[2] have obtained $-24.936\pm.075$ MeV for ${}^{35}P$ using ${}^{18}O({}^{19}F,2p){}^{35}P$ and measuring the β-end point. A number of $T_z=5/2$ nuclei are reported in this conference by Alburger.[3] Flynn and Garrett[4] used the ${}^{26}Mg(t,{}^3He){}^{26}Na$ reaction and measured -6.903 ± 0.020 keV for the ${}^{26}Na$ mass excess using a Silicon surface barrier counter telescope. At a somewhat lower accuracy, there is the 100-200 keV work of Klapisch and collaborators,[5] who used on-line mass spectrometer for masses of neutron

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ISOBARIC MASS QUARTETS

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I. INTRODUCTION

In this paper we describe the current experimental status of isobaric mass quartets. A mass quartet consists of the states which represent the four projections of isospin T=3/2 on the T_z axis. Two of the states ($T_z=\pm 3/2$) are mirrors of each other, and the other two are what is called analog states, in this case they are analogs of the two $T_z=\pm 3/2$ levels. In Fig. 1, we show two illustrative quartets which occur in the A=9 nuclei. From this figure we can see that it is not necessary for the $T_z=\pm 3/2$ levels to be ground states, and in fact it is possible to have the interesting case of many complete quartets within a given A.

The mass of the T_z member, $M(T_z)$, was shown by Wigner[1] in 1957 to be given by a quadratic equation, the isobaric multiplet mass equation (IMME)

$$M(T_z) = a + bT_z + cT_z^2$$

Theoretical discussions of the IMME can be found in the original paper as well as in several review articles.[2] In this paper we will discuss mainly the experimental status of the equation, but first we will give a short discussion about its foundation.

In the absence of charge dependent effects, the four levels would, of course, be identical and degenerate in energy. However, when treating the breaking of the degeneracy, Wigner found, using first order perturbation theory, that the effect of two-body charge dependent forces is to produce a quadratic relation. To test this result one needs therefore multiplets of $T \geq 3/2$ levels. At present only one multiplet with T>3/2 is known, and it is discussed in another paper[3] at this conference. Deviations from the IMME could

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NEW TESTS OF THE ISOBARIC MULTIPLET MASS EQUATION

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INTRODUCTION

The isobaric multiplet mass equation (IMME), first propounded by Wigner[1] in 1957, states that the masses M of members of an analog multiplet should be related by an equation quadratic in T_z

$$M = a + bT_z + cT_z^2.$$

A non-trivial test of the equation requires a multiplet of at least 4 states (i.e. T_z=3/2), and in 1964 Cerny and his collaborators completed the first isobaric quartet.[2] Since that time, some 18 quartets have been measured, a few with extreme precision, and in only one case, the lowest mass 9 quartet, is there a significant disagreement with the IMME. The present status of isobaric quartets is summarized in this conference by Benenson and Kashy. There is considerable incentive to make new tests of the equation by considering multiplets other than quartets, but only very recently has it become experimentally feasible to test the IMME even in quintets. A number of features make such tests interesting. If one represents deviations from the IMME by additional terms dT_z^3, eT_z^4, etc., only one such term can be determined in a quartet, but two in a quintet. Thus one can test the IMME more rigorously, and, in the event of a violation, gain better insight into the possible mechanisms causing it. Furthermore, many quintets include both particle-stable and unbound nuclei, and if changes in the spatial wave functions across a multiplet can cause deviations from the IMME, then quintets may be rather sensitive to that influence. Finally, if there exists a many-body charge-dependent force, the presence of two determined parameters (d and e) makes quintets an attractive testing ground.

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Precision Energy Measurements with the MSU Cyclotron*

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Precision measurements of nuclear excitation energies and reaction Q-values are being made with a magnetic spectrograph at the MSU Cyclotron Laboratory. The present emphasis is on developing techniques which exploit the improved energy standards made possible by the atomic mass measurements of L. G. Smith.[1] This energy scale as suggested by Smith and Wapstra in Reference 1 is a significant improvement on the scales based on the ^{198}Au 411-keV γ-ray (±19 ppm) and the Po alpha particle energy (±100 ppm).

The present nuclear excitation energy measurements in light nuclei utilize the transition energies in ^{15}N determined by Greenwood and Helmer[2] based on the $^{14}N^{2}H-^{15}N^{1}H$ atomic mass doublet measured by Kerr and Bainbridge.[3] A re-analysis of the ^{15}N excitation energies including the Smith measurement is in progress.[4]

The energy levels measured in this work were populated via the (p,p') reaction on thin targets containing ^{15}N to provide the calibration lines. Uracil, $C_4H_4N_2O_2$, and melamine, $C_3H_6N_6$, are compounds which are available enriched in ^{15}N and which make targets suitable for these experiments. All known energy levels below 9 MeV excitation energy in ^{12}C, ^{16}O, and ^{15}N have been observed in spectra obtained on nuclear emulsions with 3-5 keV resolution. A least squares analysis is in progress to determine the excitation energies of these lines to within ±200-400 eV. Preliminary results show that the ^{16}O 6.9 and 7.1 MeV lines are about 2 keV lower than the published values of 6918.8±0.6 keV and 7118.67±0.35 keV.[5]

Similar techniques are currently being used in very accurate measurements of the relative masses of unstable nuclei. A measurement currently in progress is the determination of the mass of ^{12}N with an accuracy of ±1 keV. The technique involves the simultaneous recording of the ^{16}O(p,t) ^{14}O, ^{14}N(p,t) ^{12}N, and (p,p') spectra on nuclear emulsions. The (p,p') spectra provide a precision scale to relate the ^{12}N mass to that of ^{14}O. The preliminary result for the mass excess of ^{12}N is 17339±2 keV.

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PRE-EQUILIBRIUM NEUTRON SPECTRA

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The high-energy components of charged-particle spectra have been tested against pre-equilibrium[1] and intranuclear-cascade[2] calculations, but there have been almost no neutron spectra available for such tests. Coincidental to studies of (p,n) reactions which excite isobaric analog states,[3] continuous neutron spectra were obtained for targets of ^{48}Ca, ^{90}Zr, ^{120}Sn, and ^{208}Pb at E_p=25 (not ^{208}Pb), 35, and 45 MeV. In each of these 11 cases spectra were measured at 32 angles between 0° and 160°. Angle-integrated spectra were prepared for comparison with predictions of pre-equilibrium models.

Theory and experiment generally agree to within a factor-of-two, although the predicted spectra have significant differences which depend upon the manner of computation of the energy-dependent mean free path of nucleons in nuclei. The longer the mean free path, the greater the neutron emission rate. When the mean free path is obtained from the imaginary part of the optical model, a rather phenomenological approach, the results are better than when free nucleon-nucleon cross sections, corrected for the Pauli principle in nuclear matter, are used.

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GAMOW-TELLER STRENGTH OBSERVED IN (p,n) REACTIONS

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Enhancement of an approximately 6-MeV(base width) region of the $T_<$ continuum has been observed in $^{90}Zr(p,n)^{90}Nb$ and $^{120}Sn(p,n)^{120}Sb$ spectra obtained with 35- and 45-MeV protons.[1] The broad structure is centered at excitation energies of about 8 MeV in ^{90}Nb and 11 MeV in ^{120}Sb, just above the isobaric analog of the ground state (IAS) for each target.

The angular distributions suggest a $0^+ \rightarrow 1^+$ transition similar to the electromagnetic M1. However, since the (p,n) reaction lowers T_z, there is a closer analogy to Gamow-Teller β^- decay. The spin-orbit splitting between the $g_{9/2}$ and $g_{7/2}$ orbits plus the repulsive residual interaction between the neutron and neutron hole predict an M1 excitation of ^{90}Zr at approximately 9-10 MeV. The analog of this state should be about 9-10 MeV above the IAS in ^{90}Nb. Its anti-analog should be about 6 MeV lower,[2] in good agreement with the observed excitation. The measured cross sections are also consistent with microscopic DWBA calculations of (p,n) to the anti-analog of the giant M1.

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High-Spin States in Lighter s-d Shell Nuclei

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There is extensive experimental evidence pertaining to positive-parity states with spins between 4 and 10 in the nuclei A=19-28. It appears justifiable to assume that much of this level structure has its origins in dominantly sd-shell configurations. We have calculated the energies and wave functions of all states in the A=19-24 region and of the high-spin states in the A=25-29 region with a full sd-shell basis space and a new empirical Hamiltonian which gives a very accurate reproduction of low-excitation-energy phenomena. (The Hamiltonian is an improved version of the one used with quite some success by Preedom and Wildenthal and by Whitehead, Watt and Cole in various sd-shell calculations.)

Two aspects of the calculated results are of interest in the present context. First, all experimental evidence which can be categorized under "collective" or "rotational band" phenomena is exceedingly well reproduced by the theory. This includes the general J(J+1) trend of excitation energies, the specific perturbations of this ordering, the precise energies of the higher-spin members of a band, and the observed B(E2) rates (the last calculations employ the canonical half-unit-added effective charges). Second, in contrast to results obtained with the so-called "realistic interactions", states of non-collective nature and high spin occasionally occur below the rotational-band state of the same spin. In general, the specificity of the band structure breaks down at spins of 6 or greater and, even in the absence of this breakdown, the B(E2) values fall much below the rotational estimates in the high-spin region.

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HIGH SPIN 4 QUASIPARTICLE STATES IN ^{176}Hf

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The study of high spin states in even-even nuclei has been restricted mainly to positive parity yrast states; virtually nothing is known about high spin ($I>12$) states based on simple intrinsic excitations. It is therefore of interest to explore such non-yrast states to ascertain if their behaviour can be described in terms of the simple models which are applicable at lower spins and excitation. To this end, we have sought to identify the high spin 4 quasiparticle bands in ^{176}Hf by using the (α,4nγ) reaction.

We have performed prompt and delayed γ-ray singles and coincidence experiments, as well as angular distribution and excitation function measurements. A new $K^\pi=14^-$ isomer ($T_{1/2}$=432 μsec) at 2866 keV, was discovered which decays through two previously known K=8$^-$ two quasiparticle bands. By special delayed coincidence techniques, which allow the use of an effective coincidence resolving time of ~500 μsec without a prohibitively high chance rate, we have isolated the γ-rays feeding this isomer.

The 4 quasiparticle states which have been identified are listed in Table 1, where their energies are compared with calculated energies.[1] The effect of the residual proton-neutron interactions is represented by the difference between the observed energies and E_o (defined in the table).

A well-behaved rotational band (A=11.2 keV, B=-3.0 eV) built on the $K^\pi=14^-$ isomer was identified up to spin 19. From cascade-crossover ratios and angular distribution measurements we obtain for the band $g_K=0.59\pm.02$, using values of Q_o and g_R appropriate for the ground state band. This is in excellent agreement with the calculated value for the configuration listed in Table 1. A second rotational band based on the K=(16$^+$) state has also been tentatively identified up to spin 20.

TABLE 1.--High Spin 4 Quasiparticle States in ^{176}Hf.

K^π	Configuration	Energy (keV) exp.	E_o[a]	$E_{calc.}$[b]
14^-	$7/2(404)_p 9/2(514)_p 7/2(514)_n 5/2(512)_n$	2866	3158	2838
15^+	$7/2(404)_p 9/2(514)_p 9/2(624)_n 5/2(512)_n$	(3080)	3360	3190
16^+	$7/2(404)_p 9/2(514)_n 9/2(624)_n 7/2(514)_n$	(3266)	3419	3061
12^+	$7/2(404)_p 5/2(402)_p 7/2(514)_n 5/2(512)_n$	-	3094	2928

[a] E_o is the sum of the energies of the consituent 2 quasiparticle states.

[b] $E_{calc}=E_o$+p-n residual interactions (from ref. 1.).

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HIGH-SPIN LEVEL STRUCTURE IN $^{186-194}$Pt*

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Levels of the nine nuclei $^{186-194}$Pt have been investigated by Os(α,xnγ) reactions using the M.S.U. cyclotron. A brief report, describing the dominant systematic features of the level spectra and attributing the acute backbending behaviour observed in the positive parity yrast sequences of the even-A nuclei to intersections of rotation-aligned bands built on ($\nu i^{-2}_{13/2}$) and ($\pi h^{-2}_{11/2}$) structures with the "normal" ground bands, has been recently published[1]. In all four odd-A nuclei, decoupled $\nu i^{-1}_{13/2}$ bands, strongly resembling the ground bands of the adjacent core nuclei, and many other high-spin positive parity states have been established. Qualitatively, these rather complex level spectra can be accounted for reasonably well in terms of the coupling of an $i_{13/2}$ neutron hole to a triaxially deformed core, using the treatment of Meyer-ter-Vehn[2]. Low-lying $21/2^{(-)}$ bands are also systematically observed in the odd-A nuclei and are attributed to combinations of $\nu i_{13/2}$ with members of the 5^-, 7^-,.... bands identified in the even Pt nuclei. The B(E2) values for the $7^- \rightarrow 5^-$ and $25/2^{(-)} \rightarrow 21/2^{(-)}$ transitions in ^{190}Pt-^{194}Pt have all been found to be close to 30 s.p.u. The yrast cascades in ^{191}Pt, ^{189}Pt and ^{187}Pt terminate in isomeric states with half-lives of 95, 143 and 310 μs, respectively, which contrast with the ∿ 4 d half-lives of the $13/2^+$ isomers in ^{193,195}Pt. [The 145 and 95 μs isomers currently ascribed to ^{190}Pt and ^{192}Pt should now be re-assigned to ^{189}Pt and ^{191}Pt.] A detailed ^{191}Au radioactivity study now in progress promises to yield important supplementary information about the nature of the decay modes of the μs isomers. Other interesting aspects of the level structure of these shape transitional nuclei will be discussed.

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HIGH-SPIN LEVEL STRUCTURE IN TUNGSTEN ISOTOPES 177-182†

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The *yrast* level structures have been relatively well worked out by (HI,xn) and (α,xn) reactions for most of the deformed even-even isotopes in the region from Sm to Os. The systematics developed from these studies have generally seemed consistent with the dominant role played by $i_{13/2}$ neutrons in the backbending behavior in the *yrast* bands.[1,2] A gap in our knowledge has existed for the tungsten isotopes, however, and we here report the results of studies on those nuclei. Experiments carried out by (α,$xn\gamma$) reactions on enriched ^{177}Hf and ^{180}Hf targets have determined that the most distinct g.r.b. anomaly occurs for ^{180}W. This pattern is consistent with the relatively high degree of particle-core decoupling displayed in the $i_{13/2}$ rotational band[3] in ^{179}W. One might expect that the more normal behavior of the ground bands in ^{178}W and ^{182}W would then be reflected in less decoupled $i_{13/2}$ neutron structures in ^{177}W and ^{181}W compared to ^{179}W, and this is indeed found to be the case.

The simplicity of this picture is complicated, however, by recent data from the Julich group[4] which strongly suggest the importance of decoupled $h_{9/2}$ proton structures in the ^{182}Os backbending behavior. The qualitative consistency between *yrast* band behavior in even-A nuclei and the degree of decoupling displayed by $i_{13/2}$ band structures in odd-N neighbors throughout the rare-earth deformed region suggests therefore that both proton and neutron decoupling effects may influence *yrast* band behavior in the even-A W and Os isotopes. (It seems quite likely that this is the case in the shape-transitional platinum isotopes.[5])

In ^{182}W, the ground band displays almost perfect rotational structure at least to spin 14. The K = 10$^+$ isomeric state proposed earlier by Nordhagen *et al.*[6] has been characterized in our work as the 9/2$^+$[624] × 11/2$^+$[615] $i_{13/2}$ two-neutron configuration, and its band structure is identified to spin 15. A crossing of this band and the well-behaved ground band is expected at spin 16, and the near-degeneracy of the two spin-16 states may offer a unique opportunity to deduce the mixing between these two bands at relatively high spins.

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