SECTION III

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Proton Decay of the Isobaric Analogs of the Ground States of ^{206}Pb, ^{207}Pb, ^{208}Pb, and ^{209}Bi†

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The $(p,n\bar{p})$ reaction has been measured on the lead isotopes ^{206}Pb, ^{207}Pb, and ^{208}Pb and on ^{209}Bi. Coulomb-energy differences are extracted from the positions of the $\bar{p}$ peaks. Proton decay widths are also obtained and compared with values from resonance experiments and with a previous value from ^{209}Bi$(p,n\bar{p})$.

I. INTRODUCTION

The $(p, n\bar{p})$ reaction[1] has been observed in a number of nuclei from ^{67}Zn to ^{209}Bi.[2-4] This reaction allows one to study the position and width of the isobaric analog state[5] (IAS) populated in the (p, n) reaction without the difficulty of neutron detection. In principle, proton decay widths of the IAS can also be measured if the (p, n) cross section leading to the IAS is known. However, for nuclei in the lead region, decays to more than one final state are observed and therefore *relative* proton decay widths can be obtained independent of the (p, n) cross section. These same widths can also be obtained by resonant elastic and inelastic proton scattering on a target with one less neutron than is required for the $(p, n\bar{p})$ experiments. This illustrates another feature of the $(p, n\bar{p})$ reaction. Since it can be used to study nuclei that cannot be reached by resonance reactions on stable nuclei, it provides complementary information. For example, the IAS studied by ^{206}Pb$(p, n\bar{p})$ can only be reached by a resonance reaction on the unstable nucleus ^{205}Pb.

Earlier measurements of the partial widths for decay of the IAS in ^{208}Bi had shown agreement between the resonance measurements and the ^{208}Pb$(p, n\bar{p})$ experiment. However, measurements of the ^{209}Bi$(p, n\bar{p})$ reaction gave a relative proton width for the IAS in ^{209}Po which differed significantly from the measurements in ^{208}Bi. This was surprising, since one would not expect the extra $h_{9/2}$ proton in the ^{209}Bi parent nucleus to make a significant difference to the proton decay widths. This discrepancy encouraged us to repeat the ^{208}Pb$(p, n\bar{p})$ experiment as a check on the earlier measurements. In addition, measurements on ^{206}Pb and ^{207}Pb were also made, and the ^{209}Bi$(p,n\bar{p})$ experiment was repeated.

II. EXPERIMENT

The experimental arrangement is similar to that discussed in an earlier paper on ^{209}Bi.[4] The reactions were studied at many energies from 21.3 to 35 MeV using the proton beam from the Michigan State University isochronous cyclotron. A standard counter telescope of cooled silicon detectors was used to detect the protons. Deuteron spectra were taken simultaneously, since the (p, d) reaction produces the same final nuclei and therefore provides an energy calibration. The deuteron resolution also gives an accurate check of the target thickness measurement. Spectra were taken at many angles to avoid contaminant peaks and to check kinematic effects. Various targets of thickness from 1 to 6 mg/cm^2 were used in the experiment.

Kinematic effects are very important in a discussion of the $(p, n\bar{p})$ reaction, since both the energy of the detected protons and the shape of the peak depend on the angle of detection. This dependence arises from the angular distribution of the recoiling nuclei and therefore depends on the (p, n) angular distribution, which changes as the bombarding energy is changed. Calculations of both of these effects for model (p, n) angular distributions were shown in a previous paper.[4] Even for heavy nuclei the shift and the broadening of the peak is significant and must be taken into account when extracting widths, even though the intrinsic width of the analog state is large (>200 keV) and dominates the observed width of the peak. A calculation for the energy shift of the $\bar{p}$ peak using a measured (p, n) angular distribution[6] at 24.8 MeV is shown in Fig. 1 together with the experimental kinematic shifts for ^{209}Bi. The Bi target is quite free of impurities and allows a more complete angular distribution to be obtained than could be done for lead. Line-shape calculations at various angles are shown in Fig. 2 for the same (p, n) angular distribution. A Lorentzian function with a 220-keV total width is also shown on the same scale. The line shapes fold in such a way that the total observed full width at half maximum (FWHM)

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$^{19}F(d, p)^{20}F$ and the Nuclear Structure of ^{20}F†

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The reaction $^{19}F(d, p)^{20}F$ has been studied with 16-MeV deuterons. Outgoing protons were detected in photographic emulsions in a magnetic spectrograph. Spectroscopic factors were extracted and combined with previous information and compared with results of shell-model calculations performed in a complete *sd*-shell basis. Of the previously known 25 states below $E_x = 4.5$ MeV, angular distributions measured at 14 angles were obtained for all but the 5 at $E_x = 1.824$, 2.871, 3.761, 4.20, and 4.21 MeV. Strong stripping angular distributions were observed for 10 states – 6 dominated by $l = 2$, and 4 by $l = 0$. These 10 states agree reasonably well in position and strength with the 10 lowest shell-model states predicted to have appreciable amounts of the configuration [^{19}F(g.s.) $\otimes$ $1d_{5/2}$ or $2s_{1/2}$ neutron)].

I. INTRODUCTION

The spectroscopy of ^{20}F is typical of non-self-conjugate odd-odd nuclei; the knowledge about it is extremely scant in view of the effort that has been expended. The most notable early work on its structure was that of El Bedewi[1] in 1956. Using an 8.9-MeV deuteron beam and one of the first heavy-particle spectrographs, he was able to obtain excitation energies and angular distributions for a great many of the states in ^{20}F. His analysis of the angular distributions was limited by the use of the plane-wave Born approximation (PWBA). However, as we shall see below, his results for the few strong states were qualitatively correct.

Accurate excitation energies have been measured[2] up to $E_x = 6.043$ MeV by use of the reactions $^{18}O(^3He, p)^{20}F$ and $^{19}F(d, p)^{20}F$ at low bombarding energies. Information on the γ decay of levels of ^{20}F has been obtained in studies of the reactions $^{18}O(^3He, p\gamma)^{20}F$,[3-7] $^{19}F(d, p\gamma)^{20}F$,[3,8] $^{19}F(n, \gamma)^{20}F$,[9-12] and $^{18}O(t, n\gamma)^{20}F$.[13] Further studies include measurements of lifetimes[13-16] of excited ^{20}F levels, angular-distribution measurements of the reaction $^{19}F(d, p)^{20}F$ obtained with a polarized deuteron beam,[17] and a study of the reaction $^{22}Ne(p, ^3He)^{20}F$.[18] Studies of the reactions $^{18}O(^3He, p)^{20}F$ and $^{22}Ne(d, \alpha)^{20}F$ have also been reported recently.[19] The experimental results concerning ^{20}F are excellently summarized in the review by Ajzenberg-Selove.[20]

Directional-correlation measurements[7] in the re-

Collective Effects Shown by the (p, t) Reaction on the Closed-Shell Nucleus, ^{141}Pr

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The reaction ^{141}Pr$(p,t)^{139}$Pr at 40 MeV strongly populates collective states in the residual nucleus. The shapes of the angular distributions, taken at 5° intervals between 15 and 65°, show the inadequacies even of finite-range, two-nucleon-pickup distorted-wave Born-approximation calculations and the need for inclusion of higher-order effects.

The (p, t) reaction on ^{141}Pr has been studied as part of a general investigation of the systematics of the (p, t) reaction on spherical and deformed rare-earth nuclei. The residual nucleus of this reaction, ^{139}Pr, has been extensively studied through the ϵ/β^+ decays of the ground and metastable states of ^{139}Nd.[1] Because of the large number of very dissimilar states established in this decay scheme, 23 below 2.2 MeV, it was thought that here would be an excellent place to begin this general investigation.

In the present work, ≈800-μg/cm^2 ^{141}Pr targets prepared by vacuum evaporation on 25-μg/cm^2 carbon backings were bombarded with 500-nA beams of 40-MeV protons from the Michigan State University sector-focused cyclotron. A dE/dX, E counter telescope consisting of two cooled Si surface-barrier detectors was used to identify and measure the energies of the outgoing scattered particles. Triton spectra were taken between 15 and 65° at 5° intervals. Figure 1 contains triton spectra taken at the laboratory scattering angles of 25 and 35°. The over-all experimental resolution was 50 keV full width at half maximum. The excitation energies corresponding to the various triton peaks were determined internally by making a correspondence between some of the more obvious triton groups and the previously determined states in ^{139}Pr. In addition, an independent energy measurement of some of the more intense triton groups was conducted using a broad-range magnetic spectrometer, utilizing a 3-cm Si position-sensitive detector.

The experimental angular distributions, together with distorted-wave Born-approximation (DWBA) predictions, are displayed in Fig. 2. The distorted-wave predictions for various l transfers were calculated using a zero-range, cluster-transfer approach[2] as well as a more rigorous finite-range, two-nucleon-pickup formalism.[3] These are denoted by broken and continuous curves, respectively. Optical-model and bound-state parameters used in generating these theoretical curves appear in Table I.

The angular distribution corresponding to the $\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$ ground-state transition corresponds to an ap-

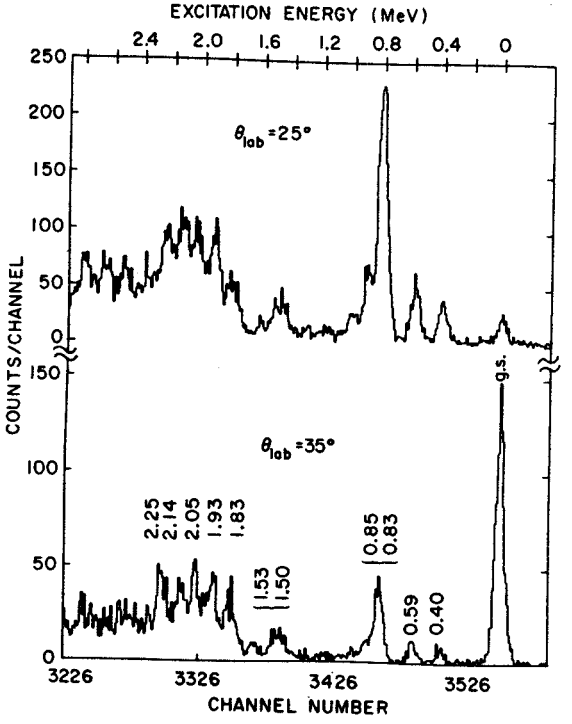

FIG. 1. Two spectra (θ_{lab} = 25 and 35°) of tritons from the ^{141}Pr(p,t) reaction at 40 MeV.

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Proton Inelastic Scattering from ^{48}Ca†

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Inelastic proton scattering from ^{48}Ca has been measured at beam energies 25, 30, 35, and 40 MeV. Angular distributions from 13 to 97° for 22 inelastic states were obtained. Analyses with the collective distorted-wave Born approximation are presented. A direct comparison of the excitation of the ^{48}Ca 3.830-MeV 2^+ and 6.342-MeV 4^+ states is made with the low-lying excited 2^+ and 4^+ states of ^{50}Ti and ^{52}Co.

I. INTRODUCTION

Doubly magic nuclei, in general, have been studied in great detail both experimentally and theoretically. Perhaps the exception to this statement is ^{48}Ca. From the experimental standpoint only a few of the low-lying states of ^{48}Ca have well established spin and parity. From the theoretical point of view ^{48}Ca is of interest because of the purity of its double-closed-shell structure. Jaffrin and Ripka[1] have tested the occupation numbers and find that the $1f_{7/2}$ shell and the inner neutron shells are at least 97% closed. It is because of the strong theoretical motivation and of our interest in developing the (p,p') reaction as a probe in microscopic structure that we undertook the present (p,p') experiment on ^{48}Ca.

The level structure of ^{48}Ca has also been investigated in other experiments such as (α, α'),[2,3] (e, e'),[4] (t,p),[5] (p,p'),[6] and $(p,p'\gamma)$.[7] The (α, α') and (e, e') experiments probably should be repeated with the now available better resolutions. In principle, then, at least some of the ambiguities in the present assignments of the low-lying levels could be removed.

II. DESCRIPTION OF EXPERIMENT

The experiment was carried out using the proton beam from the Michigan State University sector-focused cyclotron. Figure 1 shows the cyclotron and beam-handling system. The two horizontal bending magnets M3 and M4 are used to momentum analyze the beam and M5 deflects the beam into the goniometer.[8] More complete descriptions of the properties of the energy analysis system have been published elsewhere.[9,10] During this experiment the slits S1 and S3 were set at 15 mils for beam energy resolution of ±5 keV. S2 was set at 100 mils to yield a beam divergence of ±2 mrad. The Faraday cup is located in a shielded beam dump 12 ft beyond the goniometer.

The scattered protons were detected with two surface-barrier Ge(Li) detectors designed specifically for this experiment.[11] The two detectors were separated by 14.7° and were located outside the 16-in. scattering chamber. The detectors coupled to the scattering chamber vacuum via a sliding seal. A monitor counter at a fixed angle viewed the scattered beam through a 1-mil Kapton window.

The target was a commercially prepared self-supporting foil of ^{48}Ca approximately 1.08 mg/cm^2 thick. The composition of the target as determined by the Isotopes Division of Oak Ridge National Laboratory is listed in Table I. The target was stored in vacuum when not in use and transferred to the scattering chamber in vacuum via a target-transfer system.[8]

Inelastic proton spectra were taken every 5° from 13 to 97°. The over-all energy resolution was 25–30 keV full width at half maximum. Each counter subtended an angle of about 0.5° in the scattering plane. The scattering angle was checked by comparing the positions of the H and ^{12}C contaminant peaks relative to the ^{48}Ca ground state and found to be accurate to within 0.1°. The energy of the incident protons determined by mea-

Decay of ^{170}Lu to Levels in ^{170}Yb†

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The locations of 70 energy levels in ^{170}Yb were deduced from Compton-suppressed γ-ray singles, three-crystal γ-ray pair, conversion-electron, and Ge(Li)-Ge(Li) γ-γ coincidence measurements on the electron-capture-β^+ decay of ^{170}Lu. Both chemically separated and isotopically separated sources of ^{170}Lu were used in collecting the data. A total of 550 γ-ray transitions have been observed in the ^{170}Lu decay spectrum, 220 of which are definitely assigned to the ^{170}Yb level scheme from 112 coincidence spectra. These definitive transitions account for 93% of the total observed γ-ray intensity. An additional 118 γ-ray transitions were placed on the basis of excited-state energy differences. Eight $E0$ transitions were observed in the conversion-electron data. Each of four excited 0^+ states identified has less than 1% β decay feeding from the 0^+ parent. Spin and parity assignments are proposed for 46 levels in addition to the ground-state rotational band members. The ^{170}Yb level structure is compared with available theoretical calculations, and a preliminary interpretation of several features of the decay scheme is presented.

I. INTRODUCTION

The most complicated radioactive decay yet studied is the electron-capture (EC)-β^+ decay of 2.15-day ^{170}Lu to the levels of ^{170}Yb. Early attempts to interpret the complex γ-ray spectrum from NaI(Tl) data were largely unsuccessful, and until recently, the best available data consisted primarily of conversion-electron spectra.[1-3] With the advent of germanium detectors, however, several groups[4-8] renewed their efforts at unraveling this very complex decay. Hansen and co-workers[9] established 0+ as the ground-state spin and parity of ^{170}Lu. Paperiello *et al.*[10] carried out directional-correlation measurements on several of the more intense transition cascades in this decay and have definitely established the spins of 10 levels in ^{170}Yb. Concurrent with the work reported here were the recent studies reported by Bonch-Osmolovskaya and coworkers[11, 12] who employed Ge(Li) detectors, electron-γ, γ-γ, and electron-electron coincidences, in an effort to define the decay scheme. They placed some 177 transitions of 280 seen in the decay, thus accounting for almost 87% of the total γ-ray intensity.

In this work we report the results of extensive γ-ray singles, γ-γ coincidence, and conversion-electron measurements. Compton suppression and three-crystal pair-spectrometer techniques were used to accurately define the energies and intensities of the ^{170}Lu γ-ray transitions. Measurements at lower energies (<1.2 MeV) were carried out with isotopically separated sources. An on-line computer and multiparameter data acquisition system were used in conjunction with two Ge(Li) detectors and an isotopically separated ^{170}Lu source to carry out a detailed study of the γ-γ coincidence spectra. Conversion-electron studies were carried out using chemically separated lutetium sources and a Si(Li) detector. On the basis of these data, we have constructed a level scheme for ^{170}Yb consisting of 70 excited states. Of 550 γ-ray transitions identified, over 200 have been placed on the basis of γ-γ coincidence data and another 118 were placed on the basis of energy differences; these two groups of γ rays account for 93 and 3% of the total γ-ray intensity, respectively. Significant differences exist between our decay scheme and that of Bonch-Osmolovskaya *et al.*,[12] and slight differences distinguish our decay scheme from the less complete level scheme of Mihelich.[13]

II. EXPERIMENTAL

A. Target and Source Preparation

Sources of ^{170}Lu were prepared by the ^{169}Tm-$(\alpha, 3n)^{170}$Lu reaction by irradiating 40-mg samples of Tm_2O_3 at the Lawrence Berkeley Laboratory 88-in. cyclotron with 40-MeV α particles. 3-h irradiations at about 20-μA beam current produced about 1 mCi of ^{170}Lu activity for each experiment.

The lutetium activity was separated from other

Study of (^{3}He, t) Reactions at 70 MeV to Isobaric Analog States of ^{50}Cr, ^{62}Ni, and ^{90}Zr†

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The analysis of (^{3}He, t) reactions at 70 MeV to isobaric analog ground states of ^{50}Cr, ^{62}Ni, and ^{90}Zr have shown an energy dependence in the extracted isospin-dependent interaction strengths consistent with results at lower energies; the interaction strengths are approximately 50% smaller than at lower bombarding energies. The shapes of the form factors in a macroscopic analysis are nuclei-dependent. A mass-three optical potential with a real strength of about 110 MeV and a volume imaginary term is strongly preferred in the (^{3}He, t) calculations.

I. INTRODUCTION

Charge-exchange reactions to isobaric analog states (IAS) of target ground states have been studied quite extensively in recent years with both (p, n)[1,2] and (^{3}He, t)[3-6] reactions at a variety of bombarding energies. The analysis of the differential cross sections for such reactions primarily has used the distorted-wave Born approximation (DWBA) in a macroscopic (generalized optical-potential) or microscopic (nucleon-nucleon interaction) framework, and has yielded information on the strength and form of the isospin-dependent interaction. Recent studies by Fadner, Kraushaar, and Hayakawa[5] of (^{3}He, t) transitions to IAS in several nuclei at bombarding energies between 21.4 and 37.5 MeV have shown a marked energy dependence in the extracted strength of this isospin interaction and a variation in the extracted shapes of the isospin term (for the macroscopic analysis) for different nuclei. We have extended the study of (^{3}He, t) reactions to 70 MeV (the highest reported bombarding energy has been 50 MeV[7]) by examining transitions to IAS of the ground states of ^{50}Cr, ^{62}Ni, and ^{90}Zr to provide more information on the energy dependence of the charge-exchange interaction.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The reactions ^{50}Cr, ^{62}Ni, ^{90}Zr(^{3}He, t) were studied at a bombarding energy of 70 MeV using ^{3}He ions accelerated in the Michigan State University sector-focused cyclotron. The experiment was conducted in a 40-in. scattering chamber with the tritons detected in a 1-cm stack of three Si(Li) detectors. A ΔE-E particle identification program was used in conjunction with the Sigma-7 computer. An over-all resolution of 150 keV was obtained, which was detector limited. The targets were all 1-mg/cm^2 rolled foils. An energy spectrum for the reaction ^{62}Ni(^{3}He, t)^{62}Cu is shown in Fig. 1. At all angles the 0^+ IAS was populated

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Shell-Model Calculations for ^{22}Na and ^{22}Ne

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Shell-model calculations have been performed for the nuclei ^{22}Na and ^{22}Ne. The model space is made up of all Pauli-allowed combinations of six particles in the orbits $0d_{5/2}$, $1s_{1/2}$, and $0d_{3/2}$. An inert ^{16}O core is assumed. The two-body interaction which is employed has been obtained by empirically modifying some of the matrix elements of Kuo's interaction in order to achieve an rms best fit between the observed energies of 72 levels in the $A=18$–22 region and the corresponding shell-model eigenvalues. Single-particle energies are taken from the ^{17}O spectrum. Calculated results for excitation energies, electromagnetic transition strengths, and spectroscopic factors for single-nucleon transfer are presented and compared with existing data.

I. INTRODUCTION

The shell model has been used successfully to describe the low-lying spectra of nuclei near neutron and proton closed shells. With the advent of sophisticated computer codes,[1] it has become possible to calculate the properties of nuclei further from closed shells. In particular, it has been shown that many aspects of the collective features of nuclei several nucleons removed from ^{16}O in the s-d shell can be well reproduced by shell-model calculations in which all of the s-d nucleons are active.[2-5]

Several aspects of the $A=22$ nuclei make them of particular interest from the standpoint of attempting to understand collective nuclear phenomena in terms of many-body microscopic calculations. These systems appear to be among the most highly deformed nuclei in the light-mass region. In addition, there have been extensive experimental studies of ^{22}Na and ^{22}Ne which have assigned spins and parities to many low-lying levels and have measured the strengths of many electric quadrupole and single-nucleon transfer transitions.

Since one wants to observe the fullest consequences of the two-body part of the nuclear Hamiltonian, it is desirable to study systems with as many active particles as possible. If the active particles are distributed without restriction over the three sd-shell orbits, the shell-model states for $A=22$ have dimensions as large as can be handled straightforwardly with our techniques. The $A=22$ systems thus constitute the best place to study the many-particle shell-model structure in this region if one is to avoid introducing the additional complication of basis truncation within the s-d shell space itself.

Finally, the $A=22$ systems are of interest because, despite significant successes in explaining some features of their behavior, several aspects of the structure of the low-lying levels seemed to be reproduced poorly by previous calculations.[2,3,5] In general, the results of shell-model calculations reproduce the detailed features of doubly odd nuclei less successfully than those of doubly even and even-odd nuclei. Thus a fully successful accounting for the properties of ^{22}Na would significantly increase confidence in the shell-model description of the structure of nuclei in this region.

II. TECHNIQUES OF CALCULATION

The shell-model calculations presented here are of the same type as those presented in Ref. 2, hereafter referred to as HMWP, and the notations and conventions of this reference are used in the present paper. The derivation of the Hamiltonian used in the present work is discussed in detail in Ref. 6. Briefly, the single-particle energies were taken from the observed spectrum of ^{17}O. For the $0d_{5/2}$, $1s_{1/2}$, and $0d_{3/2}$ orbits they are equal to -4.15, -3.28, and $+0.93$ MeV, respectively. The two-body matrix elements were obtained by adjusting selected two-body matrix elements of the "$K+{}^{17}$O" interaction used in HMWP so as to reach an rms best fit between 72 experimental-level energies in the $A=18$–22 region and the corresponding shell-model eigenvalues.

The "$K+{}^{17}$O" interaction of HMWP is one of the

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Widths of Analog States in Bi and Po from (p, n) Spectra*

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Isobaric analog states have been observed in the neutron spectra of (p, n) reactions on targets of ^{206}Pb, ^{207}Pb, ^{208}Pb, and ^{209}Bi. After removal of instrumental resolution effects, the natural widths are, respectively, 196 ± 26, 203 ± 32, 202 ± 34, and 151 ± 34 keV. Except in the ^{206}Pb case, these widths are substantially smaller than those observed in $\bar{p}$ spectra from $(p, n\bar{p})$ experiments on the same target nuclei but are in agreement with (p, p') resonance results in the two cases that have been measured.

I. INTRODUCTION

Recent $(p, n\bar{p})$ experiments on the lead isotopes[1] and on ^{209}Bi[2] indicate a discrepancy between the total widths of the isobaric analog states (IAS) measured in these experiments and the widths obtained from (p, p') resonance experiments.[3,4] The greatest discrepancy was for the IAS in ^{207}Bi, where the ^{207}Pb$(p, n\bar{p})$ reaction gave a width greater than 500 keV, whereas the width of the same state measured by ^{206}Pb(p, p') was merely 170 keV.[3] The only other case directly comparable was that of the IAS in ^{208}Bi, where the ^{208}Pb$(p, n\bar{p})$ reaction gave a width of 317 ± 24 keV, compared to 220 ± 20 keV obtained from the ^{207}Pb(p, p') reaction.[4] The IAS in ^{209}Po was similar to the ^{208}Bi case. Surprisingly, the total width for the IAS in ^{206}Bi measured by the ^{206}Pb$(p, n\bar{p})$ reaction was quite small (230 ± 38 keV) and thus more in line with the resonance systematics, although a direct comparison could not be made because the required target (^{205}Pb) is unstable.

Since the decay channels available in the $(p, n\bar{p})$ and (p, p') experiments are the same and the formation channels are different, one might expect the latter to be the source of the discrepancy in the observed width of the IAS. Perhaps the (p, n) reaction populates the states underlying the IAS in a significantly different manner than the resonance reaction. If so, one might expect to see evidence of this in the neutron spectrum of the (p, n) reaction. Previous (p, n) data on ^{208}Pb[5] did not have sufficient energy resolution to determine the total width of the analog state.

To help cast further light on this question, the (p, n) reaction was measured on the isotopes ^{206}Pb, ^{207}Pb, ^{208}Pb, and ^{209}Bi with good enough resolution to directly determine the intrinsic widths of the corresponding analog states.

II. EXPERIMENT

The experiment used the neutron time-of-flight facility of the Michigan State University Cyclotron Laboratory. This system[6] makes use of the natural bunching of the cyclotron beam pulses. The neutron detector is the liquid scintillator NE-213, deoxygenated and encapsulated in a 2-in.-diameter $\times$ 3/4-in.-thick glass cell mounted on an RCA-8575 photomultiplier. Start and stop timing signals are derived from a constant-fraction discriminator on the photomultiplier and from the cyclotron rf voltage through a divide-by-2 scaler, respectively. Two-dimensional pulse-shape analysis is used to distinguish neutrons from γ rays.

In order to achieve both high-neutron energy

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Calculations of Allowed Beta Decay in the ($0d$, $1s$) Shell*

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Allowed β-decay transition rates and half-lives have been calculated for ($0d$, $1s$) shell nuclei with $A = 17$–22, 23–24, 27–29, 30–34, and 35–39. For nuclei with $A = 17$–22 and 34–39, the calculated logft values have a rms deviation of 5% from experiment, with no discrepancies greater than 12%. For nuclei nearer the middle of the shell there are more significant discrepancies between experiment and theory. The calculated logft values are used to predict the half-lives of some light elements. The predicted half-lives for which there are no experimental measurements are: ^{20}Mg (0.1 sec), ^{21}O (1.2 sec), and ^{22}O (0.15 sec). The logft values relevant to the solar neutrino experiment are discussed.

I. INTRODUCTION

This paper presents calculations of strengths of allowed β-decay transitions for the ($0d$, $1s$) shell nuclei with $A = 17$–22, 23–24, 27–29, 30–34, and 35–39. The shell-model wave functions of Wildenthal *et al.*[1-6] are used to describe the initial and final nuclear states. We present calculated logft values for the approximately 100 transitions for which there are experimental measurements, and we give predictions for approximately an equal number of decays which may be measurable. We also use these calculated logft values to predict β-decay half-lives. As will be seen, the agreement between the present calculations and experiments is consistently quite good for the nuclei for which the complete ($0d$, $1s$) shell-model basis space could be used. On the other hand, agreement with experiment is not as consistently good for calculations in the middle of the shell where significant truncations of the model space were necessary.

The calculation of β-decay transition rates is interesting for several reasons. (1) There are few uncertainties in the operators involved and in the connection between the experimentally measured quantities and those predicted by the theory. (2) Because the β-decay operators only connect single-particle states which have the same orbital angular momentum and because the initial and final states are in different nuclei, the matrix elements of the β-decay operators tend to be sensitive to aspects of wave functions not extensively tested in comparisons of theoretical results with nucleon transfer and γ-decay data. Hence, we have the opportunity to learn more about the detailed efficacy of the extant sets of wave functions in the ($0d$, $1s$) shell. (3) As indicated above, there are a large number of experimentally measured decays which can be compared with calculated values. (4) If the calculations turn out to be reasonably successful, the results can be used to predict the half-lives of some of the neutron- and proton-rich nuclei which have not yet been observed. Such predictions might aid in designing experiments to observe these nuclei. And (5) calculated β-decay transition rates are needed to evaluate the results of Davis's experiment[7] to measure the solar neutrino flux using the $^{37}\mathrm{Cl} + \nu \rightarrow {}^{37}\mathrm{Ar} + e$ reaction.

II. DESCRIPTION OF THE CALCULATION

A. Operators

β-decay transition rates are expressed in terms of a logft, where t is the partial half-life for the decay to a given final state and f is a "statistical rate function" which takes account of the energy released in the decay and the Coulomb field of the final nucleus.[8] For allowed decays, ft is given

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Shell-Model Calculation for Masses 27, 28, and 29: General Methods and Specific Applications to ^{27}Al, ^{28}Si, and ^{29}Si

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A shell-model calculation for $A=27$, 28, and 29 nuclei has been carried out in a truncated $0d_{5/2}$-$1s_{1/2}$-$0d_{3/2}$ basis space with a modified-surface-δ-interaction Hamiltonian. A comparison of the calculated results for level energies, single-nucleon spectroscopic factors and $E2$ and $M1$ transition strengths in ^{27}Al, ^{28}Si, and ^{29}Si with the corresponding experimental values indicates that a unified and quantitive explanation of nuclear structure around $A=28$ can be obtained via shell-model techniques.

I. INTRODUCTION

We present here a description of a shell-model calculation for the mass region $A=27-29$ and some specific results for ^{27}Al, ^{28}Si, and ^{29}Si. In associated papers are presented: (1) a detailed study of $E2$ and $M1$ decays for all nuclei of this region using the present wave functions,[1] and (2) theoretical predictions based on the present work for the level energies, wave functions, and spectroscopic factors in ^{27}Mg, ^{28}Al, ^{28}Mg, and ^{29}Al.[2]

Despite extensive experimental investigation[3] (and in another sense, because of it) and a multitude of strong-coupling and weak-coupling collective-model calculations, it seems fair to say that a fully satisfying and internally consistent understanding of the nuclear structure around ^{28}Si has not yet been achieved. The structure of ^{27}Al seems better described in a weak-coupling picture[4,5] built on the 2^+ first excited state of ^{28}Si than it does in a simple Nilsson picture[6,7] with the usual assumption of a prolate ground-state rotational band. However, either of these simple approaches leaves many significant features unexplained, and even more complicated collective-model calculations involving mixing[8] of Nilsson bands or rotation-vibration mixing[9] still fail to account for important aspects of the experimental situation. A recent suggestion[10] has been that an oblate-shape assumption for the low-lying states of ^{27}Al can produce an accounting for $B(E2)$ and spectroscopic-factor observations.

The energy levels of ^{28}Si are clearly not typical of either the simple rotational or simple vibrational model. Calculations have been carried out with Hartree-Fock[11] and SU_3[12] techniques with some success. Projected Hartree-Fock techniques together with vibration-interaction corrections[13,14] give a better accounting for energies and $B(E2)$ properties in ^{28}Si, but the single-particle characteristics of these wave functions have not been thoroughly explored yet.

The structure of ^{29}Si is generally well accounted for with either a straightforward band-mixed Nilsson calculation[15,16] or with an intermediate core-coupling approach[17,18] and seems to offer the least resistance to theoretical interpretations of any set of phenomena in this region.

A particularly interesting feature of this region is that ^{29}Si has long been known to require an oblate deformation for a Nilsson-type interpretation[19] and ^{27}Al, to the extent that the same model applied, seemed to require a prolate shape. Hartree-Fock calculations for ^{28}Si tended to yield ambiguous results concerning the shape of this nucleus until measurements of the quadrupole moment of the $J^\pi=2^+$ first excited state indicated oblateness. Thus one outstanding challenge to a theory for the region is to predict, rather than incorporate as parameters, the phenomena corresponding to this nominal change of shape occurring in the progression from ^{27}Al to ^{29}Si.

Our present study presents a simultaneous, internally consistent treatment of this mass region, in which the only essential variation between ^{27}Al, ^{28}Si, and ^{29}Si is the change in active particles from 11 to 12 to 13. We examine level energies, single-nucleon-transfer properties, and electromagnetic decays. The results are in consistent reasonable accord with experimental data and

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States in Odd-Odd ^{62}Cu Populated by the Decay of ^{62}Zn

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The decay of 9.2-h ^{62}Zn to states in odd-odd ^{62}Cu has been studied with the aid of large-volume Ge(Li) γ-ray detectors. 19 γ rays were found to belong to this decay, and all were placed in a decay scheme containing states in ^{62}Cu at 0 ($J^\pi = 1^+$), 40.94 (2^+), 243.44 (2^+), 287.98 (2^+), 426.3 (3^+), 548.4 (1^+), 637.5 (1^+), 915.6 ([1]$^+$), 1142.5 ([0,1]$^+$), 1280.8 ([0,1]$^+$), and 1429.9 keV ([1,0]$^+$). These were combined with existing in-beam γ-ray particle-transfer data to yield a rather complete ^{62}Cu level scheme. The status of shell-model calculations in this nuclear region is discussed, and it is demonstrated that a gratifying number of facts about the low-lying ^{62}Cu states can be explained using simple odd-odd configurations as predicted by the neighboring odd-mass nuclei.

I. INTRODUCTION

The odd-odd nuclide, $^{62}_{29}Cu_{33}$, contains a single proton and five neutrons outside the doubly closed $f_{7/2}$ shell. Consequently, its states should be amenable to interpretation in fairly straightforward shell-model terms. Also, many states and trends in nearby odd-mass nuclei are known, providing reasonably trustworthy input for predicting the properties of its odd-odd states. Unfortunately, relatively few states are known in ^{62}Cu itself, and even fewer have been well characterized. In this paper, we reexamine the decay of 9.2-h ^{62}Zn to ^{62}Cu, using the largest Ge(Li) γ-ray detectors we have been able to obtain in order to pick up weak feedings that previously had gone undetected. We then correlate our findings with those of previous investigators and with data from scattering reactions in an attempt to obtain a more coherent understanding of the structures of the ^{62}Cu states.

Since the discovery of ^{62}Zn in 1948 by Miller, Thompson, and Cunningham,[1] it has been studied by many groups. Hayward[2] determined the end-point energy of its β^+ spectrum to be 0.66 ± 0.01 MeV and observed K and L conversion electrons from a 41.8 ± 0.2-keV transition, the K/L ratio indicating it to be $E1$ or $M1$. Nussbaum *et al.*[3] determined that the first excited state of ^{62}Cu lies at 41.3 ± 0.3 keV and that $(36 \pm 3)\%$ of the ^{62}Zn feeding passes through this state. From α_K and $K/(L+M)$ they assigned the 41.3-keV transition an $M1$ multipolarity.

The first reasonably complete decay scheme was formulated by Burn, Meyerhof, Kraushaar, and Horen,[4] who performed extensive electron and NaI(Tl) γ-ray spectroscopy, including coincidence and γ-γ angular correlation experiments. They deduced states in ^{62}Cu at 0, 0.042, 0.30, 0.55, 0.63, and 0.70 MeV.

In the last few years there has been a flurry of activity about the neutron-deficient members of the $A = 62$ mass chain. Four groups[5-8] have reported Ge(Li) γ-ray studies on the decay of ^{62}Zn, and two other groups[9,10] have reported on the decay of 9.7-min ^{62}Cu itself. Antman, Pettersson, and Suarez[5] performed the first high-resolution Ge(Li) γ-ray experiments (in conjunction with electron experiments), and they and Roulston, Becker, and Brown[6] demonstrated conclusively the doublet nature of the $\approx$245-keV γ-ray peak and the existence of a 507.6-keV γ ray. These data were essential to the construction of a correct decay scheme, and the two groups arrived at almost identical decay schemes containing the first five excited states in ^{62}Cu that are populated by ^{62}Zn decay. The most precise half-life determination for ^{62}Zn, 9.2 ± 0.1 h, is also the work of Antman, Pettersson, and Suarez. Bakhru[7] also performed high-resolution Ge(Li) γ-ray spectroscopy, including coincidence experiments, and he measured the half-life of the 42-keV state to be 2.5 ± 0.1 nsec. His decay scheme, however, differs in several placements from the others. And the most recent paper on ^{62}Zn decay, by Hoffman and Sarantites[8] and again including results from γ-γ coincidence experiments, shows a decay scheme almost identical to those of Refs. 5 and 6.

Nuclear reaction and in-beam studies have been reported, also. Davidson *et al.*[11] have used the ^{62}Ni($p, n\gamma$) reaction to study the decay of the ex-

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Proton Capture by ^{7}Be and the Solar Neutrino Problem*

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It is shown theoretically that the ^{7}Be$(p,\gamma)^8$B reaction cross section contains substantial contributions from p and d partial waves at laboratory energies, and extrapolations to stellar energies based on the assumption of pure s-wave capture are therefore erroneous. However, there is no change in the predicted solar neutrino flux, because the calculated low-energy cross-section factor, 31 eV b, is essentially the same as the empirical value in current use.

I. INTRODUCTION

The recent experiments of Davis[1] have set an upper limit of 1.0 SNU on the neutrino flux from the sun (1 SNU = 10^{-36} captures per target atom per sec), in sharp disagreement with the theoretical prediction of 9 SNU, calculated by Bahcall and Ulrich.[2] The rare termination of the p-p chain ^{7}Be$(p,\gamma)^8$B$(e^+\nu)2\alpha$ results in energetic neutrinos and is calculated to contribute 7.3 SNU. It is therefore important to have an accurate estimate of the rate of this reaction in the solar interior. Very detailed measurements of the cross section for ^{7}Be$(p,\gamma)^8$B have been carried out by Kavanagh *et al.*[3] (see Barnes[4]) at laboratory energies $E_p = 0.165$ to 10.0 MeV. A theoretical extrapolation to lower energies based on a calculation by Tombrello[5] yielded a zero-energy cross-section factor[6] $S(0)$ of 0.034 keV b, where, if σ is the cross section and E_p the lab proton energy in MeV,

$$S(E_p) = 0.87441\,\sigma E_p \exp(3.9734\,E_p^{-1/2})$$

for the ^{7}Be$(p,\gamma)^8$B reaction. A calculation by Aurdal[7] similar to that of Tombrello gave $S(0) = 0.044$ keV b, but the new data of Kavanagh *et al.* were not used in that extrapolation. The value $S(0) = 0.030$ keV b actually adopted by Bahcall and Ulrich[2] is lower than either of these, and is presumably the result of an empirical extrapolation.

Proton capture by ^{7}Be involves the radiative transition of a proton in a continuum state to the 2^+ ground state of ^{8}B, bound by 137.2 keV. Only dipole radiation is of importance at the energies considered here. Because the spin and parity of ^{7}Be are $\frac{3}{2}^-$, capture from the s and d partial waves leads to $E1$ radiation, and from the p wave, $M1$. Higher partial waves cannot contribute to dipole radiation. The calculations of Tombrello[5] and Aurdal[7] assumed that only s-wave capture was significant. The present work shows that while this is approximately true in the solar environment ($E_p \approx 20$ keV), it is not the case at laboratory energies, even as low as 150 keV. The small binding energy of ^{8}B results in a spatially extended wave function, enhancing capture from the p and d partial waves.

II. DERIVATION OF THE CROSS SECTION

The total cross section for dipole capture in the reaction $A(a,\gamma)B$ is

$$\sigma_1 = (16/9)\pi E_\gamma^{\,3}(\hbar c)^{-4}(M_a c^2/2E_a)^{1/2} \times \sum_{\mu m M_A M_B} (2s+1)^{-1}(2J_A+1)^{-1}|T_1^\mu|^2,$$

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Mass-25 Isobaric Multiplets*

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High-precision mass determinations have now been made for all four members of the lowest two $T=\frac{3}{2}$ states in the $A=25$ system. The results are used to compute the coefficients of the isobaric-mass-multiplet equation.

I. INTRODUCTION

The isobaric-mass-multiplet equation relates the masses of the $2T+1$ members of a multiplet with isobaric spin T. The equation is usually given as

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

where T_z is the z component of the isobaric spin, $T_z=\frac{1}{2}(N-Z)$. The coefficients a, b, and c are functions of the mass number A and spin J^π of the levels as well. The equation, in principle, relates the masses of any multiplet of analogous levels.

Deviations from the predictions of the isobaric-multiplet equation are usually measured by citing the magnitude of d, the coefficient of a cubic term required to fit the masses. In terms of the measured masses $M(T_z)$, the d coefficient has a very simple form for a $T=\frac{3}{2}$ system, i.e.,

$$d=\tfrac{1}{6}\{M(\tfrac{3}{2})-M(-\tfrac{3}{2})-3[M(+\tfrac{1}{2})-M(-\tfrac{1}{2})]\},$$

where $M(T_z)$ is the mass of the level in the T_z nucleus.

Thus the result $d=0$ implies that the spacing between inner members is $\frac{1}{3}$ the spacing between the outer members. One can also see from the above equation that the uncertainty in d is 3 times more sensitive to the accuracy of the masses of the $T_z=\pm\frac{1}{2}$, $T=\frac{3}{2}$ levels than it is to the $T_z=\pm\frac{3}{2}$ levels.

In the present paper we are discussing the lowest two $T=\frac{3}{2}$ levels in the $A=25$ nuclei. These are the ground and first excited states of ^{25}Si and ^{25}Na and the lowest two $T=\frac{3}{2}$ states in ^{25}Al and ^{25}Mg with

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Shell-Model Calculations for $A = 18$, 19, and 20 Nuclei with Core Excitation Included Explicitly

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Eigenvalues and eigenvectors for all low-lying positive- and negative-parity nuclear states of $A=18$, 19, and 20 are calculated in a shell-model basis of all Pauli-allowed $0p_{1/2}$-$0d_{5/2}$-$1s_{1/2}$ configurations outside an inert ^{12}C core. Two different effective Hamiltonians are used. One is based on a reaction matrix treatment of the Hamada-Johnston potential. The second one is obtained by varying the 33 effective Hamiltonian matrix elements to reach a least-squares fit between 153 experimental level energies in nuclei in the $A=13$–22 region and the corresponding shell-model eigenvalues. The energy level spectra and single-nucleon spectroscopic factors from these calculations are compared to the available experimental data in this region. The calculations are also examined for the existence and characteristics of sequences of levels which might be called "rotational bands."

I. INTRODUCTION

The conventional nuclear shell model has been applied with considerable success to the study of properties of low-lying states of nuclei at the beginning ($A=18$–22) of what is called the s-d shell.[1] In these calculations, an inert ^{16}O is assumed, and active particles are distributed in the $0d_{5/2}$, $1s_{1/2}$, and $0d_{3/2}$ single-particle orbits. This model is obviously limited, since there is ample evidence that ^{16}O is not an ideal closed-shell nucleus. Some of this evidence involves the existence of excited states in the observed spectrum of ^{16}O and the existence of negative-parity states at low excitation energies in $A=17$, 18, and 19 nuclei. Zuker, Buck, and McGrory[2] (ZBM) have studied the structure of ^{16}O in a conventional shell-model calculation with the assumption of an inert ^{12}C core and active $0d_{5/2}$, $1s_{1/2}$, and $0p_{1/2}$ orbits. In this model space, there exist numerous excited states in the $A=16$ system, and the ZBM calculation accounted for many of the observed properties of the spectrum of ^{16}O below 15 MeV. Calculations in this same model space were subsequently made for ^{17}O and for the $A=18$ system,[3,4] in each case with considerable success.

There are many interesting properties of nuclei with $A=19$ and 20 which cannot be explained by the conventional shell model with an inert ^{16}O core. These include the existence of an apparent $K=\frac{1}{2}^-$ rotational band of states in ^{19}F which is all but degenerate with the ground-state $K=\frac{1}{2}^+$ band in that nucleus, the observed "extra" 0^+ and 2^+ states in ^{20}Ne between 6 and 8 MeV, the existence of possibly two low-lying negative-parity rotational bands in ^{20}Ne, and the occurrence of several states in observed spectrum of ^{20}F which do not occur in any "good" shell-model calculation with an ^{16}O core. It is of interest to see if the ^{16}O-core-excited model which accounts so well for the properties of ^{16}O, ^{17}O, and the $A=18$ nuclei can account for some of these "anomalous" properties of $A=19$ and 20 nuclei. A preliminary study has indicated that such is the case.[5] In the present paper, we present in some detail the results of calculations for nuclei with $A=18$–20 in terms of a $0p_{1/2}$-$0d_{5/2}$-$1s_{1/2}$ ("*pds*") configuration shell model. We restrict ourselves here to discussion of excitation energies and spectroscopic factors for single-nucleon transfer reactions, deferring to a later paper a discussion of electromagnetic properties of states in these nuclei as calculated in terms of this model.

In Sec. II, we describe the calculation in detail. In Sec. III we present a nucleus-by-nucleus discussion of energy levels and spectroscopic factors. In Sec. IV we briefly discuss the core excitation present in the model calculations. In Sec. V, we compare our calculations with other calculations of these nuclei. The results are summarized in Sec. VI.

II. DESCRIPTION OF THE CALCULATIONS

In the following sections, we will discuss the results of three different shell-model calculations of the properties of low-lying states in $A=18$–20 nuclei. In two of the calculations an inert ^{12}C is

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Study of ^{173}Hf Levels Populated in the Decay of ^{173}Ta

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The decay of ^{173}Ta was studied using high resolution Ge(Li), Si(Li), and Si surface-barrier detectors in singles and coincidence modes. The ^{173}Ta activity was produced via the reaction ^{165}Ho(^{12}C,4n)^{173}Ta, at a carbon beam energy of 6.3–6.9 MeV per nucleon. All spectra were obtained from chemically separated Ta sources. Besides the previously known energy levels of ^{173}Hf, the following levels in keV were determined: 255.5, 451.9, 508.9, 635.8, 775.5, 785.3, 811.7, 927.5, 942.5, 1020.3, 1111.4, 1127.0, 1192.8, 1248.3, 1450.0, 1574.2, 1655.6 1667.1, 1694.3, and 2263.3. Rotational bands based on the $(1/2)^-$[521] (g.s.), $(5/2)^-$[512] (107.2 keV), and $(7/2)^+$[633] (197.5 keV) Nilsson states were observed. The half-lives of the $(5/2)^-$[512] and the $(1/2)^+$[633] band heads were determined to be (182 ± 20) nsec and (160 ± 40) nsec, respectively. The probability of the radiative $E1$ transition between the [633] and [512] band heads was calculated within the framework of Nilsson model including the pairing and Coriolis interactions. From measurement of the β^+ end-point energy, the mass difference between ^{173}Ta and ^{173}Hf was determined to be 3670 ± 200 keV.

1. INTRODUCTION

In-beam γ-ray spectroscopic studies have recently revealed substantial deviations from the strong coupling model[1,2] in the even-parity bands of odd-neutron deformed nuclei in the rare-earth region. This development initiated new interest in the investigation of the level structure of these nuclei as populated in radioactive decay. The quieter environment of radioactivity experiments as compared with the in-beam work enables one to perform experiments crucial for the confirma-

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$^{90}Zr(p,p')^{90}Zr^*$ Reaction at 40 MeV

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Differential cross sections for the excitation of the 0^+ (1.75-MeV), 2^+ (2.18-MeV), 5^- (2.32-MeV), 4^+ (3.08-MeV), 6^+ (3.45-MeV), 8^+ (3.60-MeV), and the 2^+ (3.31-MeV) levels in ^{90}Zr by 40-MeV protons have been measured between 15° and 115°. The data are compared with the results of distorted-wave (DWA) collective-model calculations and DWA microscopic-model calculations. Both macroscopic and microscopic treatments of core polarization are considered. Effects from noncentral components in the projectile-target interaction have been investigated and an imaginary central component has been included in this interaction in the cases where a completely microscopic model is used for the target nucleus. A coupled-channels calculation has been performed in order to investigate multiple excitation contributions to the cross section for the 0^+ (1.75-Mev) state.

I. INTRODUCTION

In recent years the $^{90}Zr(p,p')^{90}Zr^*$ reaction has been a favorite subject for physicists working on the microscopic model for inelastic proton scattering.[1-3] The main reason for this is the substantial range of multipolarities available in the transitions from the ground state of this nucleus to its first excited 0^+, 2^+, 4^+, 5^-, 6^+, and 8^+ states, whose wave functions consist mainly of two protons distributed in the $2p_{1/2}$- and $1g_{9/2}$-shell model orbitals. The present paper reports on a new experimental study of this nucleus carried out with 40-MeV incident protons. Differential cross sections have been measured for the excitation of the six states named above, as well as for the excitation of the state at 3.31 MeV. These data, combined with the results of earlier experiments at 12.7,[2] 18.8,[1] and 61.2 MeV,[3] give a reasonably complete picture of the energy dependence of the cross sections from 10–60 MeV. The angular distribution for the $L=0$ transition, however, had previously been measured only at the comparatively low energy of 12.7 MeV.[2] Thus the present measurement significantly extends our knowledge of this monopole transition and can provide an additional test for various aspects of the reaction theory.

The microscopic model for inelastic proton scattering has undergone considerable development in recent years. It is now fairly well established that cross sections can be understood in calculations with "realistic interactions,"[4-9] provided that "knock-on" exchange contributions are included and reasonable target wave functions are used. Most calculations have previously considered only the real central components of the projectile-target interaction. However, recent studies have pointed out that the shapes of differential cross sections can be improved by including an imaginary component in the interaction[10,11] and also that the two-body spin-orbit force may be important for transitions of high multipolarity.[12]

In the case of ^{90}Zr, reasonable target wave functions require consideration of core polarization effects.[2,3] This can be done using macroscopic[13,14] or microscopic[7,15,16] models for the core. In the first model the contributions from core polarization are described in terms of a single parameter which can be treated phenomenologically or determined from other data such as effective charges when they are available. In the second model, core-excited admixtures in the valence wave functions are estimated perturbatively using "realistic" coupling interactions. It is interesting to note that inelastic scattering is one of the few methods by which the effect of core polarization in transitions of high multipolarity can be studied.

The data from the present experiment have been analyzed using both the collective model and the microscopic model. The deformation parameters

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(p, n) Isobaric Analog Transitions in Targets of ^{27}Al, ^{51}V, and ^{90}Zr at 22, 30, and 40 MeV*

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Angular distributions for (p,n) transitions to isobaric analog states of ^{27}Al, ^{51}V, and ^{90}Zr targets have been measured at proton energies of 22, 30, and 40 MeV. The data have been compared with results of macroscopic distorted-wave Born-approximation calculations employing various form factors: pure volume, pure surface, and mixtures of real volume with imaginary surface. The comparisons show that: (i) The surface interaction describes the data rather well, particularly at the lower energies, whereas the volume interaction is adequate only at 40 MeV; (ii) complex mixtures of volume and surface give good descriptions of most of the data if the mixture is a variation of the isospin part of the Becchetti-Greenlees potential with either increased surface-to-volume ratio or increased imaginary radius; (iii) use of the unmodified Becchetti-Greenlees geometry gives a poor fit to much of the data; (iv) the strength of the isospin interaction decreases with increasing energy, in general agreement with other charge-exchange work. Most of the decrease here occurs between 22 and 30 MeV. This is true for the surface interaction and for each of the two complex interactions.

I. INTRODUCTION

In (p, n) transitions between isobaric analog states (IAS) the isospin interaction may be the main, in many cases the total, interaction causing the transition. Consequently, the most direct manner of studying the isospin interaction is through these transitions. Several such studies[1-5] have been reported, but there is as yet no clear-cut indication of underlying simplicities or systematics in the interaction. The earlier studies, reviewed by Satchler,[6] have raised questions as to the radial form of the isospin interaction, that is, whether or not it is surface peaked. Also, there is very little evidence as to whether the interaction must be complex[7] or energy dependent.[8-10] To answer such questions will likely require a rather thorough study in which a wide range of target nuclei and proton bombarding energies are employed.

We describe here the measurements and analyses of (p, n) transitions to ground-state analogs of the target nuclei ^{27}Al, ^{51}V, and ^{90}Zr at incident proton energies of 22, 30, and 40 MeV. The experimental angular distributions were compared with macroscopic distorted-wave Born-approximation (DWBA) calculations employing both a real (volume or surface-peaked) and a complex isospin interaction. Since the interaction was taken to be spherically symmetric, only monopole transitions were used in the calculations for both even-A and odd-A targets.

II. EXPERIMENTAL PROCEDURE

Thin targets of ^{27}Al(6.2 mg/cm^2), ^{51}V(7.9 mg/cm^2), and 97.8% enriched ^{90}Zr (2.0 mg/cm^2) were bombarded with protons from the Michigan State University cyclotron. The resulting neutron spectra were measured with a time-of-flight system[11] which makes use of the natural bunching of the cyclotron beam pulses. The neutron detector is the liquid scintillator NE-213, deoxygenated and encapsulated in a 2-in.-diam × $\frac{3}{4}$-in.-thick glass cell mounted on an RCA-8575 photomultiplier. Start and stop timing signals are derived from a constant-fraction discriminator on the photomultiplier and from the cyclotron rf voltage through a divide-by-2 scaler, respectively.

Two-dimensional pulse-shape analysis is used to distinguish neutrons from γ rays. An isometric display of a typical two-dimensional spectrum is shown in Fig. 1, where the number of events is plotted against the variables pulse height and decay

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Three-Neutron Pickup Reaction on $^{13}C^{\dagger}$

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Angular distributions of ^{6}He particles from the three-neutron pickup reaction ^{13}C(^{3}He, ^{6}He)^{10}C have been measured for transitions to the two lowest states of ^{10}C, the $J^{\pi} = 0^{+}$ ground state and 3.35-MeV $J^{\pi} = 2^{+}$ state. Observed anomalies in the shapes and magnitudes of these distributions cannot be explained theoretically by zero-range distorted-wave Born-approximation calculations.

I. INTRODUCTION

The (^{3}He, ^{6}He) reaction has been used over the past three years principally for the precise measurement of masses of proton-rich nuclei in the $2s$-$1d$ shell.[1] These nuclei, such as ^{25}Si, are the $T_z = -\frac{3}{2}$ member of isospin multiplets, and the resulting masses have provided a test of the isobaric multiplet mass equation. This reaction has also been recently used to extend our knowledge of proton-rich nuclei in the $1f_{7/2}$ shell and also to obtain the spectra of these nuclei.[2] The extremely small cross sections which have been measured for the (^{3}He, ^{6}He) reaction have inhibited the measurement of detailed angular distributions for most targets. A partial angular distribution for the ^{12}C(^{3}He, ^{6}He)^{9}C reaction measured earlier,[3] together with some angular distribution data on various targets, showed enough structure to make a strong case that a direct-reaction mechanism is principally involved in this reaction.

The present experiment is aimed at testing the reaction mechanism by studying a case in which both initial and final states are well known, the ^{13}C(^{3}He, ^{6}He)^{10}C reaction. The initial interest was inspired by a measurement of ^{6}He spectra at $\theta_{lab} = 9°$ in which the yield to the $J^{\pi} = 2^{+}$, 3.35-MeV level of ^{10}C was found to be about 40 times greater than the yield to the $J^{\pi} = 0^{+}$ ground state. This ratio aroused theoretical curiosity and also led to the present measurement of a more complete angular distribution for this reaction.

II. EXPERIMENTAL METHOD AND RESULTS

The ^{13}C(^{3}He, ^{6}He)^{10}C reaction was induced with 70.3-MeV ^{3}He from the Michigan State University cyclotron. The reaction particles were detected in an Enge split-pole spectrograph. The position on the focal plane was measured in a detection system consisting of a single-wire proportional counter with $\frac{1}{2}$-mil Kapton entrance and exit windows.[4] A thin plastic scintillator mounted on a photomultiplier tube was placed behind the proportional counter and provided time-of-flight information and also some particle discrimination based on the energy loss in the plastic scintillator.

A block diagram of the electronics used in the experiment is shown in Fig. 1. The setting of the various coincidence requirements is considerably simplified by the use of partial coincidence requirements. Thus the spectrum corresponding to

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Properties of γ-Ray Transitions in ^{56}Co from ^{56}Ni Decay and ^{56}Fe$(p, n\gamma)^{56}$Co

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The ^{56}Ni ϵ decay and the ^{56}Fe$(p, n\gamma)^{56}$Co reaction with beam energies between 5.5 and 8.4 MeV have been used with Ge(Li) spectrometers to study the properties of γ rays from states of ^{56}Co below 2.86 MeV excitation. From ^{56}Ni ϵ decay both the γ-ray spectrum and γ-γ coincidences were studied. γ-γ coincidences, γ-ray excitation functions, γ-ray angular distributions, and absolute cross sections were measured for the ^{56}Fe$(p, n\gamma)^{56}$Co reaction. An ϵ decay scheme for ^{56}Ni, which includes six γ rays, and an energy-level diagram for ^{56}Co, which includes 35 γ rays (14 of which are reported for the first time) from 20 excited states, are presented. Comparison of the data from ^{56}Fe$(p, n\gamma)^{56}$Co with predictions of the statistical compound-nuclear model have resulted in spin assignments (in parentheses) for the following states (energies in keV) of ^{56}Co: 158.4(3), 576.6(5), 829.7(4), 970.3(2), 1009.2(5), 1114.6(3), 1450.8(0), and 1720.3(1). Branching ratios are presented for 14 γ rays from these eight states and multipole mixing ratios are given for 12 of these γ rays (10 are predominantly *M*1). The data are consistent with a spin-4 assignment to the ground state. Contrary to previous suggestions, evidence from all experiments indicates that only one state (believed to be the antianalog of the ^{56}Fe ground state) exists in ^{56}Co in the neighborhood of 1451 keV excitation. The level energies, γ-ray multipole mixing ratios, and γ-ray branching ratios agree, in general, with shell-model predictions of McGrory.

I. INTRODUCTION

The earliest investigations[1-4] of the low-lying excited states of ^{56}Co began with the ϵ decay of ^{56}Ni. These studies, which included measurements of the ^{56}Ni half-life,[1] the γ-ray spectrum,[1,3,4] γ-γ angular correlations,[1,3] the internal-conversion electron spectrum,[2] and lifetimes of some ^{56}Co states,[1] produced valuable information. However, only selected states below 2.1 MeV could be populated and unambiguous spin assignments for these states could not be made.

More recently, experiments involving the two-particle transfer reactions, ^{54}Fe$(^3$He$, p)^{56}$Co,[5-9] ^{54}Fe$(\alpha, d)^{56}$Co,[10] ^{58}Ni$(p, ^3$He$)^{56}$Co,[11] and ^{58}Ni(d, α)-^{56}Co,[6,7,9,12,13] and the charge-exchange reactions,

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ELASTIC AND INELASTIC SCATTERING OF PROTONS FROM ^{6}Li BETWEEN 25 AND 45 MeV

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Abstract: The elastic and inelastic scattering of protons from ^{6}Li has been studied at incident energies of 25.9, 29.9, 35.0, 40.1 and 45.4 MeV. The 2.18 MeV (3^+, $T = 0$) first excited state of ^{6}Li was found to be strongly excited, but the 3.56 MeV (0^+, $T = 1$) second excited state was quite weakly excited. Angular distributions for excitation of the 2.18 MeV level were measured at all five energies, while angular distributions for excitation of the 3.56 MeV level were extracted only at 25.9 and 45.4 MeV. To test the applicability of the optical model for the scattering of protons from such a light nucleus the elastic scattering angular distributions have been analyzed using the eleven-parameter search code SEEK. Available polarization angular distributions were included in the analysis. Reasonable fits to the data have been obtained with an average geometry potential. Theoretical estimates of the real part of the optical potential and the inelastic scattering differential cross sections have been made using the microscopic model for proton-nucleus scattering. Both phenomenological and realistic forces have been considered and the necessary nuclear transition densities have been extracted from experimental elastic and inelastic electron scattering data. An estimate of a possible spin-spin term in the optical potential has also been made.

1. Introduction

Various groups have previously reported measurements of elastic and inelastic cross sections for proton scattering from ^{6}Li in the energy region 25–50 MeV [refs. [1–4])]. One of the purposes of the present experiment was to improve the knowledge of the energy dependence of the ^{6}Li+p elastic cross sections. This is important in the case of such a light nucleus as there may be contributions from resonances in the compound system at some energies and information about the optical potential extracted at a single energy could prove to be misleading. An analysis of the elastic data has been made using a conventional phenomenological optical potential. Existing polarization

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2.F Nuclear Physics A192 (1972) 417—425;

STUDY OF THE $^{27}Al(^3He, p)^{29}Si$ REACTION

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Abstract: The $^{27}Al(^3He, p)^{29}Si$ reaction has been studied at bombarding energies between 9 and 14 MeV. Comparison of the experimental angular distributions at 14 MeV incident energy with two-nucleon transfer distorted-wave Born approximation (DWBA) calculations is made to test shell-model wave functions of the target ground state and the residual ground and excited states.

E NUCLEAR REACTIONS $^{27}Al(^3He, p)$, $E = 9$–14 MeV; measured $\sigma(\theta)$. Natural target.

1. Introduction

The differential cross sections of two-nucleon transfer reactions such as $(^3He, p)$ are sensitive to correlations in nuclear wave functions [1]) which may not be examined in other types of experiments. Hence, the experimental study of such processes, and comparison of the results with the predictions of nuclear structure calculations, should provide a rather unique tool for testing the theoretical wave functions and the residual interactions used in the Hamiltonians.

The present work is part of a systematic investigation of the $(^3He, p)$ reaction on nuclei in the $2s-1d$ shell. In this paper we discuss the reaction $^{27}Al(^3He, p)^{29}Si$. Shell-model calculations have recently been performed for both the initial and final nuclei in a truncated $1d_{\frac{5}{2}}-2s_{\frac{1}{2}}-1d_{\frac{3}{2}}$ basis space with a "modified" surface delta interaction (MSDI) Hamiltonian [2]). The model space in which these calculations are made includes, for ^{27}Al, all 11-particle configurations with 8 or more particles occupying the $d_{\frac{5}{2}}$ orbit and, for ^{29}Si, the configuration with 8 particles in the $d_{\frac{5}{2}}$ orbit, 4 particles in the $s_{\frac{1}{2}}$ and 1 particle in the $d_{\frac{3}{2}}$ orbit plus all 13-particle combinations with occupation numbers of the $d_{\frac{5}{2}}$ orbit greater than or equal to 9.

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INVESTIGATION OF THE $^{32}S(^3He, p)^{34}Cl$ REACTION

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Abstract: The $^{32}S(^3He, p)^{34}Cl$ reaction has been studied at an incident energy of 24 MeV. The proton spectra were analysed with a multiangle magnetic spectrograph and angular distributions have been measured for states in ^{34}Cl up to 3.4 MeV of excitation energy. Two sets of shell-model wave functions, which use the same configuration space but different treatments of the effective residual interaction, are tested by comparing two-nucleon transfer DWBA calculations with the experimental angular distributions.

E NUCLEAR REACTIONS $^{32}S(^3He, p)$, $E = 24$ MeV; measured $\sigma(\theta)$.
^{34}Cl levels deduced J, π, L. Natural target.

1. Introduction

The basic feature of a two-nucleon transfer reaction is its coherence property These coherence effects complicate on one hand the extraction of spectroscopic information from the experimental data but at the same time can be exploited to test not only the magnitudes but also the relative phases of various components in shell-model wave functions. Much of this latter information is inaccessible by other kinds of observation. The present work is part of a systematic study of (^{3}He, p) reactions on target nuclei in the upper half of the 2s-1d shell. The aim is to make a sensitive test of various shell-model calculations which have been performed for this mass region [1–4]). In this paper results for the reaction $^{32}S(^3He, p)^{34}Cl$ are reported. For both the initial and final nuclei shell-model calculations have recently been performed [2, 3]) in a truncated $(1d_{\frac{3}{2}})^{n_1}(2s_{\frac{1}{2}})^{n_2}(1d_{\frac{1}{2}})^{n_3}$ vector space, where n_1, the number of particles occupying the $1d_{\frac{3}{2}}$ orbit, is greater than or equal to 10. Two different empirical Hamiltonians were used in these calculations. One set makes use of the modified surface delta interaction (in the following referred to as MSDI wave functions), whereas the second set starts from the same interaction and treats the two-body

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ENERGY LEVELS IN ^{142}Nd

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Abstract: The excited states of ^{142}Nd were studied by means of the decay of 40 sec ^{142}Pm and the ^{142}Nd(p, p′) reaction via isobaric analog resonances. Approximately sixty levels of ^{142}Nd were observed below 5.3 MeV excitation, including several neutron particle-hole states excited strongly in (p, p′) at $f_{\frac{7}{2}}$, $p_{\frac{3}{2}}$, $p_{\frac{1}{2}}$ and $f_{\frac{5}{2}}$ analog resonances. We have collected together all known energy levels in ^{142}Nd and have proposed J^{π} assignments for 22 excited states. We have also compared the experimental level spectrum (positive-parity states only) with a calculated one based on the shell model.

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RADIOACTIVITY ^{142}Pm; measured $T_{\frac{1}{2}}$, E_γ, I_γ. ^{142}Nd deduced levels, J, π, γ-branching.
NUCLEAR REACTIONS ^{142}Nd(p, p′) at analog resonances, $E = 9.505$, 10.245, 10.805 and 11.070 MeV; measured $\sigma(E_p, \theta)$. ^{142}Nd deduced levels, J, π, particle-hole states.

1. Introduction

The nucleus $^{142}_{60}Nd_{82}$ is interesting from a nuclear structure viewpoint because of its closed core of 82 neutrons. Most of the low-lying states of ^{142}Nd should, therefore, arise from proton couplings in the $1g_{\frac{7}{2}}$, $2d_{\frac{5}{2}}$, $2d_{\frac{3}{2}}$, $3s_{\frac{1}{2}}$ and $1h_{\frac{11}{2}}$ shell-model orbits. A

† Research jointly sponsored by the US Atomic Energy Commission under contract with the Union Carbide Corporation and by the National Research Council of Canada and the US National Science Foundation. Preliminary results were reported previously [36]).
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SHELL MODEL CALCULATIONS FOR MASSES 27, 28 AND 29: SPECIFIC APPLICATION TO ^{27,28}Mg AND ^{28,29}Al

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Abstract: A shell model calculation has been performed in a truncated $1d_{\frac{3}{2}}$, $2s_{\frac{1}{2}}$, $1d_{\frac{5}{2}}$ configuration space with a modified surface-delta-interaction Hamiltonian for the $T = 1$, $\frac{3}{2}$ and 2 nuclei of $A = 27$–29. The parameters of the model Hamiltonian were obtained from a fit to experimental data from $T = 0$ and $T = \frac{1}{2}$ nuclei of the same region. Excitation energies, single-nucleon spectroscopic factors, electric quadrupole moments and transition strengths and magnetic dipole moments and transition strengths were calculated. Decay properties of the $T = 2$ and $T = 1$ multiplets in $A = 28$ and the $\Delta T = 1$, M1 transitions from $T = \frac{3}{2}$ levels in $A = 27$ and 29 nuclei have been studied in particular. The results indicate that the present shell model is able to describe quantitatively the nuclear structure around mass 28 in a unified approach in a fashion similar to the excellent descriptions available in this same theoretical framework for lighter and heavier mass regions of the sd shell.

1. Introduction

Nuclei around mass 28, where the nuclear shape changes from prolate to oblate [1]), have been the object of many extensive theoretical and experimental studies, of which the results are compiled in ref. [2]). Discussions in terms of collective models are mostly concentrated on a few aspects of particular nuclei. The collective models frequently account very well for certain characteristics [4, 5, 9, 10]) but they all fail, variously, to explain at the same time many other significant features in $A = 27$–29 nuclei. Of the four nuclei considered here, only the structure of ^{27}Mg is reasonably well understood in terms of the single-particle Nilsson model [3–9]), and even here deformation parameters of different signs are required to explain the transition rates [4, 5]) and the spectroscopic factors [9]). No significant evidence was been found so far to place ^{28}Al [ref. [11])] and ^{29}Al [refs. [12–15])] in a simple rotational picture, while an intermediate-coupling version of the SU(3) model [16]) reproduces only some of the characteristics of the ^{28}Mg energy spectrum.

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Germanium-64

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The new isotope ^{64}Ge has been produced via the reaction ^{64}Zn(^{3}He,3n)^{64}Ge, chemically isolated, and its decay studied. Since ^{64}Ge is therefore nucleon stable, it can in principle have an important role in the synthesis of mass 64 by α capture during explosive stellar events, as proposed by Arnett, Truran, and Woosley. However, from the measured half-life (62.3± 2.0 sec) and β-decay systematics, it appears that this mechanism is probably responsible for a negligible fraction of the observed abundance of mass 64.

Recently Arnett, Truran, and Woosley[1] (ATW) have shown that the elements on the high-mass side of the iron peak in the elemental abundance curve can be synthesized in an explosive stellar event. The process involves, for example, a quasiequilibrium among ^{4}He, ^{56}Ni, ^{60}Zn, and ^{64}Ge, and the resulting abundances for mass 60 and 64 depend primarily on the corresponding binding energies. Since ^{64}Ge has never been observed experimentally, ATW used for that isotope a value of the binding energy calculated by Garvey *et al.*[2] The abundances obtained[1] for masses near 64 are typically 2 orders of magnitude smaller than those observed in nature.

This discrepancy could possibly be removed if ^{64}Ge were more tightly bound, since production of that nuclide by radiative α capture would then be enhanced. In that hope, a number of intensive

New Proton-Rich Nuclei in the $1f_{7/2}$ Shell*

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We have measured the masses of ^{43}Ti and of the previously unknown nuclei ^{47}Cr, ^{51}Fe, and ^{55}Ni. These proton-rich members of $1f_{7/2}$-shell mirror pairs are important for extensions of nuclear mass relationships to the $Z>N$ region.

In this Letter, we report mass measurements of $1f_{7/2}$ shell nuclei which have $Z=N+1$, and are thus members of the heaviest mirror pairs known. The present measurements represent the first observation of ^{47}Cr, ^{51}Fe, and ^{55}Ni. The heaviest previously known nucleus with $Z>N$ was ^{49}Mn, whose mass was found by Cerny *et al.*[1] to be consistent with a predicted value of -37.72 ± 0.08 MeV in an experiment with the ^{40}Ca(^{12}C,t) reaction. The mass of ^{43}Ti has also been previously determined by the reaction ^{40}Ca(α,n)^{43}Ti.[2] The line of nuclear stability in the $1f_{7/2}$ shell is at least two neutrons from the $N=Z$ line, and the observation of $T_z=-\frac{1}{2}$ nuclei in this shell requires the transfer of three or more particles. Since all possible higher-Z targets have a neutron excess of at least four, we have extended the (^{3}He, ^{6}He) reaction to its maximal value as a probe for the study of proton-rich nuclei.[3,4]

Beams of 65- to 75-MeV ^{3}He ions from the Michigan State University sector-focused cyclotron were used to perform these experiments. The ^{6}He particles were analyzed and detected in the focal plane of an Enge split-pole magnetic spectrograph. The energy scale was determined from a number of well-known Q values including those for the (^{3}He,^{6}He) reaction on ^{48}Ti, ^{13}C, and ^{12}C. Detection of the ^{6}He particles was performed variously with photographic emulsions, silicon position-sensitive detectors, and gas-filled resistive wire proportional counters. In each case different techniques were used to enhance the discrimination of the ^{6}He particles relative to the dominant background of protons, deuterons, and α particles.

Most of the data were taken with a wire proportional counter. In this case a novel technique was employed to discriminate against the background particles. The time of flight of the particles was measured using a signal from a plastic scintillator behind the wire counter. The total energy signal from the plastic was also used to aid the identification. The flight path in the spectrometer (about 3 m) is very well suited to this method since it produces about a 25-nsec time difference between the ^{6}He particles and the major source of background, α particles. The stop signal for the clock was provided by the radio

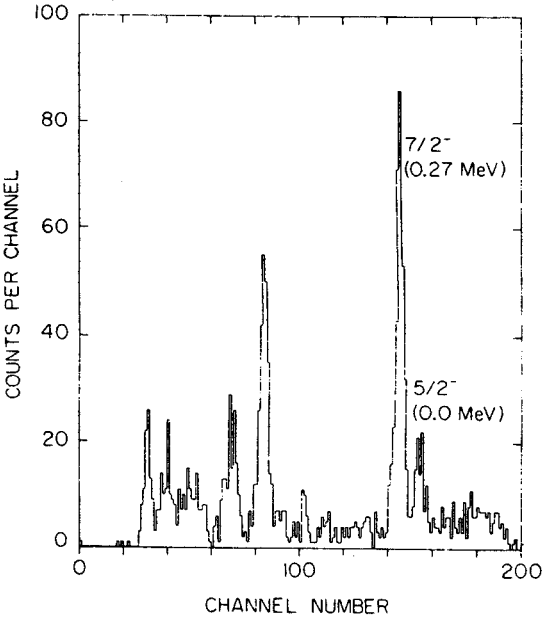

FIG. 1. Energy spectrum of ^{6}He from the reaction ^{54}Fe(^{3}He,^{6}He)^{51}Fe. The ^{3}He bombarding energy is 70.8 MeV and the laboratory scattering angle is 9°.

Some Comments on the Cross Section of ^{37}Cl for Solar Neutrino Absorption*

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Nuclear wave functions from recent shell-model calculations are used to evaluate the log(ft) values relevant to the neutrino absorption cross section of ^{37}Cl.

In order to understand better the causes and/or consequences of the unexpectedly low yield of the solar neutrino experiment,[1] we have re-examined some of the assumptions which underlie the calculation of the neutrino absorption cross section of ^{37}Cl. As has been pointed out,[2,3] there is very little uncertainty in the calculated absorption cross section for low-energy neutrinos ($E_\nu < 2.22$ MeV) in the reaction $\nu + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$ since this calculation depends only upon the measured electron capture rate of ^{37}Ar and other known quantities. However, there are unmeasured quantities which enter into the calculation of absorption cross sections for neutrinos with energies greater than 2.22 MeV.

These uncertainties result from the lack of experimental β-decay log(ft) values for some of the transitions which connect the ^{37}Cl ground state with excited states of ^{37}Ar. Under the standard assumption that isospin is a good quantum number, the measurement of the delayed proton spectrum from the β decay of ^{37}Ca provides log(ft) values for transitions to the excited states of ^{37}Ar above 3 MeV[4] relative to the superallowed transition to the $J=\frac{3}{2}$, $T=\frac{3}{2}$ state at 4.993 MeV in ^{37}Ar. (This latter state is the isobaric analog of the ^{37}Cl ground state.) Transitions to excited states below 3 MeV have not been observed and the absolute rate for the 4.993-MeV isobaric analog state has not been measured. Hence, estimates for their contributions to the neutrino capture cross section must be based on nuclear structure calculations.

When the solar neutrino experiment was first proposed, Bahcall made simple shell-model estimates of these log(ft) values based on the assumption that the relevant low-lying states of ^{37}Ar and ^{37}Cl could be described by couplings of three nucleon holes in the $0d_{3/2}$ shell-model orbit.[2] In this note we report values for these transitions based on the most complete nuclear wave functions presently available. These wave functions span the full $0d_{5/2}$-$1s_{1/2}$-$0d_{3/2}$ space. Single-nucleon transfer and $E2$ and $M1$ strengths calculated with these wave functions agree well with experimental results from the $A=35$–38 region.[5] In particular, the wave functions yield predictions for stripping and pickup to ^{37}Ar that are consistent with recent experimental results.[6,7] These same experimental results point up the inadequacy of Bachcall's simple model for the lowest $\frac{1}{2}^+$ and $\frac{5}{2}^+$ states. The transitions which are in question proceed to the levels in ^{37}Ar at 1409 keV ($J^\pi=\frac{1}{2}^+$), at 2797 keV ($J^\pi=\frac{5}{2}^+$), and at 4993 keV ($J^\pi=\frac{3}{2}$, $T=\frac{3}{2}$). We have calculated the log(ft) values for the corresponding shell-model states with both the "11.0h + ASPE" and "12.5p + ^{17}O" wave functions of Ref. 5. The results are substantially the same. We discuss the results from "11.0h + ASPE" because there is some indication that this set gives a slightly better accounting for $A=37$ and 38 data than does "12.5p + ^{17}O." The predicted log(ft) values for the ^{37}Ar transitions are shown in Table I and Fig. 1. These numbers were obtained as part of a general study of β decay in this region of the nuclear chart.[8] We have calculated all the β decays for which experimental data exist in the mass ranges $A=17$–23 and 34–39 and the overall percentage rms deviation between calculated and experimental log(ft) values in these nuclei was 5%.

We show in Fig. 1 the calculated and experimental energies and log(ft) values for the states of ^{37}Ar (^{37}K). By examining this figure, one sees

TABLE I. The calculated log(ft) values for transitions which connect the ground state of ^{37}Cl with excited states in ^{37}Ar. These log(ft) values are needed to predict the solar neutrino absorption cross section.

J_f	T_f	E_x (keV)	log(ft) Bahcall	log(ft) Present calculation
3/2	1/2	0	(5.06)[a]	5.14
1/2	1/2	1409	4.48	5.44
5/2	1/2	2797	4.34	4.36
3/2	3/2	4993	3.28	3.30

[a]This is an experimental number, based on the electron capture of ^{37}Ar.

Collective and Higher-Order Effects Shown by the (p, t) Reaction on the Deformed Nucleus ^{159}Tb

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The reaction ^{159}Tb$(p,t)^{157}$Tb at 30 MeV strongly populates collective states in the residual nucleus. Angular distributions of β and γ vibrational and ground-state rotational band members are presented and compared with distorted-wave Born-approximation predictions. We also include evidence supporting the importance of indirect multiple-step processes accompanying the (p,t) reaction. The (p,t) reaction is shown to be a powerful spectroscopic tool for populating higher-lying rotational band members in odd-mass deformed nuclei.

The (p,t) reaction on ^{159}Tb continues a general study of the characteristics of the (p,t) reaction on odd-mass rare-earth elements. From a previously completed investigation[1] of the (p,t) reaction on the closed-shell nucleus ^{141}Pr, it was found that this reaction proceeds predominantly through a direct mechanism at the bombarding energies used in this study, and that large cross sections exist for the population of collective vibrational states within the residual nucleus ^{139}Pr. However, unlike the previous study, the present investigation involves permanently deformed target and residual nuclei. These provide a very suitable system for studying and further testing the collective characteristics previously associated with the (p,t) reaction. The (p,t) reaction is shown to be a powerful spectroscopic tool for populating higher-lying rotational band members in odd-mass deformed nuclei.

In this study an ≈ 300-μg/cm^2 metallic target of ^{159}Tb was bombarded with 30-MeV protons accelerated by the Michigan State University sector-focused cyclotron. The scattered tritons were analyzed with an Enge split-pole magnetic spectrometer and collected on photographic plates. Spectra were taken between 10° and 75° at 5° intervals in the lab system with an overall energy resolution of 15–20 keV, although higher-resolution spectra (10 keV full width at half-maximum) have also been obtained at some angles.

From previous radioactivity studies,[2,3] rotational bands built upon the ground state and a β vibrational excitation of the ground state have been identified in the ^{157}Tb nucleus. In addition, the presence of a $K=\frac{1}{2}$ band based at 598 keV of excitation was also indicated. There are two possibilities for the origin of such a $K=\frac{1}{2}$ band in this nucleus. It can be explained as a rotational band superimposed either on the $\frac{1}{2}^+[411]$ single proton state expected in this region, or on a γ vibrational state based on the $\frac{3}{2}^+[411]$ ground state. The vibrational origin of these states is strongly suggested both from systematics and from the very small decoupling parameter associated with this band. The empirical value of this decoupling parameter is $\approx \frac{1}{20}$ of the calculated value[2] for a $\frac{1}{2}^+[411]$ band based on a nuclear deformation of $\eta = 5$, and it is of opposite sign. However, experimentally determined K-conversion coefficients imply significant $M1$ admixtures in transitions de-exciting this band to the ground band; these should be formally forbidden for states having a vibrational origin, although band mixing could easily account for this phenomenon.

The ^{159}Tb(p,t) triton spectrum taken at the lab scattering angle of 20° appears in Fig. 1. The most striking feature of this spectrum is the strong population of the ground-state rotational band, with members certainly up to $\frac{13}{2}^+$ and possibly as high as $\frac{17}{2}^+$ being excited. At 598 keV one finds three states that, within experimental uncertainty, correspond to the first three members of the previously discussed $K^\pi = \frac{1}{2}^+$ rotational band. In addition, if one generates the $\frac{7}{2}^+$ and $\frac{9}{2}^+$ members of this band by parametrizing the simple rotational energy relationship, one finds two additional states populated by this reaction which appear to be the next two members of this (γ vibrational) band. In light of the established tendency of the (p,t) reaction to populate collec-

INELASTIC PROTON SCATTERING FROM ^{138}Ba AND ^{144}Sm AT 30 MeV *

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Measurements of the inelastic scattering of 30 MeV protons from ^{138}Ba and ^{144}Sm have been carried out with 7–10 keV energy resolution. Differential cross sections were measured for levels up through 3.4 MeV excitation energy. For most of these states J^π assignements are suggested on the basis of angular distributions distinctly characteristic of angular momentum transfer L = 2, 3, 4, or 6.

The stable N = 82 nuclei are interesting because they allow one to study the effects of adding from four to twelve valence protons to a doubly closed Z = 50, N = 82 core. We have measured excitation energies and angular distributions in ^{138}Ba (6 valence protons) and ^{144}Sm (12 valence protons) with the (p,p′) reaction. The results indicate that high resolution inelastic proton scattering with ≈ 30 MeV beams can be an effective tool for making J^π assignements in this mass region as well as for identifying levels and measuring their precise energies.

The present data were taken with the Michigan State University cyclotron and Enge split-pole spectrograph. Energy resolutions obtained with nuclear emulsions varied between 7 and 10 keV, FWHM, for the inelastic proton groups. A spectrum for ^{144}Sm is shown in fig. 1. The identical configuration of experimental equipment and the same momentum calibration of the spectrograph were used in both the ^{138}Ba and ^{144}Sm measurements. The spectrograph calibration used as final reference values the known excitation energies of some previously observed levels in ^{138}Ba and ^{144}Sm (see table 1).

Average values of excitation energies measured in the present work are listed in table 1. The results for ^{138}Ba are in almost complete agreement, both as regards the number of levels up to E_x = 2.9 MeV and their precise energies, with the concensus of previous investigations [1–3, 9]. Our results for ^{144}Sm represent a considerable addition to the experimental knowledge [4, 5] of this nucleus.

Angular distributions for some of the ^{138}Ba and ^{144}Sm (p,p′) transitions are shown in fig. 2. (The cross section normalization (± 15%) is based on a comparison of our measured elastic scattering to optical model predictions using the parameters of Becchetti and Greenlees [6].) Inspection of the angular distributions shows that the shapes of the distributions for each of the known 2^+ states are essentially identical. And, although fewer samples are available, similar statements can be made for the distributions, respectively, for 3^-, 4^+ and 6^+ states. We have derived empirical "characteristic" shapes for the different L-value transitions by averaging over the data for all states reached by a particular known L. These shapes are also shown in fig. 2.

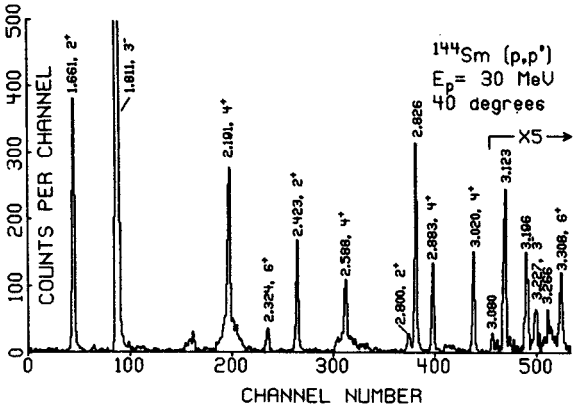

Fig. 1. Spectrum from ^{144}Sm(p,p′) at 40°. The resolution is about 7 keV. The broad bumps under certain of the peaks correspond to protons which scatter from ^{24}Mg and ^{28}Si impurities and hence lie a different focal plane in the spectrograph. The 3^- peak at 1811 keV was too intense to be counted on this plate.

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SPINS OF STATES IN ^{19}O NEAR 2.7 MeV EXCITATION*

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A distorted-wave analysis of angular distributions from the $^{17}O(t, p)^{19}O$ reaction leads to spin-parity assignments of $9/2^+$, $7/2^+$, and $3/2^+$ for the states at E_x = 2.37, 2.78, and 3.07 MeV, respectively, in agreement with recent γ-ray decay data, but not with assignments commonly quoted in the literature.

It has been known for many years that the nucleus ^{16}O is a reasonably good closed-shell nucleus. The nuclei in the immediate vicinity of ^{16}O are expected, therefore, to exhibit simple structure and to be easily amenable to interpretation in terms of the shell model. In particular, the low-lying states of ^{19}O, which differs from ^{16}O only by the addition of three neutrons, are known to be well described by $(sd)^3$ configurations. The nucleus ^{19}O is rather difficult to investigate experimentally; it can be conveniently studied only by means of the $^{17}O(t,p)^{19}O$ and $^{18}O(d,p)^{19}O$ reactions. A level scheme for the low-lying states of ^{19}O is shown in fig. 1; the spin-parity assignments include those of the present work. Because of the limited means available for studying the nucleus ^{19}O, an examination of the $^{17}O(t,p)^{19}O$ reaction by means of distorted wave analysis and shell-model wave functions was undertaken.

In a recent compilation [1], spin-parity assignments of $(3/2^+)$, $9/2^+$, and $(3/2, 5/2, 7/2)^+$ are given for the levels at 2.37, 2.78, and 3.06 MeV, respectively. The principal evidence for a $3/2^+$ assignment to the 2.37 MeV level is an apparent $l_n = 2$ angular distribution in a study [2] of the $^{18}O(d,p)^{19}O$ reaction at a bombarding energy of 5 MeV. This assignment, however, is not required by data on the same reaction obtained at higher bombarding energies [3–5]. The $^{17}O(t,p)\ ^{19}O$ angular distribution to this state has been tentatively assigned $L = (2)$ [6, 7] and the γ-ray decay is solely to the $5/2^+$ ground state [8, 9]. The $9/2^+$ assignment for the 2.78 MeV state appears [1] to rest only on the observation of an $L = 2$ angular distribution for this state in the $^{17}O(t,p)^{19}O$ reaction [3, 6, 7]. This level also decays solely to the ground state [2, 8, 9]. A recent

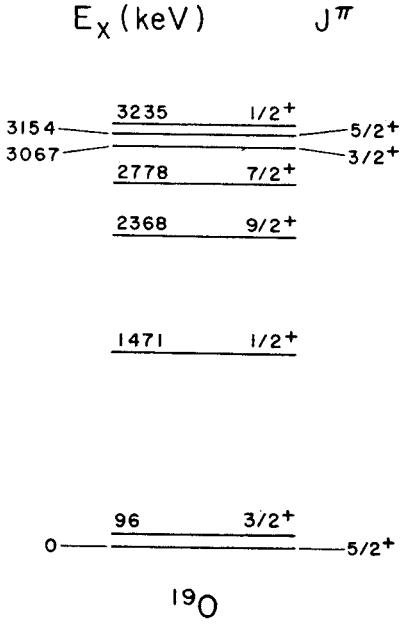

Fig. 1. Energy level diagram of ^{19}O for the states below 3.5 MeV excitation.

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MICROSCOPIC (p, p') CALCULATIONS AND POLARIZATION CHARGES WITH LARGE BASIS SHELL-MODEL WAVE FUNCTIONS*

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Techniques have been developed for performing microscopic model DWBA calculations of inelastic nucleon-nucleus scattering using large basis shell-model wave functions to describe the nuclear states involved. For the case of ^{138}Ba at a bombarding energy of 30 MeV, we obtain good fits to the data by including the exchange amplitude in the DWBA and assuming a state and multipole independent polarization charge.

Major advances in the microscopic describtion of inelastic proton scattering are being made through the use of realistic effective interactions [1, 2], the treatment of "core polarization" [3–8], and inclusion of the exchange amplitude in the distorted wave calculation [1, 9–11]. The evolution from a ubiquitous collective model approach to a realistic microscopic approach has recently been reviewed by Satchler [12]. Microscopic analyses of the (p, p') reaction have to date concentrated on doubly closed shell nuclei such as ^{16}O and ^{40}Ca, for which particle-hole wave functions are available, and on nuclei with one or two valence nucleons, where simple shell-model wave functions can be used. This note describes the expansion of such microscopic analyses to the much larger number of nuclei which have many active valence particles and whose states can be described by large basis shell-model wave functions.

We have made an initial application to the $N = 82$ nucleus ^{138}Ba. For ^{138}Ba, we obtain good fits to the shapes of the angular distributions and find polarization charges which are essentially independent of the multipolarity of the transition.

The experimental data, shown in figs. 1 and 2, were obtained at 30 MeV bombarding energy, using protons from the MSU sector-focussed cyclotron and an Enge split-pole spectrograph to detect the scattered particles. Energy resolution was approximately 8 keV, FWHM. A full discussion of the experimental work will be given elsewhere [13].

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Proton [14, 15] and neutron [16, 17] transfer reactions on the $N = 82$ nuclei indicate that $Z = 50$, $N = 82$ forms a good doubly closed core. The $N = 82$ nuclei are formed by adding protons to this core; ^{138}Ba has six such valence protons. The basis space for the shell-model wave functions we use [18] consists 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 for the shell-model calculation was parameterized in terms of the modified surface delta interaction (MSDI), with the four single particle energies and the two MSDI parameters fixed by fitting to energy levels of known J^π in the $N = 82$ nuclei from ^{136}Xe through ^{140}Ce. Eigenvalues and eigenfunctions calculated for $N = 82$ nuclei from $A = 134 - 140$ with this interaction give good agreement with experimentally known energy levels, pickup and stripping spectroscopic factors and electromagnetic data [18, 19].

In order to calculate inelasic scattering cross sections from these wave functions, it is necessary to obtain the structure amplitudes $S(J_i J_f J; T_i T_f T; j_1 j_2)$, where the notation is that of Madsen [9, 20]. We have modified the Oak Ridge-Rochester shell-model codes [21] to calculate these amplitudes in a form convenient for use in DWBA calculations. The distorted wave calculations in the present case were performed with the code DWBA 70 [22] of Raynal and Schaeffer, which includes the knock-on exchange amplitude. This code is based on a helicity formalism [23] which automatically accounts for all values of orbital angular momentum L and spin angular momentum S that can be transferred in a given transition. The exchange contribution is

EFFECTS OF OPERATOR RENORMALIZATION ON INELASTIC SCATTERING CALCULATIONS IN ^{40}Ca†

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Transition densities are calculated in TDA which include effects of both wave function and transition operator renormalization. These densities are used to calculate (e,e') form factors and (p,p') cross sections. Results are compared with experiment.

In most theoretical calculations of inelastic scattering one needs a normalization constant in order to obtain a (p, p') angular distribution or (e, e') form factor whose magnitude agrees with the corresponding experimental result. This constant, often referred to as the "effective charge", is typically about 1.5 for protons and 0.5 for neutrons.

The need for an "effective charge" arises from the fact that shell model calculations are of necessity performed in truncated vector spaces. However, as has been pointed out by a number of authors [1], the use of a truncated model space need not introduce errors if the operators employed in the calculation are properly renormalized. This has been recognized in a number of structure calculations [2], where instead of the "bare" two body interaction the investigators used an effective interaction obtained by taking core polarization effects into account. In addition, Gillet [3] and collaborators have achieved considerable success in their RPA calculations of transition moments and transition densities. These latter authors did not use a "realistic" force, however, but a force whose parameters were adjusted to produce agreement with experimental energy spectra.

The purpose of the present work is to examine the effect of operator renormalization on transition densities in cases when a "realistic" two-body interaction – in this case Sussex matrix elements – is employed.

The results presented here are particle-hole calculations for the lowest 3^- and 5^- states of ^{40}Ca. The calculations were done in TDA in a model space consisting of p-f shell particle states and s-d shell hole states. Correction effects, including ground state correlations, were included via second order perturbation theory, i.e. all terms linear in the energy denominator were retained in renormalizing both the two-body interaction and the transition operators. Graphs representing the various terms are shown in fig. 1. In these graphs an average energy denominator of $2\hbar\omega$ was used, with the exception of the ground state correlation graphs in which the exact single particle energies were employed.

The particle-hole amplitudes resulting from these calculations are given in table 1. They differ from the previously reported [4] amplitudes due to the inclusion here of single particle-hole excitations of $3\hbar\omega$. Using these amplitudes and harmonic oscillator radial wave functions (oscillator constant $\alpha = 0.498$) we constructed renormalized charge and matter transition densities, $\rho_J(r)$ and $g_J(r)$, for transitions of multipolarity J, which are the reduced matrix elements

$$\langle J^\pi || \sum_i \frac{\delta(r - r_i)}{r_i^2} Y_J(r_i) || 0 \rangle ,$$

with the sum running over protons for $\rho_J(r)$ and over protons and neutrons in $g_J(r)$.

In Born approximation the form factor for inelastic electron scattering [5] is related to the charge transition density by

$$|F(q)|^2 = \frac{4\pi}{Z^2} \frac{2J_f + 1}{2J_i + 1} \left| \int_0^\infty j_J(qr)\, \rho_J(r)\, r^2\, dr \right|^2$$

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THE MASS OF ^{29}S*

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The mass of ^{29}S has been measured with the ^{32}S(τ, ^{6}He) reaction at 70 MeV. The mass excess is -3.16 ± 0.05 MeV.

The ground state of ^{29}S is the fourth member ($T_z = -3/2$) of a mass quartet which includes the lowest $T = 3/2$ states in ^{29}Si ($T_z = 1/2$) and ^{29}P ($T_z = -1/2$) and the ground state of ^{29}Al ($T_z = +3/2$). The half-life of ^{29}S has been measured [1] to be 195 ± 8 ms by observing the delayed protons following the proton bombardment of natural S and P targets. Previous attempts to measure its mass have only shown it to be consistent with the predictions of the isobaric multiplet mass equation and Coulomb energy systematics [2].

The present measurement consisted in observing the ^{32}S(τ, ^{6}He)^{29}S reaction at 7.5° nd 10° in a split-pole spectrograph. Fig. 1 gives a schematic representation of the apparatus. A 70.5 MeV ^{3}He beam was produced by the Michigan State University Cyclotron. The position on the focal plane was measured by a charge division wire proportional chamber. A plastic scintillator behind the proportional counter was used for particle identification by time-of-flight and total energy. This information plus the energy loss in the wire counter produced spectra which are virtually 100% ^{6}He particles.

The main difficulty of the experiment consisted in producing and maintaining a thin target containing sulfur. A self-supporting CdS foil with 800 μg/cm^2 areal density was used, and did not flake off or change thickness under bombardment. This is crucial to the experiment since target thickness is an important source of error in measurements of this type. The best spectrum obtained is shown in fig. 2. A much shorter run on a Mg target, which provided one of the calibrations, is also shown in fig. 2. The background in the CdS spectrum is due to the cadmium isotopes which produce profilic ^{6}He particles leaving the final nuclei in highly excited states (15–20 MeV). At 10° the ^{29}S yield was reduced significantly, and at 12° no peak corresponding to ^{29}S was observed in the spectrum.

The mass determination was made by comparing the rigidity of the ^{6}He particles leading to ^{29}S to those from the ^{24}Mg(τ, ^{6}He)^{21}Mg [3] and ^{58}Ni(τ, ^{6}He)^{55}Ni [4] reactions. The target thickness of the three targets ^{24}Mg, ^{58}Ni, and CdS was measured with americium α-particles both before and after the experiment. The resulting mass excess for ^{29}S is -3.16 ± 0.05 MeV.

The isobaric multiplet mass equation, with the most accurate values for the mass of the three other members [5], predicts a mass excess of -3.14 ± 0.03 MeV for ^{29}S. Hence the present experiment is consistent with a quadratic T_z dependence. A cubic fit to the four masses of the form $M(T_z) = a + bT_z + cT_z^2 + dT_z^3$ gives $a = -11\,137 \pm 9$, $b = -5\,025 \pm 16$, $c = 200 \pm 13$ and $d = 3 \pm 11$ keV.

The c-coefficient obtained can be compared to a shell model calculation [6] which used the simplest possible configuration for the $5/2^+$ spin and parity found for the ground state of nucleus ^{29}Al. The

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COLLECTIVE CONTRIBUTION TO ESCAPE WIDTH OF ANALOG RESONANCES*

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The collective isovector monopole state decreases escape widths of analog states by 10–20%. Thus spectroscopic factors determined in previous calculations are too small by this amount. The monopole has a much greater influence on the spreading widths; the reason it is less important in the decay width is that the transition density is more external to the nucleus.

The first calculations of the decays of analog states neglected many-body effects, and their successes made it appear that nothing further was needed [e.g. 1]. Later, more detailed calculations showed that in fact predicted spreading widths were much too large [2–4]. By spreading width is meant the excess width of the analog over the sum of the partial widths due to proton decays. It arises from the mixing of the analog with more complicated nuclear states. The problem was resolved by Mekjian who noted that the Coulomb interaction induces spreading mainly via an isovector monopole state [5]. As a result of the collectivity of this state, spreading is much reduced.

The importance of the collective isovector monopole excitation was first stressed by Bohr, Damgaard and Mottelson [6], in the question of corrections to superallowed beta decay. Other physical phenomena which may be influenced by this state include isotope shifts [7] and Coulomb energies [8], although the effect is smaller than ref. [8] indicates [9]. We here treat the effect of the monopole on escape widths of analogs. It will be seen that the monopole collectivity reduces the widths by 10–20%. This is in contrast to the situation with spreading widths, which are reduced by a factor of five or so. The reason for the difference is that the transition density for particle decay is peaked several fm from the nuclear surface, while the monopole transition density and the damping transition density are concentrated at the surface.

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To derive the decay width of analogs, we shall use the following expression for decay amplitude:

$$\gamma = \langle \phi_c | V_c | A \rangle + \frac{\langle \phi_c | V_N | M \rangle \langle M | V_c | A \rangle}{E - E_M - i\Gamma_M/2} \quad (1)$$

In this equation $|A\rangle$ is the analog state, defined with the isospin lowering operator on the parent state $|\pi\rangle$ as $|A\rangle = (T^-/\sqrt{2T})|\pi\rangle$. The state $|M\rangle$ is the isovector monopole of the residual nucleus, with a mean energy E_M and width Γ_M. The interaction V_c is the one-body central Coulomb field, and V_N is the two-body nuclear interaction. Finally, ϕ_c is the continuum wavefunction of the ejected particle plus the residual nucleus. Eq. (1) may be derived as an approximation from the general theory of analog states given in ref. [4]. The relation between the amplitude in eq. (1) and the observed escape width is given in the same reference. The continuum wavefunction ϕ_c may be determined from an optical potential, and should be orthogonal to the single particle orbits in the state $|A\rangle$.

For the calculation we shall need the transition density between the monopole state and the residual nucleus ground state,

$$\delta\rho(r) \equiv \langle M | \tau_z \psi^+(r)\, \psi(r) | \rangle . \quad (2)$$

We shall also need the transition potential associated with the monopole state,

$$\delta V(r) = \sum_i \langle M | V_N(r - r_i) | \rangle \quad (3)$$

For a short-range interaction and neglecting exchange, δV is proportional to $\delta\rho$. A simple estimate of the ef-

AN ANOMALOUS M1 TRANSITION IN ^{38}Cl*

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The observed enchangement of the M1 transition in ^{38}Cl between the 3^- state of the "$d_{3/2}$-$p_{3/2}$ multiplet" and the 4^- state of the "$d_{3/2}$-$f_{7/2}$ multiplet" is explained..

The analysis of the energies of the low-lying states of ^{38}Cl and ^{40}K was one of the early quantitative successes of nuclear shell model theory. [1, 2] If we speak in terms of an ^{16}O core, then the first states of ^{38}Cl should arise in lowest order from the configuration $(\nu d_{5/2})^6$, $(\pi d_{5/2})^6$, $(\nu s_{1/2})^2$, $(\pi s_{1/2})^2$, $(\nu d_{3/2})^4$, $(\pi d_{3/2})^1$, $(\nu f_{7/2})^1$, where ν denotes neutrons and π denotes protons. Similarly the lowest states of ^{40}K should arise from the configuration formed by adding two more protons to the $d_{3/2}$ orbit. The $d_{5/2}$ and $s_{1/2}$ orbits are thus always filled, as is the $\nu d_{3/2}$ orbit, and we describe ^{38}Cl in terms of $(\pi d^1_{3/2} - \nu f^1_{7/2})$ couplings and ^{40}K in terms of $(\pi d^{-1}_{3/2} - \nu f^1_{7/2})$ couplings.

In the early shell model analyses of this region, these simple configurations were assumed and it was shown that the observed energies of the 2^-, 3^-, 4^-, and 5^- states in ^{40}K can be obtained almost exactly by applying the appropriate particle-hole transformation rule to the energies of the first 2^-, 3^-, 4^-, and 5^- states of ^{38}Cl. The accuracy achieved in this transformation was then, and has been since, taken as confirmation that the wave functions of the states involved did indeed closely resemble the simple initial assumptions. Subsequent measurements [3, 4] have disclosed a higher lying multiplet in each nucleus which can be described in similar fashion as couplings of a $d_{3/2}$ particle (hole) with a $p_{3/2}$ particle, although the transformation of energies is not as accurate as for the lower sets of states.

Recently, however, measurements have revealed some characteristics of ^{38}Cl states which are difficult to reconcile with the simple description just outlined [5, 6]. Chief among these data is strong M1 transition from the 3^- state of the $(d_{3/2}-p_{3/2})$ multiplet to the 4^- state of the $(d_{3/2}-f_{7/2})$ multiplet. This transition is, of cource, l-forbidden to the extent that the wave functions of the states actually follow the description given heretofore. Other data which cast doubt on the purity of these ^{38}Cl states are the spectroscopic factors for (d, p) stripping on ^{37}Cl [7]. These experiments show some admixing of $l = 1$ into the supposed $(d_{3/2}-f_{7/2})$ 3^- state.

We have calculated energies and wave functions for ^{38}Cl, ^{39}K, and ^{40}K in a model space which includes active $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, $f_{7/2}$, and $p_{3/2}$ particles, using the codes of French et al. [8]. The two-body matrix elements used in our Hamiltonian were calculated from the Sussex relative oscillator matrix elements [9] with space truncation effects added [10], and the single-particle energies were chosen to yield calculated spectra for ^{38}Cl, ^{39}K, and ^{40}K in simultaneous best agreement with the experimental spectra. The values for $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, $f_{7/2}$, and $p_{3/2}$ are, respectively, −9.40, −4.90, −2.77, −2.52, and 0.00 MeV. Some of these results for ^{38}Cl and ^{40}K are summarized in fig. 1 and table 1. The experimental and predicted S-factors for the ^{37}Cl(d, p)^{38}Cl reaction are presented in table 2.

Our predictions for these observables (our M1 calculations use operators calculated from the bare-nucleon g-factors) are in uniform good agreement with the observed values. In particular, for ^{38}Cl the mixing of the $l = 1$ and $l = 3$ strengths for the 3^- states

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STATES IN ^{163}Ho AND ^{167}Tm POPULATED THROUGH THE (p, t) REACTION ON ^{165}Ho AND ^{169}Tm

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The (p, t) reaction at 30 MeV on the deformed nuclei, ^{165}Ho and ^{169}Tm, strongly populates collective states in the residual nuclei. Indirect multiple-step processes evidently play an important role, and the reaction is a powerful tool for populating higher-lying rotational band members.

Previous work involving the (p, t) reaction on the spherical ^{141}Pr nucleus [1] and the strongly deformed ^{159}Tb nucleus [2] has demonstrated the potential of this reaction as a very powerful tool for probing collective characteristics. In particular, the study of the ^{159}Tb(p, t) reaction revealed large cross sections associated with the population of β- and γ-vibrational and ground-state rotational band members.

In the present study $\approx$400 μg/cm^2 metallic targets of the elements were bombarded with 30 MeV protons accelerated by the Michigan State University sector-focused cyclotron. The scattered tritons were analyzed with an Enge split-pole magnetic spectrometer and collected on nuclear emulsions. All spectra were taken at the scattering angle of 20° with an overall energy resolution of $\approx$10 keV FWHM.

A triton spectrum obtained from ^{165}Ho is shown in fig. 1. In this spectrum one finds a strong population of the $K^\pi = \frac{7}{2}^-$ [523] ground-state rotational band with level spacings similar to those occuring in the same band in ^{159}Tb. From Coulomb excitation experiments conducted on ^{165}Ho by Seaman et al. [3], one would expect from systematics to observe the $K^\pi = \frac{3}{2}^-$ and $\frac{11}{2}^-$ γ-vibrational bands at $\approx$500 keV and $\approx$700 keV, respectively. And indeed one does observe a set of states originating at 562 keV which appear to have some intensity interrelationships. If one assumes that the 562 and 618 keV states are the first two members of the $K = \frac{3}{2}$ γ-vibrational band and that higher members are generated by parameterizing the simple $I(I+1)$ energy relationship, one finds convincing evidence for the presence of additional members up to a spin of $\frac{15}{2}$. However, no evidence for the presence of a $K = \frac{11}{2}$ γ-vibrational band could be found in our spectrum.

As in the case of ^{159}Tb [2], the (p, t) reaction on ^{165}Ho is found to strongly populate rotational as well as vibrational states in the residual nucleus. The present study has identified six members of the $K = \frac{7}{2}$ ground-state rotational band and seven members of the $K = \frac{3}{2}$ γ-vibrational band. Moreover, with the single exception of the 791 keV peak, these states completely exhaust the (p, t) reaction strength occurring below the pairing gap in the ^{163}Ho nucleus. The origin of the strongly excited 791 keV state cannot be determined from our data since it does not appear to have any relationship to any other states in our spectra. Being below the pairing gap, this state certainly must be a collective excitation, but whether it be a β, γ or octupole state is not clear from our data alone.

The triton spectrum from the ^{169}Tm(p, t) reaction appears in fig. 2. As in the previous results, the ground-state rotational band of ^{167}Tm is found to be strongly

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FUTURE CYCLOTRONS*

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ABSTRACT

This paper reviews future trends in cyclotron design, first briefly from the point-of-view of cyclotrons now in construction and second from the point-of-view of design features. The topics covered include the choice of a conventional or separated-sector magnet, the use of dees or cavities for acceleration, possible flat-topping of the rf wave, the impact of new technologies on design and operation, and extensions of the cyclotron concept to higher energies.

INTRODUCTION

From the earliest times humans have derived pleasures from listening to the pronouncements of enlightened prophets regarding what lies ahead. The pleasant sensations are particularly keen and meaningful if the prophet is a person with convincing super-natural power. To be convincing it helps to refer to tangible evidence—tea leaves, lines in the hand, and crystal balls have been widely used. In addition the prophet enjoys an important credibility advantage if his view of the future is pleasant. In this paper I will employ these time-tested techniques. A proper substitute for tea leaves at a cyclotron conference is obviously to study the mystic patterns of orbitry from the great God DigiComptus. And in order to have an optimistic picture of the future I will specifically exclude all references to money, thus clearly leaving only pleasant things to consider. With these stipulations understood, let us go on to a happy hour of dreams.

Thinking of how to look at the future, two different, mutually interesting perspectives occur. One is to look from the point-of-view of projects—machines being built or proposed. The other is to look from the point-of-view of design features—what are likely to be the main features of new cyclotrons, how will they resemble present machines, how will they differ? Many other papers at this conference present material telling us about the future as seen from the project point-of-view; the main emphasis of this paper will therefore be on design features. To begin with though it is useful to take a brief look at projects since many of the things I want to consider in the discussion of design features have their origins in present projects.

PROJECTS IN PROGRESS

Isochronous cyclotrons with proton energy of 100 MeV or greater are listed in Table I. Four of these are nearing completion—one

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DESIGN STUDY FOR A COMPACT 200 MeV CYCLOTRON*

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ABSTRACT

A preliminary study has been carried out for a variable energy, 200 MeV cyclotron which is designed for both nuclear physics and medical research. The operational and structural features of this machine are modeled closely on our present 50 MeV cyclotron. The magnet would have the same gap, but twice the diameter (3m) and twice the number of trim coils (17), and it would have four (instead of three) sectors with sufficient additional spiral. The rf system would operate in the 10-20 MHz range, with two 90° dees carrying up to 70 kV. This cyclotron would produce protons at energies up to 200 MeV, and other ions to corresponding energies. By extending our present phase selection and single turn extraction techniques to this cyclotron, the energy resolution of the extracted beam would be: $E/(\Delta E)=7000$. With proton currents of about 2 μA, the beam emittances would be 0.3 mm-mrad radially and 2.5 mm-mrad axially. The estimated cost of the cyclotron itself would be around two million dollars.

INTRODUCTION

The MSU 50 MeV cyclotron has been outstandingly successful in producing extracted beams (particularly of protons) having exceptionally fine energy resolution and unusually small emittance.[1] This success has led us to investigate the design of a 200 MeV cyclotron having comparable performance characteristics. This 200 MeV cyclotron would possess the basic structural and operational features of our present machine including the central region geometry, the phase selection slits, and the single turn (resonance) extraction system.

The 200 MeV magnet would have the same magnet gap and the same maximum field strength as our present magnet, and would therefore have about twice the pole diameter (125 in). However, this magnet would have four sectors with sufficient spiral to compensate the additional relativistic defocusing. The magnet therefore resembles that of the Maryland 100 MeV cyclotron.[2]

The suggested design for the rf system of the 200 MeV cyclotron is closely modeled on the present Maryland and MSU machines. This rf system would operate in the 10-20 MHz range with two dees, about 90° in angular width, allowing for both even and odd harmonic operation. Since these dees would be positioned within the magnet gap, the maximum dee voltage would be restricted to about 70 kV.

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AN OPTIMIZED MULTI-PARTICLE CENTRAL REGION FOR THE MICHIGAN STATE UNIVERSITY ISOCHRONOUS CYCLOTRON*

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ABSTRACT

Centered orbits are highly desirable in a cyclotron since problems with resonances are minimized and beam stability is greatly improved. The Michigan State University Cyclotron, as originally designed, produces accurately centered orbits in first harmonic operation and performs acceptably on second harmonic. Third harmonic operation, on the other hand, has never been adequate due to very large centering errors. The basic origin of these centering problems is the gap crossing resonance, and the effect of this resonance is highly sensitive to the angular width of the dees. Studies herein show that with a proper selection of both the central region geometry and the dee angle this centering problem can be effectively eliminated. Appropriate configurations have been worked out for harmonics H=1, 2, and 3, using 138°, 90°, and 60° dees respectively, and confirmed in electrolytic tank studies. To implement this new design, a major cyclotron improvement program has been initiated based on a system of interchangable dees. Basic features of this new design and computational results for the optimized geometries are discussed.

INTRODUCTION

In the Michigan State University Cyclotron, third harmonic operation (rf frequency three times the orbital frequency) is essential for producing the most important heavy ion beams, as well as very low energy protons and deuterons. Third harmonic operation has, however, thus far not been adequate for experimental needs due to large orbit centering errors. In view of this we decided some time ago to restudy and redesign the central region with the objective of improving third harmonic performance.

The advantages of centered orbits in a cyclotron have been widely discussed; problems with resonances are minimized, beam stability is greatly improved, and extraction is easier. The major problem in centering third harmonic orbits is the so-called gap crossing resonance[1] in which the acceleration process drives orbits off center as a result of a resonant interaction between the three sector magnet geometry and the basically two sector electric gap geometry. Moreover, when the orbits are off center, resultant rf phase deviations from gap to gap tend to drive the orbits still further off center. Since this latter effect increases with harmonic number, the centering problem is fundamentally more severe as the harmonic number increases.

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APPLICATION OF A NEW FIELD TRIMMING PROGRAM TO THE MSU CYCLOTRON*

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ABSTRACT

In order to improve the performance of isochronous cyclotrons, a new computer program "Fielder" has been developed which carries out field trimming calculations on a more rational basis. Using an iterated least-square process, this program adjusts the trim coil currents and the rf frequency so as to fit the (central ray) phase-energy curve to a prescribed function, including a given non-zero initial phase value. In addition, the least-square fitting is subjected to constraints which serve to produce "energy stability" as well as "energy focusing" in the extracted beam. This program has been applied to the MSU cyclotron for a wide range of operating conditions, and has invariably produced significant improvements in the resultant phase-energy curves.

INTRODUCTION

Variable energy cyclotrons require an efficient system for determining the multitude of "knob settings" necessary to produce a specific ion beam with a given energy. The MSU cyclotron has operated successfully for a long time with the use of a computer program "Set-op" which provides these knob settings as part of its output.[1]

In order to achieve certain operational improvements, it was decided to rewrite the main part of the Set-op program which calculates the trim coil currents and the rf frequency. As a result, we have developed a completely new field trimming program "Fielder" which systematically determines the values of these parameters on a more rational basis.

In this paper we present a brief description of the Fielder program together with some of the results obtained from its application to our 50 MeV cyclotron. This program was also used in the design study for a compact 200 MeV cyclotron which was described in an earlier paper.[2]

Although the techniques employed in Fielder should be generally useful, this program was specifically designed to fulfill the more demanding requirements of those cyclotrons which operate under a separated turn regime. A copy of this program (Fortran listing), together with a more complete description, can be obtained by writing to the authors.

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OPTIMIZED USE OF A CYCLOTRON FOR HIGH RESOLUTION STUDIES OF NUCLEI*

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ABSTRACT

The effectiveness of an accelerator in nuclear physics research hinges heavily on the energy resolution which can be obtained in actual experiments. Contributions to the resolution from the energy spread and incoherent phase space distribution of the beam, the kinematic effects in the nuclear reaction proper, the energy loss in the target, and the aberrations, must all be included. Optimization for one or the other of these factors is in some cases at the expense of a broadening in other contributions and a compromise point is actually the choice for minimum line width. A manually adjusted optimization system has been in use for some time in our laboratory and has given momentum resolutions of 1 in 20,000 in a variety of test situations and of 1 in 10,000 on a rather regular basis in extended runs. A second generation optimization system is being developed which will make more extensive use of the computer both for calculating best values and for on-line control of system elements.

INTRODUCTION

Particle beams are an essential tool in the study of nuclear phenomena. Practically all of the information on nuclear systems is obtained from measurements of the scattering of particles by nuclei and the emission of ensuing electromagnetic radiation. Nuclei exist in "energy states" which live for varying times and whose properties are generally widely different. Thus our ability to extract the information required for a better understanding of nuclei is intimately tied to our ability to resolve various nuclear states.

When investigating nuclear properties with charged particle beams, we recognize two distinctly different situations in high resolution studies. In the first, the nuclear states of interest belong to the compound system formed by the merging of the incident projectile and the target nucleus. Such processes give highly excited states for the given system of nucleons, and it is the total energy spread in the beam at the target which controls the resolution. Electrostatic accelerators are best suited in such instances, but excellent results can be obtained with cyclotrons by selecting a fraction of the total beam with the required energy spread.[1] At MSU, for example, we have done experiments of this type with a resolution of 1 keV in beams with energies of 5 MeV.

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Nuclear Data Sheets for A = 101

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Abstract: The 1961 version of the Nuclear Data Sheets for A = 101 has been revised on the basis of experimental data published prior to September 1, 1972. The present evaluation contains information obtained from approximately 70 papers.

There are currently nine nuclei known for A = 101. Only the presumed ground states and half-lives have been determined for ^{101}Zr and ^{101}Cd. Decay-scheme studies of ^{101}Zr and ^{101}Cd have established two levels in ^{101}Nb and ^{101}Ag, respectively.

The identification of levels in ^{101}Mo and some subsequent spin and parity assignments depend primarily on recent sub-Coulomb stripping results. The identification of levels in ^{101}Mo fed by the β-decay of ^{101}Nb is somewhat uncertain at this time. Nine levels in ^{101}Pd have been identified from the β-decay study of ^{101}Ag, but the data are not sufficient to assign spins and parities. ϵ/β^+-decay studies of ^{101}Pd have established approximately 19 levels in ^{101}Rh and have resulted in some tentative spin and parity assignments.

During the course of the compilation, the results of 72Co16 and 72Co17 concerning the β-decay of ^{101}Mo were communicated to the compilers. This study resulted in the identification of 152 transitions and the placement of approximately 45 levels in ^{101}Tc. In addition, conversion-electron work resulted in the identification of previously unobserved levels in ^{101}Tc at 0.009317 and 0.015601 MeV, requiring a reassignment of level energies in ^{101}Tc. The stable nucleus ^{101}Ru has been studied via β-decay, γ-decay, and Coulomb excitation. As a result, a number of spin assignments for low-lying states are firm.

Some additional gaps and uncertainties remain in the data. The relative intensities of transitions depopulating the same levels in ^{101}Ru as observed in β-decay, Coulomb-excitation, and γ-decay studies do not agree in some cases. Reaction studies would help to confirm the spins of low-lying states in ^{101}Tc and ^{101}Rh and provide additional information on higher spin states in ^{101}Mo. The existing data on levels in ^{101}Pd populated by the β-decay of ^{101}Ag were obtained in early work with semi-conductor detectors and are probably incomplete at this time.

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ISOSPIN IMPURITIES IN NUCLEI

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CONTENTS

1. INTRODUCTION

The isospin quantum number, introduced to nuclear physics by Heisenberg in 1932, was applied by Wigner (1) in 1937 to describe the symmetry of the nuclear wavefunction with respect to the exchange of neutrons with protons. The operator T_3 is defined as having a value of $+1/2$ for neutrons and $-1/2$ for

[1] Guest of the Weizmann Institute while most of this review was prepared.

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The Numerical Accuracy of ^{3}He Optical-Model Calculations at 70 MeV*

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Small differential cross sections, such as those measured at back angles for 70 MeV ^{3}He elastic scattering (typically below 10^{-4} mb/sr past 130°), are difficult to calculate accurately when they result from considerable cancellation in the partial-wave sum. The codes GENOA, GIBELUMP, SNOOPY3, and DWUCK differ by as much as $2\frac{1}{2}$ orders of magnitude on $\sigma(\theta)$ for an optical-model potential describing ^{60}Ni(^{3}He, ^{3}He)^{60}Ni scattering at 71 MeV. This calculation is repeated, with a modified version of GIBELUMP, for wide ranges of the parameters affecting numerical accuracy. A study of errors in scattering matrix elements and cross sections, as functions of these parameters, reveals that criteria commonly used to determine the matching radius and number of partial waves employed in optical-model calculations yield insufficient values in this case.

1. INTRODUCTION

There is increasing evidence that the well known ambiguities in optical-model potentials for complex projectiles may be at least partially resolved through analyses including large angle elastic scattering data [1–5], especially at relatively high bombarding energies. In particular, S. M. Smith and D. A. Goldberg [1] have noted a sensitivity of back-angle deuteron, helion, and alpha-particle elastic scattering to real well depth at incident energies above 60 MeV. The characteristic feature of such data is a monotonic fall (with increasing angle) beyond the diffraction region. Such behavior is illustrated in Fig. 1, which presents 70 MeV ^{3}He elastic angular distributions, taken from targets of ^{50}Ti and ^{51}V with the MSU Sector-Focused Cyclotron [2]. Similar data have been obtained by C. B. Fulmer and J. C. Hafele. They also stress the importance of the small, back-angle cross sections for suppressing ambiguities in the ^{3}He optical-model parameters [3].

Unfortunately, we find that unusual care is required for the accurate calculation of such small cross sections, since they result from a great deal of cancellation

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DOUBLE GAMMA DECAY IN LIGHT NUCLEI

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The $0^+ \to 0^+$ double gamma decay is calculated for the nuclei C^{12}, O^{16}, Ca^{40}, Ge^{72} and Zr^{90}, using a model of the states with spherical and deformed components. Due to the similarity in the structure of the components, double gamma decay is always greatly hindered. However, for O^{16}, the calculated transition matrix is too large by at least a factor of 3; in Ca^{40} there is agreement with a recently reported measurement.

INTRODUCTION

A recent measurement of double gamma decay [1] in the transition $Ca^{40}(0_2^+ \to 0_1^+)$ makes a review of the theory of nuclear double gamma decay worthwhile. In the previous theoretical literature [2-6], estimates of transition rates are either highly inaccurate or otherwise unreliable. An improved estimate is derived below, making use of the energy-weighted dipole sum rule.

The $0^+ \to 0^+$ transitions between low-lying levels are interesting because there is still much uncertainity about the structure of excited 0^+ states. The decay normally proceeds by pair production or by internal conversion, which depend on the transition matrix element

$$M_{EO} = \sum_p r_p^2 \tag{1}$$

This matrix element is of the order of a few fm^2 which is what one would expect from a single-particle transition. Double gamma decay is proportional to the second order E1 matrix element,

$$M_{2\gamma} = \sum_{p,p',i} z_p \frac{|i\rangle\langle i|}{E_i - E_o} z_p \tag{2}$$