Section IV

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ULTRA-HIGH RESOLUTION SPECTROMETER SYSTEM FOR CHARGED PARTICLE STUDIES OF NUCLEI*

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This paper describes an arrangement for introducing feedback into a charged particle magnetic analysis system for nuclear reaction studies. In initial tests of the system, a resolution of 5 keV has been obtained in (p,p′) studies at 30 MeV with 70% of the cyclotron internal beam on target. This corresponds to a resolving power $p/\Delta p$ of 12000. Essential features of the system, in addition to the feedback, are a careful definition of the cyclotron source by means of internal slits and the use of dispersion matching to cancel the effect of coherent on-target energy spread.

1. Introduction

The crucial role of an intense source in determining the ultimate resolution of charged particle magnetic analysis systems has been discussed by Cohen[1]), who concludes that the resolution in an optimized system is predominantly controlled by source luminosity. Generally, the effective source for such an analysis system consists of an object slit at the beginning of a beam preparation system. The accelerator is tuned to maximize the transmission through this slit and thus maximize the luminosity of this effective source. In such an arrangement the dispersive properties of the accelerator are normally ignored, which, for the case of a cyclotron, is a major error (as we explain in section 2). In the system described here this difficulty is avoided by using the actual cyclotron ion source as the effective object for the system which, if all magnets are stable, is equivalent to an external slit with exactly correct "dispersion matching"[2]) (also see sec. 2). For the system we describe the stable magnet requirement is effectively provided by a feedback circuit which acts to maintain the position of the optic axis at a fixed point on the focal plane of the magnetic spectrograph.

A second important feature of our system is a "resolution meter" based on fractional transmission through a small slit in the spectrograph focal plane. Such a meter, in conjunction with "separated function" magnets[3]), allows a quick empirical adjustment of quadrupoles and sextupoles to give the best linear focus, dispersion matching, cancellation of aberrations, etc.

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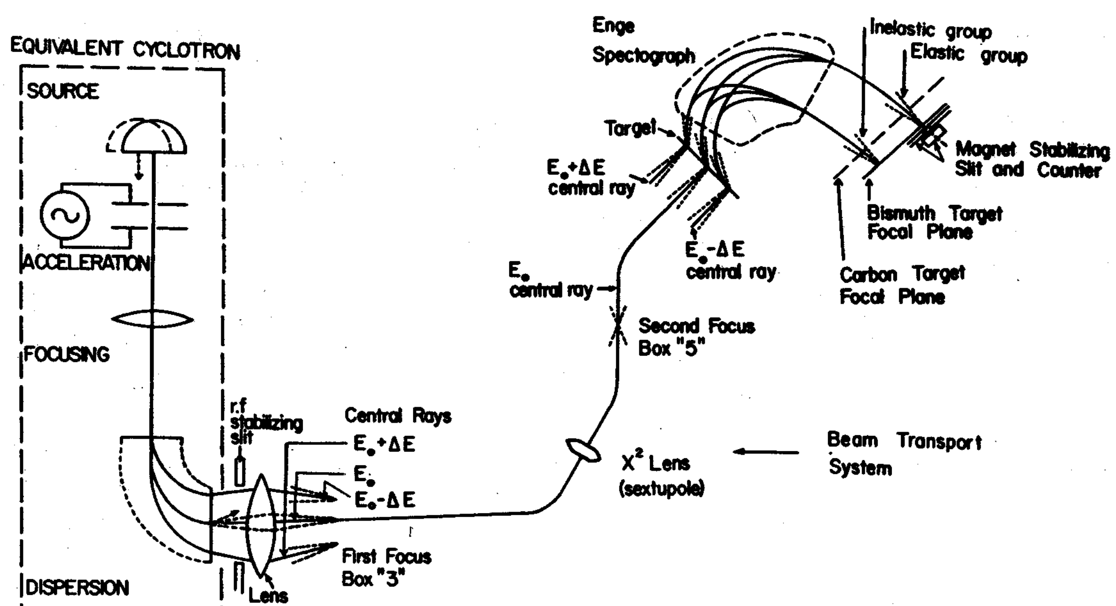

Fig. 1. "Equivalent circuit" of cyclotron and high resolution beam line.

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IMPROVING THE ENERGY RESOLUTION AND DUTY FACTOR OF ISOCHRONOUS CYCLOTRONS†

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A separated turn isochronous cyclotron can produce beams having a precise energy resolution together with a substantial duty factor if the effective voltage wave form is 'flat-topped'. Optimum flat-topping results are presented for five different harmonic combinations: $n = 1$ and 2; $n = 1, 2$, and 3; $n = 1, 2, 3$, and 4; $n = 1$ and 3; $n = 1, 3$, and 5. For a given energy resolution, the improvement in duty factor with each added harmonic is quite impressive. The success of this technique is limited by certain practical problems which are examined.

1. INTRODUCTION

If an isochronous cyclotron could be equipped with an rf system which provided a square wave voltage on the dees, then each ion pulse could extend for nearly half of the rf period, while the energy distribution within this pulse would remain quite homogeneous throughout the acceleration process. Assuming a small radial beam width, optimum conditions would then prevail for 'separated turn' operation with 100 per cent beam extraction.(1) The external beam would then possess exceptionally fine energy resolution together with a duty factor approaching 50 per cent. In addition, the transverse emittance of this beam would be directly correlated to that of the ion source or injector. In a certain sense, this cyclotron would operate like a pulsed dc accelerator.

The advantages of a square wave voltage for a classical cyclotron were first recognized by Rossi who devised a method for superimposing a third harmonic voltage on the dees, and who showed that when this voltage is one-ninth that of the main harmonic, the resultant flat-topped wave form partially fulfills the function of a square wave voltage.(2) This third harmonic flat-topping method was also investigated by Goodman as a means for improving both classical and isochronous cyclotrons.(3) Welton(4) and Blosser(5) considered voltage flat-topping as an important element in an isochronous cyclotron designed to yield superlative beam characteristics including a substantial duty factor.

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The desirable effects of a flat-topped voltage wave form can be achieved by another method under certain circumstances. Since the energy gained at successive electric gap crossings is cumulative, and since only the resultant energy is significant, the voltages corresponding to different harmonics can be applied to separate sets of dees. This procedure is particularly suitable for ring cyclotrons where the ion injection energy is substantially greater than the energy gained at any one gap crossing.(1) Moreover, as pointed out by Rickey,(6) this procedure permits the utilization of even as well as odd harmonic voltages and such combinations always produce a superior flat-topping effect, and may produce duty factors exceeding 50 per cent. These considerations formed the basis for the design of the rf system of the Indiana Cyclotron now under construction.(7) Several other cyclotrons have been proposed recently which plan to utilize the flat-topping effect of either second or third harmonic voltages.(8,9)

The present paper explores the degree of energy homogeneity which can be achieved as a function of duty factor through the admixture of a small number of harmonic voltages, and discusses some of the practical problems which may limit the success of this technique. In a subsequent paper, we intend to discuss the limitation of energy resolution imposed by the longitudinal space-charge force in cyclotrons with a substantial duty factor.

2. FORMULATION

Using the azimuth θ as the independent variable,

THE MASS OF ^{25}Si AND THE ISOBARIC MULTIPLET MASS EQUATION*

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The mass excess of ^{25}Si has been measured as 3 832 ± 12 keV via determination of the Q-value for the ^{28}Si(^{3}He, ^{6}He)^{25}Si reaction. The results are used to test the isobaric multiplet mass equation for $A = 25$.

Precise measurements of the masses of neutron deficient $T_z = -3/2$ nuclei are essential to test the isobaric multiplet mass equation [1], since these nuclei have generally been the least accurately measured members of $T = 3/2$ isobaric quartets. The isobaric multiplet mass equation (IMME), $M = a + bT_z + cT_z^2$, (where $T_z = \frac{1}{2}(N - Z)$) relates the masses of isobars under the assumptions that the specifically nuclear properties of all multiplet members are identical, and that all charge dependent forces are two-body in character.

Recent measurements of the ^{9}C mass [2], and the ^{13}O and ^{21}Mg masses [3,4] have indicated that an additional term dT_z^3 ($d = 8.0 \pm 3.7$ keV)[2] is required for the IMME for $A = 9$, while for $A = 13$ and 21 the value of such a term is consistent with zero. This letter presents a new measurement of the mass of ^{25}Si and subsequent application of the IMME to the $A = 25$ isobars.

The value of the mass of ^{25}Si presented here was determined from the average of five individual measurements of the Q-value of the ^{28}Si(^{3}He, ^{6}He)^{25}Si reaction. This reaction was induced by 70 MeV ^{3}He ions from the Michigan State University sector-focused cyclotron, and the ^{6}He particles were momentum analysed in a split-pole magnetic spectrograph.

The ^{6}He energies from ^{28}Si(^{3}He, ^{6}He)^{25}Si were measured by comparing their magnetic rigidity to that of ^{6}He particles from the ^{12}C(^{3}He, ^{6}He)^{9}C (g.s.) reaction. The Q-value for the latter reaction is now well established [2]. A comparison was obtained by measuring the spectrograph magnetic fields necessary to get the ^{6}He particles from each reaction at the same position on the focal plane. The spectrograph field behavior relative to the flat field value given by the NMR has been carefully calibrated for previous (^{3}He, ^{6}He) work [5] with a momentum matching technique [6].

The scattering angle for each run was determined to an accuracy of $\pm 0.03^\circ$ at $\theta_L \approx 10^\circ$ by measuring the magnetic rigidity of ^{3}He from ^{1}H(^{3}He, ^{3}He)^{1}H scattering from a very thin formvar target. The ^{3}He beam energies were initially determined with the beam transport analysis system, and the final precise measurements made by comparing the magnetic rigidities of ^{6}He from the ^{12}C(^{3}He, ^{6}He)^{9}C (g.s.) reaction to that of elastic scattering of ^{3}He from ^{12}C. Since the charge-to-mass ratio of these particles is different, the ratio of their magnetic rigidities is sensitive to the beam energy. Beam energies were thus determined to ± 35 keV at $E \approx 70$ MeV.

Particle detection and identification at the spectrograph focal plane were accomplished with a 300 μm silicon surface barrier position sensitive detector operating in the dE/dx mode for all particles of interest [7]. Serious background problems due to particle induced reactions in the position sensitive detector were nearly eliminated by mounting an ordinary silicon surface barrier detector behind the position detector and operating these two detectors in coincidence. Figs. 1 and 2 show ^{6}He spectra from ^{28}Si(^{3}He, ^{6}He)^{25}Si with and without this coincidence requirement. Typical ^{6}He resolution was target-thickness limited at ≈ 70 keV FWHM.

The individual measurements of the ^{28}Si(^{3}He, ^{6}He)^{25}Si Q-value were -28 008 ± 14 keV, -27 985 ± 8 keV, - 27 980 ± 7 keV, 27 998 ± 10 keV, and -27 993 ± 8 keV. A weighted average of these values gives a ^{25}Si mass excess of 3 832 ± 12 keV. Uncertainties of ± 10 keV, ± 4 keV, and ± 3 keV due to uncertainties in target thickness,

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Neutron-Hole-State Structure in $N = 81$ Nuclei. I. ^{144}Sm and ^{142}Nd (p,d)†

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Angular distributions of deuterons from the (p,d) reaction (energy resolution ~35 keV) on ^{144}Sm and ^{142}Nd at $E_p = 35$ MeV have been measured and compared with distorted-wave Born-approximation (DWBA) calculations. The DWBA calculations were performed both with and without the finite-range and nonlocality corrections. In some typical cases corrections were also included for the nuclear density dependence of the effective pn interaction. The DWBA cross sections for $l = 5$ show an enhanced sensitivity to the inclusion of these corrections. Calculations including both the nonlocality and finite-range corrections yield acceptable spectroscopic factors. Considerable fractionation of the $(2d_{5/2})_n^{-1}$ and the $(1g_{7/2})_n^{-1}$ states is observed. No measurable population of neutron states in the $82 < N \leq 126$ major shell was observed. The single-neutron-hole energies (in MeV) are as follows: $d_{3/2}$, 0.0; $s_{1/2}$, 0.45; $h_{11/2}$, 1.22; $d_{5/2}$, 1.52; and $g_{7/2}$, 2.12 for ^{143}Sm; and $d_{3/2}$, 0.0; $s_{1/2}$, 0.43; $h_{11/2}$, 1.07; $d_{5/2}$, 1.47; and $g_{7/2}$, 2.20 for ^{141}Nd. Data on the systematics of splitting and movement of these single-neutron-hole states as a function of the proton number (Z) in ^{143}Sm, ^{141}Nd, ^{139}Ce, and ^{137}Ba shall be presented in a subsequent paper.

I. INTRODUCTION

Nuclei with 82 neutrons are expected to have a closed-neutron-shell structure. There is some evidence for this from previous (d,p) measurements[1-3] on targets with 82 neutrons. Another way of checking shell closure at $N = 82$ would be by looking for small occupation probabilities of supposedly vacant shell-model orbits ($2f$ and $3p$ in the present case) via neutron pickup reactions on $N = 82$ nuclei. If shell closure is found to be good in these nuclei, then one may hope that neutron pickup reactions will be a satisfactory means of obtaining information on the neutron-hole states in $N = 81$ nuclei. There have been some (p,d),[4] (d,t)[5,6] and decay-scheme studies[7-9] on isolated cases, but the information obtained is very limited and not backed by enough systematic data to determine reasonably accurate spins and parities and values of single-neutron-hole energies in the $N = 81$ mass region. The present work is the first in a series of measurements to provide such systematic data on the structure of neutron-hole states in $N = 81$ nuclei.

Since the protons are filling some of the same orbits as the neutrons, the present work also provides an opportunity for observing the effect on the binding energy of neutrons owing to the n-p interaction between protons and neutrons in the same shell-model orbits. Furthermore, since the protons in these nuclei do not form a closed or semi-closed shell, they can contribute to some low-lying collective core excitations. Such excitations however do not occur below 1.5 MeV of excitation energy in these nuclei, so that one expects the low-lying states in the $N = 81$ nuclei to be dominantly neutron-hole states. States at higher excitation energies however, may be expected to have appreciable core excitation components mixed in them, resulting in splitting of the single-neutron-hole states.

The following section describes the experimental arrangement used in the present work. Section III describes details of three types of distorted-wave Born-approximation (DWBA) calculations performed to determine the effect of various corrections on the shape and the magnitude of the predicted differential cross sections. In Sec. IV we present the experimental results, the computed values of single-hole energies and strengths, etc., followed by a discussion of these results.

II. EXPERIMENTAL PROCEDURE

35-MeV protons from the Michigan State University variable energy cyclotron bombarded targets of ^{144}Sm and ^{142}Nd and the reaction products were analyzed in a cooled and radiation shielded ΔE-E counter telescope. The counter telescope was also equipped with magnets for electron suppression so that with a combination of the aforesaid features and a proper choice of amplifier time constants, an over-all energy resolution of ~35 keV was achieved. Particle selection was accomplished by displaying ΔE vs E in a two-parameter analysis mode where the reaction products were sorted out by drawing polynomial fits around their respective curved bands using a data acquisition program TOOTSIE.[10]

The targets (see Table I for target data and (p,d) ground-state Q values[11]) were prepared in the cyclotron laboratory by evaporating isotopically enriched inorganic compounds from a graphite boat

Proposed Michigan State University trans-uranic accelerator facility

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Presented by H. Blosser

ABSTRACT

This paper briefly describes the design of a versatile facility for accelerating ions of every element to energies sufficient to produce nuclear reactions on any target. The design utilises a large six-sector ring cyclotron with ~40 kG m average bending capability for the main acceleration. The present MSU cyclotron would be the light ion (p, d, ^3He, ^4He) injector. A number of possible heavy ion injectors are discussed, the field trimming problem is reviewed and initial studies of resonance transitions are described.

1. INTRODUCTION

The possible existence of 'islands' of nuclear stability well beyond the region of presently known nuclei is a topic of great current interest to physicists and chemists.[1] The most likely production processes for such super-heavy nuclei appear to be transfer reactions between a massive projectile and a massive target, such as $^{238}U(^{238}U, ^{178}Yb)^{298}114$, etc. Due to the large coulomb repulsion, such a reaction will only take place at bombarding energies in the range of 6–9 MeV/nucleon which is well beyond the capability of present accelerators (assuming realistic values for the ion charge state). A number of groups are hence currently planning accelerators to produce the desired energetic ions–several of these are described in other papers at this session.

The major difference between the proposed MSU facility and those envisaged by other cyclotron groups is the much larger final stage cyclotron (40·7 kGm vs 29·4, 27·0, 26·5, etc.). This large final stage cyclotron can produce the required energy using ions in a much lower charge state (for Uranium 24+ is adequate vs 33, 36, 45, etc.). The costly heavy ion injector can therefore be smaller leading to a system which we believe to be less expensive in total and with a very elegant light ion capability as an important bonus (protons up to 600 MeV, deuterons to 360 MeV, etc.). The MSU plans also to give very serious consideration

The cyclotron and the computer: a look at the present and the future*

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ABSTRACT

This paper shows that current approaches to computer control are philosophically the same and that there is a second approach which the author hopes to see implemented in the future, since it offers advantages in both cost and flexibility. Some details of computer hardware and software are described because they are of importance to persons making long range decisions. At this time, without sophisticated systems of logging and analysis which future cyclotron control systems will have, it is not possible to forecast in detail the changes computer control will bring to beam quality; however, computer control will dictate more careful attention to the engineering details of beam defining and measuring devices.

1. FUNDAMENTAL CONTROL CRITERIA

Two basic and obvious principles have dictated all control systems whether computerised or not. (1) All important settings of cyclotron parameters must be available to the human operator at all times. (2) The operator must be able to alter those settings without introducing undesirable step changes.

These two criteria have been responsible for the complexities of current systems in which the computer is an appendage rather than an integral part of control systems. We cannot do away with these criteria, but we can alter the method of control to eliminate complexity and duplication of hardware.

2. GENERALISATION OF THREE BASIC CONCEPTS

It is important to note that initial setting up of an accelerator (before knob twiddling) is a digital process as far as the operator is concerned.

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Optimisation of the cyclotron central region for the nuclear physics user*

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ABSTRACT

Beam requirements for high quality nuclear physics experiments are reviewed along with features of central region arrangements for preferentially transmitting particles satisfying the requirements. With such a central region, phase widths of 1·5° can be achieved and such phase widths in conjunction with good stabilising circuits lead to highly monochromatic beams. (External beam energy spread 0·04% *FWHM* at MSU.) Such systems also give 100% extraction efficiency and high transmission through external analysis systems. (Total transmission of 20% at MSU for 1 in 6000 energy resolution and emittance of less than 1 mm mrad.)

1. INTRODUCTION

Modern nuclear physics is a science of detail in which significant experiments are concerned in almost every case with careful determination of the individual properties of particular nuclear quantum states. Such experiments require very monochromatic beams in order to separate close lying quantum states, with good collimation in order to precisely study spatial details of the states. Desired beam currents are generally modest–usually in the range 50–500 nA on target–the limitation on current coming in most cases from the data processing system. Frequently the nuclear characteristics of greatest interest are rare phenomena and the cleanness of the setup is of great importance in separating the desired results from background phenomena.

Relative to these nuclear physics requirements, the cyclotron in its normal condition is a very intense, rather imprecise beam source. This mismatch is generally corrected by means of a beam analysis system which transmits a precisely defined sub-section of the beam to the user. The remaining beam (typically 90–99% of the total) is stopped and in so doing intense radiation and residual acitivity are produced along with intense thermal heating, all of which lead to substantial problems. Moreover these problems are all in principle unnecessary–the external analysis system is selecting a certain volume in phase space which (as a result of the character of the equations of motion) must have

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The longitudinal space charge effect and energy resolution*

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1. INTRODUCTION

In the design of isochronous cyclotrons with distinctly separated turns at extraction, calculations of energy resolution are customarily based solely on considerations of the beam phase width, the rf voltage and its resultant wave form.[1] Machines of this type have been proposed which aim at 100 μA currents with an energy resolution of 10^{-3} or better, and it appears quite likely that the hitherto neglected longitudinal space charge effect will determine the actual current or energy resolution achievable in such cyclotrons.[2] The longitudinal space charge effect was first discussed by T. A. Welton who explained how this effect tends to destroy turn separation by increasing the energy spread within a turn.[3] Welton also pointed out that this effect could be alleviated by accelerating the beam off the peak of the rf wave.[4] More recently, W. B. Powell carried out approximate calculations which indicate that the longitudinal space charge effect could nevertheless still be very serious.[5] The present paper summarises an extensive analysis of the longitudinal space charge effect and provides formulas for calculating the resultant energy spread within a turn under certain conditions.

The MSU cyclotron has been operating successfully in a separated turn mode with 100% extraction for the past three years and therefore constitutes a real prototype for the 'separated turn isochronous cyclotron'. Recently, the phase selection technique used in this machine has been refined so that proton beams up to 10 μA can be obtained with a phase width of 1·4° *(FWHM)*.[6] This narrow phase width implies an energy resolution of: $\Delta E/E = 10^{-4}$ attainable under operating conditions computed to minimise this quantity at extraction.[7] However, the dee voltage has so far been regulated only to: $\Delta V/V = (2 \text{ to } 6) \times 10^{-4}$, so that this parameter restricts the energy resolution achievable in the external beam. Experimental measurements of the longitudinal space charge effect have recently been carried out for the first time in any cyclotron. Although these results are still preliminary, they demonstrate conclusively that the properly minimised energy resolution increases with beam current. The explicit calculations presented here are aimed toward accounting for these observations.

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Cyclotron beam pulser for particle time-of-flight experiments*

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ABSTRACT

The energy resolution in time-of-flight experiments performed on a cyclotron is limited by the reaction product flight times of approximately 60 ns associated with the beam microstructure. A scheme for eliminating $N-1$ out of every N micropulses from the external beam has been developed for the Michigan State University Cyclotron. The internal beam is stopped on a collimator on the first one-half turn by applying a d.c. voltage to a radially deflecting plate located in the dee between the ion source and collimator. A 60 ns wide pulse, synchronised with the dee voltage, but with $1/N^{th}$ the repetition rate cancels the d.c. deflection voltage allowing single micropulses through the collimator. Beam currents of 1 μA time-average have been obtained with pulse widths of 0·4 ns at one-tenth the rf repetition rate. By removing a set of phase selecting slits inside the cyclotron, time-average currents of 10 μA have been obtained at 10% duty cycle with pulse-widths of approximately 1·5 ns.

1. INTRODUCTION

Time-of-flight experiments require very short bursts of particles with long waiting periods between bursts. Cyclotrons produce such short beam pulses, but the repetition rates, typically of the order of 50–100 ns, are often too high. It is possible to eliminate some of the bursts by sweeping the beam across a collimator synchronously with the orbital frequency in such a manner that only one out of N micropulses pass through the collimator and reach the experimenter's target. This can be done in two ways: by blocking the external beam or by stopping the beam near the ion source. The former has the great disadvantage that the beam thrown away activates whatever it hits and

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High resolution nuclear studies using cyclotron beams*

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Presented by E. Kashy

ABSTRACT

Various types of nuclear experiments which require high resolution particle beams are described. Examples of the performance of the MSU Cyclotron in providing such beams are given. Proton beam currents of approximately 200 nA for $\Delta E/E = 1/6000$ resolution are easily obtained at $E_p \geq 25$ MeV with internal beam currents of only 3 μA. The role of dispersion matching is discussed and preliminary results using the laboratory broad range magnetic spectrograph are shown.

1. INTRODUCTION

The importance of high resolution beams and detection systems in the study of the nucleus has been apparent for many years, especially in nuclear spectroscopy, i.e. the classification of nuclear levels, their excitation energies, decay properties, spin, parity, etc. More recently high resolution beams have proved to be essential in certain aspects of the study of isobaric analogue levels. Up to now these studies have been the exclusive domain of electrostatic accelerators, mostly the Van de Graaff type, which have in many ways the most desirable beam properties. In this paper it is shown that cyclotrons like the MSU sector focused cyclotron when used with a highly dispersive beam analyser such as the one presently in use in the MSU Cyclotron Laboratory[1] can compete successfully in a field previously reserved to electrostatic machines, and in some instances improve upon such machines.

2. TYPES OF EXPERIMENT

We can divide the high resolution experiments into two broad types: (a) where energy resolution is required on target and (b) where energy resolution of reaction products is desired. An example of the first requirement is the reaction:

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THE ISOBARIC MASS EQUATION IN $A=4n+1$ NUCLEI

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The parameters of the isobaric mass equation are calculated for the $T=3/2$ multiplets in $A=4n+1$ nuclei, for $n=2$ to $n=10$.

In first order perturbation theory the masses of an isobaric multiplet with isospin T are given by an equation quadratic in T_z [1,2,3]

$$M(\alpha, T, T_z) = a(\alpha, T) + b(\alpha, T)T_z + c(\alpha, T)T_z^2 \qquad (1)$$

where α includes all charge independent quantities.

The difference in the masses of the lowest two members of the multiplet gives the so-called Coulomb displacement energy $-E_d$.

$$E_d = -(b(\alpha, T) - c(\alpha, T) \times (N-Z-1) + \Delta_{np} \qquad (2)$$

where N and Z are the number of protons and neutrons in the lowest member of the multiplet, and Δ_{np} is the neutron proton mass difference.

A great deal of effort has been put into measuring Coulomb displacement energies from Isobaric Analog Resonance experiments. The main contribution to E_d is linear in the excess neutron distribution [4,5] $\rho^{exc}(r)=\rho^n(r)-\rho^p(r)$ and therefore E_d is a source of information concerning neutron density distribution in nuclei. However, the investigation of the excess neutron distributions in medium and heavy mass nuclei via Coulomb displacement energies is hampered by the fact that only the energy of the first two members of the multiplet is determined. So far no experiment has been performed which located a third member of an isomultiplet in nuclei with $A > 40$.

In light mass nuclei ($A < 40$) several high precision experiments have been performed in which more than two members of a multiplet were found [3,6]. In particular, all four members of several $T=3/2$ multiplets have been observed and their masses measures [3,6-11]. One of the important results of these experiments is that the mass equation (1) is very well obeyed and terms proportional to T_z^3 are smaller than experimental uncertainties [8,10]. Only the $A=9$ quartet shows deviations from eq.(1) greater than the experimental uncertainties, and there the coefficient of the T_z^3 term is very small, only 8.0 ± 3.7 keV [9].

Another consequence of measuring the masses of the entire $T=3/2$ multiplet is the determination of the parameter c. In addition to b (or E_d) we have now to our disposal a second parameter which can be used to study density distributions in nuclei. For example, one may ask the question whether it is possible to reproduce the values of both b(or E_d) and c using the same set of wave functions for nucleons outside an $N=Z$ core.

In the present work an attempt is made to calculate b and c using for both the same set of wave functions. We consider the $T=3/2$ multiplets in nuclei with mass $A=4n+1$, for $n=2$ to 10. The masses of the four members of the quartets for $A=9$, 13, 17, 21, 25 and 37 have been measured [3,6-11]; and the parameters a, b and c determined. In table 1 the experimental results for b and c are summarised. For $A=29$, 33 and 41 only the displacement energies are known experimentally [6,12].

The calculation of the displacement energies is performed using the methods outlined in ref. [5]. The main contribution to E_d is the so-called direct term [4,5] given by:

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Calculations with a $1s, 0d$ Shell Model for $A = 34$–38 Nuclei*

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Results are presented of calculations made in the full space of [illegible]-shell-model wave functions for positive-parity states in the nuclei with $A = 34$–38. We [illegible] employed in this work several different effective Hamiltonians, some of which had two-body parts obtained by reaction-matrix techniques from the Hamada-Johnston scattering potential. The observables calculated were energy-level spectra, single-nucleon spectroscopic factors, and $E2$ and $M1$ moments and transition strengths. These calculations yield fair-to-good agreement with many of the observed nuclear-structure data in this mass region.

I. INTRODUCTION

This paper presents the results of shell-model calculations for positive-parity states of nuclei with mass numbers $A = 34$ through 38. The model vector space is defined by a complete set of many-particle basis states for $A - 16$ nucleons distributed among the three single-particle orbits $0d_{5/2}$, $1s_{1/2}$, and $0d_{3/2}$. The model core is $(0s)^4(0p)^{12}$. The two-body parts of most of the Hamiltonians which we use in this space are derived by reaction-matrix techniques[1] from the Hamada-Johnston nucleon-nucleon scattering potential.[2] Following the current terminology, we shall refer to such Hamiltonians as "realistic."

One purpose of our work was to test how well the experimentally determined properties of $A = 34$–38 nuclei could be reproduced by using currently available realistic interactions. Our present $A = 34$–38 study is the natural extension of a similar study made earlier for $A = 18$–22.[3,4] As tests of a realistic interaction, the $A = 18$–22 and $A = 34$–38 projects differ in that they emphasize different aspects of the interaction. For $A = 18$–22, the model nuclear wave functions tend to be dominated by components in which all active nucleons occupy the $0d_{5/2}$ and $1s_{1/2}$ orbits. Thus for $A = 18$–22, the one- and two-body matrix elements of the effective Hamiltonian which are most important (and most severely tested) are those involving only the $0d_{5/2}$ and $1s_{1/2}$ orbits, while matrix elements involving only the $0d_{3/2}$ orbit are less important. But in the $A = 34$–38 region, where the $0d_{5/2}$ orbit is "effectively" filled for most low-lying states, matrix elements which involve the $0d_{3/2}$ and $1s_{1/2}$ orbits are the most important. Thus, studies of the $A = 18$–22 and $A = 34$–38 regions complement each other as tests of realistic interactions designed for use in $(1s, 0d)^{A-16}$ shell-model calculations.

Techniques for calculating realistic shell-model effective interactions are far from perfect[5,6]; but they have improved since the time we calculated realistic interactions for this $A = 34$–38 study, and presumably they will be improved further in the future. We realized at the start of this project that there would be uncertainties and imperfections in any particular realistic Hamiltonian that we could obtain, and for that reason we decided to examine the shell-model results from several alternative Hamiltonians. We have used four different realistic effective interactions, calculated in four slightly different ways, and with each of these realistic interactions we have tried two alternative sets of single-particle energies. In addition, we have used some two-body interactions of a considerably different character, i.e., interactions derived from considerations other than nucleon-nucleon scattering data. All in all, we have calculated shell-model results from 10 different $(1+2)$-body effective Hamiltonians.

In this paper we shall compare these alternative sets of shell-model results with each other and with experimental data. These comparisons offer some information about the probable characteris-

Neutron-Hole-State Structure in $N = 81$ Nuclei. II. ^{140}Ce and ^{138}Ba(p, d)†

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In continuation of our program of neutron-hole-state studies in $N=81$ nuclei, angular distributions of deuterons from (p,d) reactions (energy resolution ~35 keV) on ^{140}Ce and ^{138}Ba at $E_p=35$ MeV have been measured and compared with distorted-wave Born-approximation calculations including finite-range and nonlocality corrections. These calculations yield acceptable spectroscopic factors and are in fair agreement with the shapes of the experimental angular distributions. The neutron-single-hole energies have been determined. These energies (in MeV) are $d_{3/2}$, 0.0; $s_{1/2}$, 0.33; $h_{11/2}$, 1.07; $d_{5/2}$, 1.72; and $g_{7/2}$, 2.90 for ^{139}Ce; and $d_{3/2}$, 0.0; $s_{1/2}$, 0.54; $h_{11/2}$, 1.07; $d_{5/2}$, 1.71; and $g_{7/2}$, 2.93 for ^{137}Ba.

Considerable fractionation of the $(2d_{5/2})_\nu^{-1}$ and the $(1g_{7/2})_\nu^{-1}$ states is observed while the $(1h_{11/2})_\nu^{-1}$ and the $(3s_{1/2})_\nu^{-1}$ states are each observed to split mostly into two components. Systematics of the energies and strengths of the various neutron-single-hole states and their components are presented for all $N = 81$ nuclei from ^{137}Ba through ^{143}Sm and the significance of the systematics discussed. No measurable population of any neutron state in the $82 < N \leq 126$ major shell has been observed.

I. INTRODUCTION

In a previous paper[1] (henceforth referred to as Paper I) we reported our results on the analysis of (p, d) measurements on the $N=82$ nuclei of ^{144}Sm and ^{142}Nd[1] together with a study of the effects of different values of lower cutoff, finite-range and nonlocality (FRNL) corrections, and density dependence of the effective pn interaction on the shapes and magnitudes of distorted-wave Born-approxima-

THE STRUCTURE OF THE LIGHTER $N = 82$ NUCLEI*

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Shell-model predictions for nuclei which can be characterized as 1, 2 and 3 protons outside the doubly-magic $N = 82$, $Z = 50$ core give a good accounting for recently discovered features of ^{133}Sb, ^{134}Te and ^{135}I.

Recent advances in experimental techniques have made possible the quantitative study of the lighter-mass nuclei having 82 neutrons [1-4]. Spectra have been obtained for ^{133}Sb, ^{134}Te and ^{135}I; these nuclei correspond respectively to one, two and three protons outside the $Z = 50$, $N = 82$ doubly-magic ^{132}Sn core. The properties of these systems are interesting because their presumed simplicity should permit a relatively unambiguous delineation of the various facets involved in nuclear structure phenomena. The nuclei around ^{208}Pb have been extensively studied in this same spirit in order to extract such quantities as effective charges and effective g-factors. Next to the ^{208}Pb neighborhood, the $N = 82$ region may well exhibit the best "closed shell" behavior available to us. In addition, the $N = 82$ region provides what the lead region does not, namely a long string of nuclei (14 have been studied at present) built by adding protons to the doubly-magic core. Thus for $N = 82$ we will have the opportunity to pursue the consequences of our deductions based on the simple, "few" nucleon systems through a series of "many" nucleon systems.

Actually, of course, because of the accidents of nuclear stability, the situation has been reversed in the $N = 82$ region. The naturally stable, many-proton, systems have been extensively investigated, both experimentally and theoretically, for some time, while the few-proton nuclei have just begun to be studied. In this note we present theoretical predictions for the structure of the $Z = (50 + 1, 2, 3$ and $4)$, $N = 82$ nuclei and compare these results to the presently available experimental data.

* Research supported in part by the National Science Foundation.

Our predictions for ^{133}Sb, ^{134}Te and ^{135}I are based on previous shell-model calculations for heavier $N = 82$ nuclei [5]. These calculations employed an MSDI residual interaction [6,7] and a model space comprised of all $0g_{7/2}$ - $1d_{5/2}$ configurations plus all configurations formed by exciting one particle from the $0g_{7/2}$ - $1d_{5/2}$ subspace to either a $2s_{1/2}$ or $1d_{3/2}$ orbit. In our initial work [5] we chose values for the SDI strength and for the single-particle-energy (SPE) splittings which optimized agreement between model and experimental excitation energies for all known positive-parity $N = 82$ states in $A = 136 - 146$ inclusive. Subsequently, because the model space is most appropriate for the lighter $N = 82$ nuclei, we readjusted the SDI strength and the SPE splittings to optimize agreement only for $A = 136 - 140$. The significant change which results from the new approach is an increase, from 0.48 MeV to 0.88 MeV, of the $0g_{7/2}$ - $1d_{5/2}$ SPE splitting. (In all of this work we have employed the shell model computer codes described by French, Halbert, McGrory and Wong [8]).

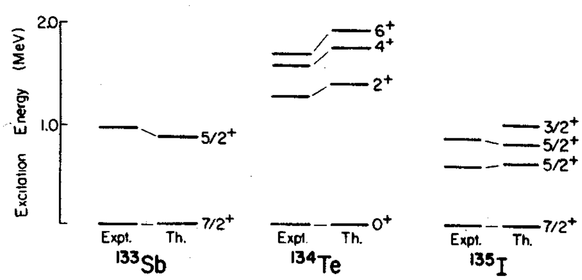

Fig. 1. Calculated and experimentally inferred spectra of the nuclei ^{133}Sb, ^{134}Te and ^{135}I.

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Structure of Nuclei with Masses $A = 30$–35, as Calculated in the Shell Model

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Properties of positive-parity states of nuclei with $A = 30$–35 have been calculated in a shell-model space which encompasses all Pauli-allowed basis vectors of all configurations $(0s)^4(0p)^{12}(0d_{5/2})^{n_1}(1s_{1/2})^{n_2}(0d_{3/2})^{n_3}$ for which $n_1 \geq 10$. Two different empirical Hamiltonians, one of a δ-function form, were used. Calculated energies and spectroscopic factors are in good agreement with an extensive body of experimental data. The model wave functions also yield satisfactory agreement with many available experimental data on electric quadrupole observables if effective charges of $0.5e$ are added to the proton and neutron. The model predictions for magnetic dipole observables are generally in qualitative agreement with experimental observations, but inconsistencies between theory and experiment are more noticeable in this area.

I. INTRODUCTION

This paper describes the results of a series of shell-model calculations which have been carried out in an attempt to understand the structure of energy levels in nuclei of $A = 30$–35. The properties of these nuclei present an attractive challenge to theoretical interpretation in that experimental information[1] about spins and parities of observed levels in this mass region is extensive and there are also many data on lifetimes, spectroscopic factors, and the like. Thus, any theory for these nuclei can be critically examined with unusual thoroughness.

Despite all this experimental activity, there have been relatively few theoretical investigations of these nuclei. This probably results from the fact that experimental phenomena typical of the region do not readily yield to analysis by the simplest forms of any of the popular models for describing nuclear structure. The level structures of $A = 30$–35 do not exhibit obvious rotational features to the extent found, for example, in $A = 20$–25. Thus, the most straightforward Nilsson-type calculations for nuclei with $A \geq 30$ are not as successful as for the lighter nuclei of the *sd* shell.[2] However, more involved calculations of this kind have successfully accounted for some properties of individual nuclei.[3] Similarly the simplest kind of weak-coupling vibrational calculation meets with little success in this region,[4] although recent, more sophisticated intermediate-coupling calculations[5] appear promising.

A detailed shell-model calculation of the structure of these nuclei was first made by Glaudemans and his co-workers[6] in a study which assumed an inert ^{28}Si core and active $1s_{1/2}$ and $0d_{3/2}$ orbits. They treated all nuclei from $A = 29$–40, but the results obtained for the lighter nuclei were obviously impaired in some respects by the omission of an active $d_{5/2}$ orbit. This region was also studied via shell-model methods as part of a general survey of the *sd* shell by Bouten, Elliot, and Pullen.[7] By making simplifying assumptions about the Hamiltonians and the wave functions, they were able to include effects of some excitations out of the $d_{5/2}$ orbit. However, they presented and discussed only energy-level spectra.

The results of previous calculations, and examination of the experimental data, strongly suggest that any conventional shell-model calculation for the $A = 30$–35 region should allow some excitation out of the $d_{5/2}$ orbit. As we shall discuss further below, there are no obvious indications from experiment that the orbits of the $0f$-$1p$ shell are necessary for an adequate description of the properties of the low-lying positive-parity states in the $A = 30$–35 region. We have accordingly studied the properties of these nuclei by means of a conventional shell-model calculation in a vector space which includes basis states with particles in the $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$ orbits. We shall show that a

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PREPARATION OF THIN FILM DEPOSITS FROM BIOLOGICAL, ENVIRONMENTAL AND OTHER MATTER*

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A technique for preparing uniform thin film deposits (10–1000 $\mu g/cm^2$) of practically all materials of biological, environmental and nuclear physics interest is proposed. The technique involves preparing a solution or colloidal suspension of micron size particles of the substance of interest, generating a nebulized (practically invisible) mist from this liquid and condensing the mist on a rotating substrate. The cost in time and money for several materials is minimal.

1. Introduction

In the elemental analysis of materials employing nuclear reaction and scattering techniques[1–3]), it is necessary to prepare the sample in the form of a thin film (10–1000 $\mu g/cm^2$). For metallic samples and some of their inorganic compounds the technique of vacuum evaporation is commonly employed. However, for biological and environmental samples a new technique is needed. In the section below we describe a technique that enables one to prepare thin film deposits from such diverse materials as mineral and rock samples, animal tissue, blood and soluble salts using relatively inexpensive equipment. In certain materials like a whole fish, the uniformity of the deposit depends on the uniformity and size of the particles in the colloidal suspension that is prepared.

2. Preparation and deposition

Any material to be deposited must be first reduced to a solution or a suspension of microscopic particles ($\approx$1–10 μm) in an inert solvent (pure water is best for most materials). Table 1 gives a listing of the techniques used by the authors towards accomplishing this objective. The suspended or the dissolved material is placed in the container shown in the apparatus, called a nebulizer[5]), in fig. 1. The compressed gas (preferably inert) forces the liquid through a small hole (at the top of the tube partially immersed in the liquid) in the form of a high-speed spray which in turn impinges on an obstruction and thus breaks up into droplets of various sizes. The finest of these droplets are swept along by the gas escaping out of the nozzle. These droplets are so fine that they are not visible to the unaided eye. Illuminating the mouth of the nozzle reveals a cloudy mist (hence the name nebulizer) but the individual droplets are still not seen. The nebulized mist is then allowed to deposit on a rotating substrate. By mounting the nebulizer bottle on a stand that performs a slow up and down (or sideways) oscillatory motion such that all parts of the substrate receive the mist for the same length of time, a very uniform deposit can be obtained. The microscopic size of these droplets is crucial to the success of this method in obtaining a thin uniform

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TABLE 1
Reduction of biological, environmental and other matter to a solution or colloidal suspension.

Class of materials	Technique for reduction
1. Animal tissue, plants, etc.	Slow freezing to rupture the cells followed by 1) reduction to a liquidized form by a high-speed blender (e.g. Waring Scientific Blender, 15000 rpm model), and 2) immersion of an ultrasonic probe in the liquidized sample for several minutes (length depending on the quantity and type of material).
2. Blood, milk, etc.	Sonication with an ultrasonic probe if necessary to break up the individual cells (25–50 μm). In some applications (proton scattering, X-ray fluorescence) these substances may be deposited without any sonication.
3. Rock, dry wood, etc.	Grinding in a tungsten carbide mortar and pestle or a micronising mill[4]) and subjecting a paste of the material to sonication (with an ultrasonic source) if necessary.
4. Beverages and soluble materials, etc.	May be simply dissolved or diluted in pure water before deposition.

SPREADING OF THE GIANT DIPOLE: A SIMPLE ESTIMATE*

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The spreading width of the nuclear giant dipole state is related to the damping width of single-particle states, using the long-wavelength approximation. We find $\Gamma_{\text{dipole}} = \frac{4}{9}\Gamma_{\text{single-particle}}$.

One of the interesting parameters of the nuclear giant dipole resonance is the width of the state. In heavy nuclei, the width is due primarily to the mixing of the state with other configurations; particle and gamma decay widths are relatively small. Estimates of the spreading width have generally involved complicated microscopic calculations [1]. These yield detailed strength functions, but do not indicate the qualitative trends or give a gross description of the spreading.

Since the dipole state is well described by a particle-hole wavefunction, why is not the width given by the single-particle spreading widths of the particle and the hole? The answer is that there is a coherence between particle and hole which reduces the off-diagonal matrix elements responsible for the spreading.

This is a well-known phenomenon in the theory of the electron gas, occurring in the theory of the plasmon excitation [2]. The plasmon is a collective particle-hole excitation which can decay by two mechanisms:

(1) If some uncorrelated particle-hole states are degenerate with the plasmon, it will spread into these (Landau damping).

(2) The state can always decay into 2p-2h states, but the probability is proportional to the square of the momentum carried by the plasmon [3]. In the long wavelength limit, particle and hole contribute an equal and opposite amplitude to the decay to any given 2p-2h state.

We will estimate the spreading of the nuclear giant dipole state into 2p-2h states in the corresponding limit. The assumption of a long wavelength for the dipole excitation implies that there will be a perfect correlation between particle and hole matrix elements. The accuracy of this is to order $(a/R)^2$, where a is the range of the effective interaction and R is the size of the nucleus. Because of the differing isospin structure of the particle and hole matrix elements, there will be some decay into 2p-2h states even in the long wavelength limit. We also need to assume that the excitation energy of the giant dipole is large compared to single-particle energies, in order to neglect phase-space considerations in the intermediate states. We also neglect the spreading due to the single-particle structure. This has been shown to play a large role in light nuclei [4] and in deformed nuclei [5], but does not seem to be important in heavy spherical nuclei.

We first derive an expression for the damping of a single-particle state, then derive the corresponding expression for the damping of the correlated particle-hole state. Taking the ratio of the two dampings, all the details of the nuclear structure will cancel out. The principle assumption in calculating the single-particle spreading is that it damps by creating $S = 0$, $T = 0$ particle-hole pairs. Only for these quantum numbers is the energy of the particle-hole state low enough to give a high density of 2p-1h states degenerate with the single-particle state. The matrix element connecting these states is

$$\langle \mathrm{p}|V|\mathrm{p}(\mathrm{ph}^{-1})^{S=0}_{T=0}\rangle = \sum_{s,t} \sqrt{\frac{2s+1}{2}}\sqrt{\frac{2t+1}{2}}\, U(\tfrac{1}{2}\tfrac{1}{2}\tfrac{1}{2}\tfrac{1}{2};s\,0)\, U(\tfrac{1}{2}\tfrac{1}{2}\tfrac{1}{2}\tfrac{1}{2};t\,0)\, V_{st} = \tfrac{1}{8}(V_{00}+3V_{10}+3V_{01}+9V_{11}) \quad (1)$$

where V_{st} labels the spin and isospin quantum numbers of the interaction in particle-particle coupling. The giant dipole state we treat as a $T = 1$, $S = 0$ particle-hole excitation. The 2p-2h states important for damping would thus have a

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Shapes of Angular Distributions in the Reaction ^{89}Y(^{3}He,t)^{89}Zr to Antianalog and Other $T_<$ States*

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The reaction ^{89}Y(^{3}He,t)^{89}Zr to $T_<$ states in ^{89}Zr shows that the angular distributions have shapes characteristic of nonallowed L transfers and are in disagreement with microscopic predictions. The antianalog states appear not to be unique in possessing this feature.

I. INTRODUCTION

The (^{3}He, t) charge-exchange reaction has served in recent years as a useful spectroscopic tool in determining the spins and parities of states in many odd-odd nuclei. Since angular distributions with transitions to states of the same J^π seemed to be nearly identical,[1] values of J^π in the residual nucleus were assigned by comparing the shapes of the experimental angular distributions with those of transitions to known states. Also, distorted-wave Born-approximation (DWBA) calculations, with the inclusion of a tensor term[2] in the effective interaction to account for transitions to unnatural-parity states, have appeared to be quite successful in fitting the data. This agreement between calculations and data has also been obtained in cases where there is a difference in the angular-distribution shapes for transitions to different states having the same spin and parity within the same nucleus.[3] Recently, however, ambiguities have been noted[4] in (^{3}He, t) reactions with the observation that angular distributions for 0^+ to 0^+ transitions to antianalog states in ^{40}K and ^{64,66}Ga were not fitted by the calculated $L=0$ angular momentum transfer shape as expected, but by $L=1$. Transitions to 0^+ isobaric analog states in these nuclei, however, were well fitted by an $L=0$ shape. Recent examinations of other charge-exchange results[5] for transitions to $T_<$ states (states with iso-

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CORE POLARIZATION EFFECTS IN (p,p') REACTIONS*

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Let me remark first of all that, regardless of the status of its theoretical description at any moment, core polarization is a well established experimental phenomenon, or rather is well established in the interpretation of experimental phenomena in terms of a microscopic model, i.e. the shell model, in an extended version or otherwise. A typical example is the interpretation of electromagnetic transitions, in terms of effective charge. The effective charge is the bare charge of a nucleon, +1 for a proton, 0 for a neutron, plus the polarization charge. Typically for an E2 transition, as the shell model basis becomes larger, and the calculation increases in complexity, the polarization charge needed to fit experiment decreases but usually more and more slowly, until when the limits of present computing are reached, it still remains at ~0.5e. Figure 1 shows such an example taken from calculations in the s-d shell.[1]

Here the polarization charge Δe required to match experimentally observed E2 transitions in ^{33}S is shown as a function of the average number of basis states, N, in the wave functions corresponding to three models III, II and I in which the shell model basis is successively enlarged (A). Figures B and C show the same effect in a different representation. Curve 1 plots the polarization charge Δe versus neglect of components in the wave function with amplitudes less than x and curve 3 plots the average number of configurations corresponding to this neglect. It is seen that with only a few basis states, with a corresponding neglect of components with amplitudes less than 0.1, the polarization charge is ~1-1.2. Increasing the number of basis states to ~100 brings down the polarization charge required to 0.4, with the corresponding inclusion of a large number of amplitudes of the order ~1%.

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THE EFFECTIVE TWO-NUCLEON INTERACTION FROM INELASTIC PROTON SCATTERING*

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Since inelastic scattering cross-sections depend on a nuclear matrix element containing both the wave functions of the nuclear states involved and the effective interaction V_{eff} between the projectile and the target nucleons,[1] it is necessary to have an a priori value for V_{eff} before one can use inelastic scattering as a tool for nuclear spectroscopy. An approach to determining V_{eff} which I will explore in detail in this paper, is entirely empirical in nature. One examines transitions where the wave functions are well known and adjusts the strength of the two-body interaction to fit the observed cross-sections. If the results for a representative sample of cases are consistent one has obtained a workable interaction for spectroscopic studies.

This approach was tried by Satchler[2] in his early studies of inelastic scattering, but was unsuccessful for reasons which we now understand fairly well. The major difficulty was that the states involved were collective in nature so that the cross sections were greatly enhanced. On the other hand,only simple wave functions were used in the theoretical calculations, so single-particle-size cross sections were predicted, and when the two-body potential was adjusted to fit the measured cross sections, the resulting potential was unphysically large. Since the collective enhancement depends on the nucleus, the state involved, and the angular-momentum transfer (L) of the transition, the effective interaction obtained was also nucleus, state and L dependent. In addition the calculations neglected exchange contributions which depend on L and the bombarding energy,[1] and again the empirical V_{eff} mirrored this dependence. For these reasons it was not possible to find a consistent effective-interaction for the strong, spin independent part of the force. Studies[2-9] of L=0 transitions involving spin-flip or isospin-flip were more successful

PERTURBATIVE TREATMENT OF COLLECTIVE PARTICLE-HOLE STATES IN ^{40}Ca AND ^{48}Ca *

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The effects of ground state correlations and core polarization have been included in the effective particle-hole interaction and transition moments by second order perturbation theory. Energy levels and transition probabilities of 3^- collective states in ^{40}Ca and ^{48}Ca were calculated in Tamn-Dancoff approximation and compared with the results obtained by using the random phase approximation.

Considerable success has been achieved by Gillet et al. [1] in describing negative parity collective excitations in closed shell nuclei by means of a simple particle-hole model with ground state correlations taken into account via the RPA. The ground state correlations so treated consist of multiple excitations within the single particle and hole configurations originally picked for the description of the state (model space), and give, compared with the TDA calculations in the original model space, a large energy shift and an increase in collectivity as measured, for instance, by the BE3 of a 3^- state. However, the calculations used a force whose parameters were fixed by comparing calculations with experiment. On the other hand, if one wants to use a realistic force, then other types of correlation have to be taken into account, i.e. core polarization. The effect of core polarization has been found to be very important [2-4] for the particle-particle nuclear effective interaction. Kuo [5] did similar calculations for the particle-hole case using RPA and including core-polarization by perturbation. The results of the calculations were very sensitive to the way the core-polarization effects were taken into account, though some of the variations were due to an incorrect choice of backward going graphs in RPA. Similar calculations have been done by Dieperink [6]. This method treats one type of correlation - core polarization, by perturbation theory, and another - ground state correlations, by a different approximation, the RPA.

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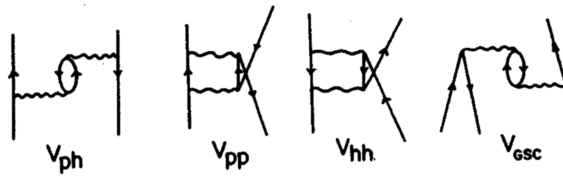

fig.2.

The present calculation compares the results of treating both effects perturbatively with the results of RPA, taking the collective 3^- states at ^{40}Ca and ^{48}Ca as an example. In perturbation theory both the effective interaction and effective transition operator have to be calculated. The effective interaction is calculated from the diagrams of fig. 2. V is the bare force, in this case Sussex matrix elements [7], $V_{2p\text{-}2h} = V_{ph} + V_{pp} + V_{hh}$ the lowest order core polarization contributions involving energy dominators $2\hbar\omega$. V_{GSC} gives the effect on the interaction of ground state correlations via 3p-3h intermediate

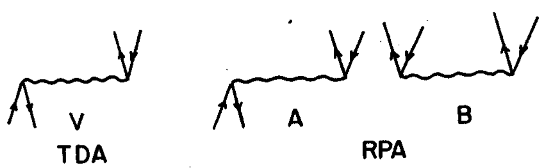

fig.1.

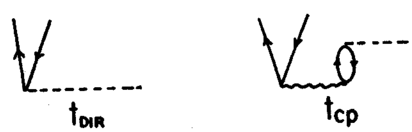

fig.3.

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CALCULATION OF THE $^{12}C+\alpha$ CAPTURE CROSS SECTION AT STELLAR ENERGIES*

By F. C. Barker†

[Manuscript received 26 July 1971]

Abstract

The $^{12}C(\alpha,\gamma)^{16}O$ cross section is calculated at stellar energies, using R-matrix parameters obtained by fitting consistently the $^{12}C+\alpha$ scattering phase shifts and the α-spectrum from ^{16}N β-decay. This limits the $^{12}C+\alpha$ channel radius to the range 5–7 fm. The S-factor at $E_\alpha = 400$ keV is calculated to lie in the range $0\cdot05$–$0\cdot33$ MeV . b.

I. Introduction

The cross section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction at α-particle energies of the order of a few hundred keV is of interest for theories of nucleosynthesis in stars. Direct experimental measurement of the cross section is not feasible below a few MeV, so that an indirect determination is necessary. The assumption usually made is that the main contributions are from the known 1^- levels of ^{16}O at $7\cdot12$ MeV (46 keV below the $^{12}C+\alpha$ threshold) and $9\cdot59$ MeV, and the greatest uncertainty comes from the value of the α-particle dimensionless reduced width θ_α^2 of the $7\cdot12$ MeV level.

Previous estimates of θ_α^2 have differed widely. A theoretical estimate by Stephenson (1966) based on models for the 1^- and 3^- levels of ^{16}O gave $\theta_\alpha^2 = 0\cdot08\pm0\cdot04$.‡ Experimental estimates have been made by various methods:

(1) Stripping reactions. From the $^{6}Li(^{12}C,d)^{16}O$ reaction Loebenstein *et al.* (1967) obtained $\theta_\alpha^2 = 0\cdot06$–$0\cdot14$,‡ while from $^{12}C(^{7}Li,t)^{16}O$, Pühlhofer *et al.* (1970) gave $\theta_\alpha^2 = 0\cdot025$‡ with the suggestion that this may be too low by a factor of $1\cdot5$ or 2. Dolinsky, Turovtsev, and Yarmukhamedov (1970) have pointed out some difficulties in obtaining reliable estimates in this way.

(2) Analysis of the $^{12}C+\alpha$ elastic scattering p-wave phase shift. With the energy dependence of the phase shift represented by a many-level R-matrix formalism, Clark (1969) obtained $\theta_\alpha^2 = 0\cdot71^{+0\cdot37}_{-0\cdot18}$, while a Caltech group (Weisser, Morgan, and Thompson 1970) found for θ_α^2 a very small value (Thompson, personal communication) with a large uncertainty. This is because θ_α^2 is involved in both the incoming and outgoing channels so that the $7\cdot12$ MeV level contributes little to the phase shift.

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‡ These estimates are all appropriate to a $^{12}C+\alpha$ channel radius of $1\cdot40(A_1^{⅓}+A_2^{⅓})$ fm $= 5\cdot43$ fm, as they were normalized by comparing reduced widths for higher ^{16}O levels with those obtained by Hill (1953) and Bittner and Moffat (1954).

THE PICKUP-STRIPPING MECHANISM FOR INELASTIC AND QUASI-INELASTIC SCATTERING

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The (h,t) reaction can be dominated by the formation of an intermediate alpha-particle cluster. This process accounts for the relatively large cross sections for high spin transfer and the $L = 1$ shape of some $0^+ \to 0^+$ transitions.

The general assumption for the (h,t) reaction mechanism is that the reaction proceeds through the charge-exchange part of the two-body nucleon-nucleon interaction [1]. However, serious discrepancies [2,3] have been seen when comparing the predictions of this model with experiment. The calculated [2] cross sections are too weak by factors from 2 to 500, the difference increasing almost exponentially with increasing spin transfer. The most striking discrepancy is the breakdown of commonly accepted selection rules for inelastic or quasi-inelastic scattering: Hinrichs et al. [3] observed an $L = 1$ shape instead of $L = 0$ for some $0^+ \to 0^+$ transitions to antianalogue states.

As proposed earlier [4] these reactions should be described by an additional mechanism which is the pickup of a particle, forming an intermediate alpha cluster, followed by stripping. In second order perturbation theory, the corresponding transition matrix is:

$$T^{(2)} = \frac{1}{(2\pi)^3} \int \mathrm{d}k \sum_n \langle \mathrm{t}^{(-)} A^* | V | \alpha (A-1)_n \rangle \times \frac{1}{E - E_n^{A-1} - E_\alpha + \mathrm{i}\epsilon} \langle \alpha (A-1)_n | V | \mathrm{h}^{(+)} A \rangle \quad (1)$$

where A and $(A-1)_n$ denote the nuclear states with A and $A-1$ particles, and t, h, and α denote the internal and optical wavefunctions of the projectile. If in addition we assume that all the states $(A-1)_n$ containing large components of a hole in the j-shell coupled to A have about the same energy E_n^{A-1}, $T^{(2)}$ becomes:

$$T^{(2)} = D_0^2 \sum_{jj'} \langle A^* | a_{j'}^+ a_j | A \rangle \langle \mathrm{t}^{(-)} \varphi_{j'} | G | \mathrm{h}^{(+)} \varphi_j \rangle \quad (2)$$

where G is the α-particle Green function, and D_0 is the one-particle transfer strength [5].

It may be seen from eq. (2) that the second order (hα), (αt) process is sensitive to exactly the same correlations between the ground and excited states as the direct (h,t) process, and may therefore be expected each time a direct (h,t) transition occurs. However, the effective interaction, $D_0^2 G$, has a nonlocality characteristic of the alpha propagation, which is much longer than the nonlocality inherent in the two-body interaction. Similar arguments could be used in favor of the formation of an intermediate deuteron. However, the coupling constant D_0 is substantially smaller in this case. We neglected the (hd), (dt) process in the computation below, although further investigations in this direction are planned.

To understand the origin of the $L = 1$ angular distribution to antianalogue states, consider the transition density for exciting the analogue state (IAS) and the antianalogue state (AAS) from the parent ground state. In ^{40}Ar, these two states are described as $[d_{3/2}^{-2} f_{7/2}^2]_{T=2}$ and $[d_{3/2}^{-2} f_{7/2}^2]_{T=1}$, respectively. Two single-particle transition den-

‡ Most of this work was done in Summer 1971 while both authors were at Michigan State University, supported by a grant from the National Science Foundation.

PHYSICAL REVIEW C VOLUME 5, NUMBER 2 FEBRUARY 1972

(p, t) Reaction on Even-Even $N=Z$ Nuclei in the $2s1d$ Shell*

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The (p,t) reaction on the even-even $N=Z$ nuclei in the $2s1d$ shell has been used to study the energy levels of ^{18}Ne, ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar, and ^{38}Ca. The energies of the excited states observed are reported along with spin and parity assignments when possible. Two-nucleon-transfer distorted-wave calculations were carried out. Comparisons are made with the shapes of the experimental angular distributions. It is found that the calculated shapes are primarily dependent upon the L transfer and the optical-model parameters. The magnitudes of the calculated cross sections are found to depend strongly not only on the optical-model parameters, but also the bound-state parameters and the configuration mixing in the initial and final nuclear wave functions.

I. INTRODUCTION

The (p, t) two-nucleon-transfer reaction has been studied for even-even $N=Z$ targets in the $2s1d$ shell. In particular, the targets were ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, and ^{40}Ca, which all have $J^\pi=0^+$ ground states. These (p, t) reactions reach states in nuclei which are two nucleons away from stability. The only other way of reaching the same nuclei by a two-body final-state reaction is the (^{3}He, n) reaction. Until recently these nuclei have not been studied to any great extent although the (p, t) reaction has been used extensively to study nuclei in the light-mass region[1-3] and in the medium-to-heavy-mass region.[4-8] These studies have shown that the shapes of the angular distributions are characteristic of the L transfer.

We denote the reaction by

$$A(p, t)B,$$

and the transferred quantum numbers by L, S, J, and T. Since the targets are all $J_A=0$, $T_A=0$, and since $T=1$ is a requirement of the (p, t) reaction, it follows that $J_B=J$ and $T_B=1$. The two neutrons bound in the triton are mostly (~95%)[9] in a state of relative spatial symmetry which requires that $S=0$. This leads to $J_B=L$ as an approximate restriction. If it is further assumed that the neutrons in the triton are in a relative s state, then the parity change is restricted to $\Delta\pi=(-1)^L$. These restrictions make the spin-parity assignments to the final nuclear states quite unambiguous once the L transfer has been established.

II. THEORY

The conventional distorted-wave method for direct reactions such as set forth by Satchler[10] was used to calculate the shapes of the angular distributions. The details of the reaction mechanism are calculated by a spin-dependent distorted-wave computer code in a zero-range approximation. Glendenning[11] developed the form factor needed in this calculation by using harmonic-oscillator wave functions for the two bound neutrons and a Gaussian wave function for the triton. It has been shown by Drisko and Rybicki[12] that the use of finite-well wave functions alters considerably the predicted cross section. We choose to follow the finite-well wave-function approach as expressed in detail in a paper by Jaffe and Gerace.[13]

The bound-state wave functions of the two neutrons are taken to be those of a particle bound in a well of the form

$$U(r)=-V_0 f(r)+\left(\frac{\hbar}{m_\pi c}\right)^2 V_S \frac{1}{r}\frac{d}{dr} f(r)\vec{l}\cdot\vec{\sigma},$$

where $f(r)$ is taken to be the standard Woods-Saxon shape with $r_0=1.25$ fm and $a=0.65$ fm as suggested by Bayman and Hintz,[6] and V_s was taken as 6 MeV, which is typical of single-nucleon spin-orbit strengths. The real well depth was adjusted so that the individual neutrons were bound by one-half the two-neutron separation energy as suggested in Refs. 6 and 12. These wave functions were expanded in terms of harmonic-oscillator wave functions with typically five to eight terms needed to fit the Woods-Saxon wave function to better than 2% out to twice the nuclear radius. The calculations of the individual form factors were carried out by the computer code TWOFRM (written by W. Gerace, Princeton University). The distorted-wave calculations were carried out with the code JULIE.[14] The distorted waves were obtained from an optical-model po-

EXCHANGE CURRENTS IN PARITY NON CONSERVING ELECTROMAGNETIC TRANSITIONS*

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It is shown that exchange currents do not contribute significantly to parity non-conserving transitions of the electric multipole type.

There has been some discussion in the literature of the role which the exchange currents necessary for gauge invariance play in parity non conserving electromagnetic transitions. Gari and Huffman [1] have considered the various processes likely to be importance and conclude that the Feynman diagram of fig. 1 dominates the conventional process of fig. 2. Eman and Tadic [2] however consider that Siegert's theorem [3] indicates that exchange currents will not contribute to electric multipole transitions.

In this letter we generalize the arguments leading to Siegert's theorem and show that they do apply to parity nonconserving transitions, leading to the result of Eman and Tadic. This conclusion depends on assumptions about the weak photoproduction terms of fig. 3, namely that they do not modify Siegert's assumption that the charges can be regarded as being localized on the nucleons. We support this assumption by showing that these terms contribute only to order k^2 relative to the leading terms as a consequence of Low's low energy theorem [4]. Part of the reason for the interest in such terms is that they provide a mechanism for one pion exchange terms which are not surpressed in Cabibbo theory by the factor $\sin^2\theta$. In case terms of order $k^2 \cot^2\theta$ are regarded as significant we show using PCAC and current algebra that such terms could be derived phenomenologically from data on radiative hyperon decays. Although such data are not available we find that these terms arise only from the $\underline{27}$ parts of the weak Hamiltonian and are sur-

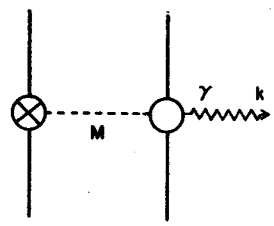

Fig. 1. The strong photoproduction exchange current found to be large by Gari and Huffman. In this and all other figures a crossed circle represent the weak parity violating interaction.

pressed by the octet enhancement mechanism. Our conclusion is therefore that parity non conserving electric multipole transitions can be calculated without considering exchange effects provided good wave functions are used. The discrepancy between present calculations [5] and experiments [6] for the tantalum transition could however lie in the crude calculation of the strength of the ρ exchange parity violating potential [7] or in deficiencies in the nuclear wave function rather than be a demonstration of the inadequacy of the Cabibbo Hamiltonian.

We now proceed to demonstrate each of our points in turn:

(i) *Siegert's theorem.* The derivation of Siegert's theorem for parity conserving transitions makes essential use of Siegert's assumption that the charge distribution in the nucleus depends solely on the nuclear coordinates; even though the exchange of mesons between the nucleons gives rise to currents in the nucleus they move so rapidly that the static charge distribution is localized on the nucleons. It only remains to demonstrate that matrix elements for electric multipole transi-

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COMPUTER COMPATIBLE SERVO SYSTEM FOR CYCLOTRON RF *

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A new servo control system, which allows computer as well as manual setup of the rf-system of the MSU-cyclotron has been built and tested. It features automatic switching to phase detectors when the desired positions are reached in order to fine-tune the system if the rf-drive goes on.

1. Introduction

The new rf-servo system allows simultaneous setup either from thumbweel switches on the console of the cyclotron or from a computer.

Since the system contains seven tunable elements, this saves a considerable amount of time, since the old system required the operator to set each element to the desired position by a manual control switch. The operator no longer is required to pay any attention to the tuning process, though it still could be done manually if so desired. Separate two-speed clocks for each servo allow a high setting speed and a matched

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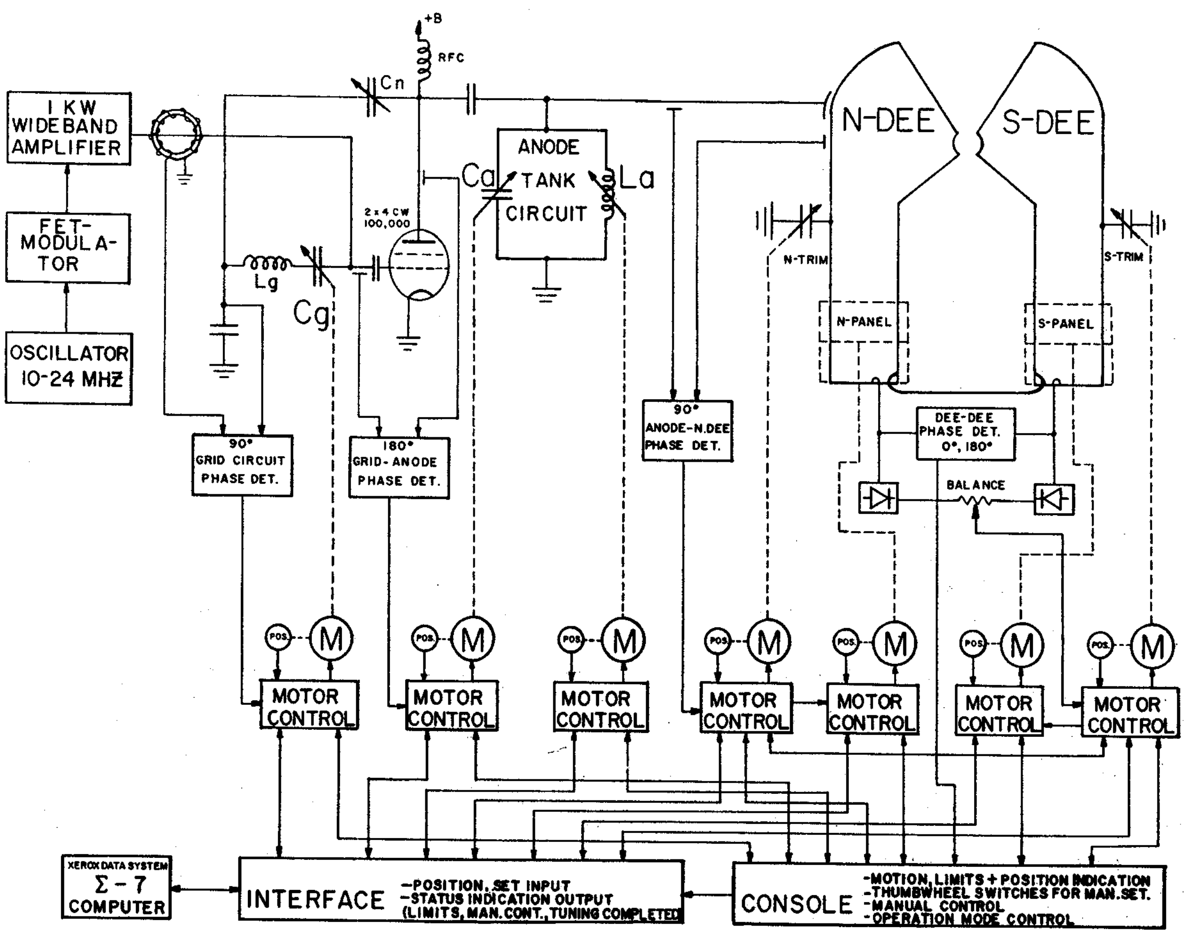

Fig. 1. Block diagram of the rf system.

PHYSICAL REVIEW C VOLUME 5, NUMBER 3 MARCH 1972

Decay of ^{141m}Sm – A Three-Quasiparticle Multiplet in ^{141}Pm

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We have studied the γ rays emitted following the decay of 22.1-min ^{141m}Sm with Ge(Li) and NaI(Tl) detectors in various singles, coincidence, and anticoincidence configurations, including Ge(Li)-Ge(Li) two-dimensional "megachannel" coincidence experiments. Of the 47 γ rays definitely established as belonging to ^{141m}Sm decay, all but six very weak ones have been placed in a consistent decay scheme. The energies in keV [and J^π assignments] of the states in ^{141}Pm populated by the decay of ^{141m}Sm are 0 [$\frac{5}{2}^+$], 196.6 [$\frac{7}{2}^+$], 628.6 [$\frac{11}{2}^-$], 804.5 [$\frac{11}{2}^+$, $\frac{9}{2}^+$], (837.1) [$\frac{9}{2}^+$], 974.0 [$\frac{9}{2}^+$], 1108.1 [$\frac{7}{2}^+$, $\frac{9}{2}^+$, ($\frac{5}{2}^-$)], 1167.2 [$\frac{13}{2}^{-(+)}$, $\frac{11}{2}^{-(+)}$, $\frac{9}{2}^{-(+)}$], 1313.2 [$\frac{13}{2}^{-(+)}$, $\frac{11}{2}^{-(+)}$, $\frac{9}{2}^{-(+)}$], 1414.8 [$\frac{11}{2}^-$, $\frac{9}{2}^-$], (1834.0) [$\frac{11}{2}^-$, $\frac{9}{2}^-$], 1983.1 [$\frac{9}{2}^-$], 2063.5 [$\frac{11}{2}^-$, $\frac{9}{2}^-$], 2091.6 [$\frac{11}{2}^-$, $\frac{9}{2}^-$], 2119.0 [$\frac{11}{2}^-$, $\frac{9}{2}^-$], and 2702.4 [$\frac{13}{2}^-$, $\frac{11}{2}^-$, $\frac{9}{2}^-$]. Less than 0.2% of the decay of $\frac{11}{2}^-$ ^{141m}Sm proceeds via an $M4$ isomeric transition to 11.3-min $\frac{3}{2}^+$ ^{141g}Sm. Two-thirds of the ^{141m}Sm electron-capture decay goes to the six (possibly seven) highest-lying states in ^{141}Pm, another example analogous to ^{139m}Nd decay of the population of a well-defined three-quasiparticle multiplet by an $N=79$ nuclide. In simple shell-model terms this can be written as $(\pi d_{5/2})^2(\nu d_{3/2})^{-2}(\nu h_{11/2})^{-1} \rightarrow (\pi d_{5/2})(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}$. Most of the remaining states can be characterized quite satisfactorily as specific single-particle and core-coupled states. The behavior of these states allows us to add considerably to the systematics of shell-model orbits and their occupations in this region below $N=82$.

I. INTRODUCTION

These results of our study of the decay of $^{141m}_{62}$Sm$_{79}$ supplement the similar work done on the decay of $^{139m}_{60}$Nd$_{79}$ by Beery, Kelly, and McHarris.[1] The decay of $\frac{11}{2}^-$ ^{139m}Nd selectively populates six high-spin states at relatively high energies in ^{139}Pr. These states were characterized as three-quasiparticle states having the configuration, $(\pi d_{5/2})(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}$, and the preferred electron-capture (ϵ) decay of ^{139m}Nd could be written as $(\pi d_{5/2})^2(\nu d_{3/2})^{-2}(\nu h_{11/2})^{-1} \rightarrow (\pi d_{5/2})(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}$.

The work on ^{139m}Nd decay led to the prediction by McHarris, Beery, and Kelly[2] that other $N=79$ or $N=77$ nuclides might possess the requisite configurations for similar ϵ or β^+ decay into three-quasiparticle multiplets. In addition to the configuration such a nuclide must also have sufficient decay energy to populate states above the pairing gap in its daughter, and it must have relatively low probability for other modes of decay – for example, if it is a metastable state the energy for the isomeric transition must be low enough to make that transition quite slow.

Working his way out from β stability, one finds that ^{141m}Sm and ^{137m}Nd are the next likely candidates. For example, the addition of two protons to the ^{139m}Nd configuration produces the very similar configuration for ^{141m}Sm, $(\pi d_{5/2})^4(\nu d_{3/2})^{-2}(\nu h_{11/2})^{-1}$. The calculated Q_ϵ is more than 5 MeV, allowing it to populate high-lying states in ^{141}Pm. Finally, as in the other $N=79$ odd-mass isotones, the $h_{11/2}$ – $d_{3/2}$ (metastable – ground state) separation is small (≈171 keV), making the $M4$ isomeric transition very slow. The results that we present in this paper do indeed confirm these predictions – a

CALCULATION OF $T=2 \rightarrow T=1 \rightarrow T=0$ M1 DECAYS IN $A=20$ AND $A=32$ NUCLEI

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Absolute strengths and branching ratios are calculated for M1 transitions between states of different isospin in two A = 4n nuclei of the sd-shell.

The gamma decay of the lowest T = 2 levels in self-conjugate A = 4n nuclei offers a unique possibility of studying T = 2,1 and 0 levels within a single system. From studies of once- and twice-forbidden capture reactions in the 2s1d-shell, strong gamma-ray cascades from (J^{π}, T) = $(0^+, 2)$ states have been reported in A = 20, 24, 28 and 32 nuclei [1]. The characteristic gamma decay proceeds with one or more cascades of M1 character where the (J^{π}, T) combinations are $(0^+, 2) \rightarrow (1^+, 1) \rightarrow (0^+, 0)$ or $(2^+, 0)$. Information on the $(1^+, 1) \leftarrow (0^+, 0)$ M1 transition strengths has been obtained from measurements of 180° inelastic electron scattering [2,3].

In this paper we report a shell model calculation of ΔT = 1, M1 transition strength for the gamma-ray cascades from $(J^+, T) = (0^+, 2)$ levels in A = 20 and 32. A realistic effective two-body interaction, deduced from the Sussex relative oscillator matrix elements and corrected for core-polarization and other space-truncation effects, has been employed [4]. An inert ^{16}O core has been assumed. Diagonalization of the energy matrices has been performed in full sd space for A = 20. For the mass 32 calculation only up to two $d_{5/2}$ particles have been allowed to be excited to $s_{1/2}$ and $d_{3/2}$ orbits. The shell model energy matrices were constructed with the codes described by French et al. [5]. The single-particle energies have been taken from the ^{17}O experimental spectrum. Except for the harmonic oscillator size, $\hbar\omega$ = 14.4 MeV, no parameters have been used. No variation of $\hbar\omega$ has been made in order to obtain accurate predictions of absolute binding energies for different mass numbers. The theoretical energies, as presented in fig. 1 and table 1 together with experimental information, have been "normalized" such that the lowest $(J^{\pi}, T) = 1^+, 1)$ state is equal to the experimental value. The excitation energies in table 1 are the experimental ones. (The values marked with asterisks are predicted values for experimentally unknown levels.) The predicted transition strengths have been calculated with the assumption of pure M1 transitions and bare nucleon g-factors.

For ^{20}Ne, the predicted absolute strengths for the transitions through the lowest $(1^+, 1)$ level, $[(0^+, 2) \rightarrow (1^+, 1)$ and $(1^+, 1) \leftarrow (0^+, 0)]$,

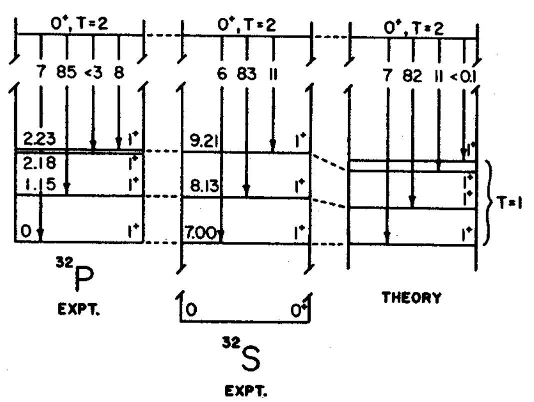

Fig. 1 The experimental and theoretical branching ratios of the $J^{\pi} = 0^+$, T = 2 levels in A = 32.

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INELASTIC ELECTRON SCATTERING FORM-FACTORS CALCULATED FROM SHELL-MODEL WAVE FUNCTIONS *

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From-factors measured for (e,e') on ^{20}Ne, ^{24}Mg, ^{28}Si and ^{32}S are well reproduced by calculations which use shell-model wave functions and scaling factors consistent with the usual effective charge assumptions.

Recent measurements [1] have yielded form-factors for inelastic electron scattering leading to the lowest 2^+ and 4^+ states of ^{20}Ne, ^{24}Mg and ^{28}Si. Older data [2] are available for ^{32}S. In this note we present results of analyses of these data which use shell-model wave functions to generate the relevant transition densities. It has been shown [3-6] that presently available data on E2 transition strengths and electric quadrupole moments in the sd-shell can be understood in terms of these same wave functions if protons and neutrons are each assumed to carry an additional charge of 0.5e, an assumption not at variance with data available from the "single particle" nuclei ^{17}O and ^{17}F. The question of interest here is whether the more detailed information contained in the experimental (e, e') form-factors can also be explained in the same terms.

The shell-model wave functions we use here have been obtained from calculations made in $0d_{5/2}$-$1s_{1/2}$-$0d_{3/2}$ basis spaces. The ^{20}Ne calculations employed the full set of states available in this space, but in the other calculations limits were placed on the numbers of allowable $d_{5/2}$ holes and $d_{3/2}$ particles so as to keep dimensions within practical bounds. The Ne and Mg shell-model calculations employed as a model Hamiltonian a (slightly) modifies [7] version of Kuo's matrix elements [8]. The ^{28}Si and ^{32}S calculations were made with versions of the modified surface-delta interaction. Details of these calculations are available elsewhere [3-5].

In the present work, these shell-model wave functions are used to generate the expectation values of the operators $(a_j^\dagger a_{j'})_J$ between the initial and final states of the target nucleus, where j, j' refer to the orbits of the active model space and J to the multipolarity of the transition. A specially adapted version [9] of the computer cod codes described by French et al. [10] is used for this procedure. These results are then appropriately combined with radial wave functions of the model orbits in order to construct transition densities $\rho_J(r)$. The form-factors for inelastic electrons scattering then follow from the expression

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

We note that, since $j_J(qr) \to q^J r^J/(2^J+1)!!$ as $q \to 0$, the expression for the form factor becomes in the limit of $q \to 0$, equal to the definition of the $B(EJ)$ of an electric transition of multipolarity :

$$\frac{Z^2[(2J+1)!!]^2}{4\pi}\lim_{q\to 0}\frac{|F(q)|^2}{q^{2J}} =$$

$$= \frac{2J_f+1}{2J_i+1}\left|\int_0^\infty \rho_J(r)r^J\ dr\right|^2 \equiv B(EJ). \qquad (2)$$

However, the complete (e, e') form factors provide a more detailed test of the transition density than is available from just the $B(EJ)$, since ρ is sampled for varying values of r as q varies. Provided the calculated and observed shapes of $|F(q)|^2$ are in reasonable agreement, the square of the isoscalar effective charge $e(\text{eff}) = e_p(\text{eff}) + e_n(\text{eff})$ (all the present transitions are $\Delta T = 0$) may be defined as the number which normalizes the form factor calculated with $e_p = 1.0$, $e_n = 0.0$ to the experimental dis-

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PHYSICAL REVIEW C VOLUME 5, NUMBER 4 APRIL 1972

Electromagnetic Transition Rates in ^{28}Al[†]

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Lifetimes for the 2nd through 12th excited states in ^{28}Al have been obtained by use of the attenuated-Doppler-shift technique. Combining these results with previous information on this nucleus makes it possible to assign spins to all of the states that have been studied. All of the information is then compared with a shell-model calculation and with other theoretical descriptions that have been advanced.

I. INTRODUCTION

In the simplest shell-model picture, the $1d_{5/2}$ subshell closes at ^{28}Si. While the closeness of the $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ subshells indicates that this simplest picture can only be a rough approximation to the true situation for the nuclei in the mass-28 region, the level scheme of ^{28}Al does give substantial support to the simple picture. This level scheme is relatively simple for an odd-odd nucleus; it has only seven levels below 2 MeV, and the two lowest states are as predicted by the $(d_{5/2})^{-1}s_{1/2}$ assignment. In order to determine how well a simple picture holds up when the stringent test of predicting electromagnetic transition rates is applied, the present work of measuring the lifetimes of the low-lying states in ^{28}Al was undertaken.

The attenuated-Doppler-shift method was much the same as in earlier Argonne work[1,2]; i.e., the spectra of γ rays in coincidence with each of two proton detectors were recorded. Figure 1 is a schematic diagram of the experimental arrangement. The pulses were processed by conventional electronics, and for each event the proton and γ-ray pulse heights in digitized form were recorded on magnetic tape. The available memory capacity was sufficient for on-line recording of some of the γ-ray spectra of interest, though others had to be obtained by sorting the data stored on the tapes. The Doppler shifts were extracted for those transitions deemed to be most useful in de-

Energy Levels of ^{25}Si from the Reaction ^{28}Si(^{3}He, ^{6}He)^{25}Si at 70.4 MeV*

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The energy levels of ^{25}Si have been measured by detecting ^{6}He particles from the reaction ^{28}Si(^{3}He, ^{6}He)^{25}Si in photographic plates on the focal plane of a spectrometer. 12 excited states were observed. The observation of a weak state at 40-keV excitation leads to a new ^{25}Si ground-state mass excess, 3.824 ± 0.010 MeV. The observed levels are discussed in terms of the isobaric multiplet mass equation and the shell model.

The (^{3}He, ^{6}He) reaction has been used previously to study the ground-state masses of proton-rich nuclei.[1-3] Six $T=\frac{3}{2}$ mass quartets have been completed this way and the results have been used to determine the coefficients of the isobaric multiplet mass equations (IMME). In principle this same equation should link the mass excesses of the excited $T=\frac{3}{2}$ states as well. The dependence of the various coefficients of the equation on excitation energy and spin can therefore be observed at a fixed value of A. The present experiment deals with the energy level scheme of ^{25}Si, which up to present was completely unknown.

Even the ground-state transitions in the (^{3}He,^{6}He) reaction are difficult to observe because of the very small cross sections (typically 1 μb/sr at the peak). Previous measurements employed a position-sensitive detector on the focal plane of a spectrometer[1,2] or a three-detector telescope.[3] When these methods are employed, the background due to neutrons and other charged particles obscures weakly populated states. In the case of the reaction ^{28}Si(^{3}He, ^{6}He)^{25}Si, the resolution (70 keV) was not good enough to observe the ground state as a doublet (as predicted by the IMME), and hence the assumption was made that the peak observed was the ground state only.[2] In the present experiment relatively insensitive photographic plates were used in the focal plane of the spectrometer. The large solid angle, kinematic compensation, and dispersion matching of the spectrometer, coupled with the insensitivity of the plates to neutrons, γ rays, and lower-mass charged particles of the same magnetic rigidity, permitted the observation of the ground state and 12 excited states in ^{25}Si.

Ilford K(−1) plates were used with absorbers stepped in thickness to keep the ^{6}He particles between 12 and 18 MeV at the surface of the emulsion. This puts the α particles at 50 to 60 MeV, typically. At this energy they leave barely observable tracks, which in the present experiment did not obscure any region of the plate in spite of the large number of α particles compared to ^{6}He particles. The elastic ^{3}He particles, however, are so numerous at the forward angles used that they blacken the plate. Fortunately they fall at the same place as ^{6}He particles corresponding to a fairly high excitation energy (about 6.7 MeV) in ^{25}Si. In general, the present method is limited to ^{6}He particles of energy greater than about $\frac{1}{2}$ the beam energy.

Data were taken at 9, 12, and 16° (lab) with a 600-μg/cm^2 natural Si target and at 9 and 12° with a 200-μg/cm^2 SiO target. The beam energy was 70.4 MeV in all cases. The energy resolution was limited mainly by target thickness to 50 keV for the natural Si target and 28 keV for the SiO target. The spectrum taken on natural Si at 9° is shown in Fig. 1. The higher-resolution SiO runs were used to attempt to resolve the first-excited-state–ground-state doublet which is shown in Fig. 2. These results show that mass measurement of ^{25}Si was predominantly of the ground state, as was assumed by the authors,[2] but that the mass should be shifted downward by 8 keV, which is within the error of their measurements. The new mass excess of ^{25}Si is 3.824 ± 0.010 MeV.

The new mass of ^{25}Si changes the coefficients of the IMME only slightly. The form of the IMME used is

$$M=a+bT_z+cT_z^2+dT_z^3.$$

The coefficients of the equation are sensitive to

1.D.1

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SHELL-MODEL CALCULATIONS FOR MASSES 27, 28 AND 29: ELECTROMAGNETIC TRANSITION RATES AND MULTIPOLE MOMENTS

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Abstract: Electromagnetic transition probabilities, multipole moments and log *ft* values have been calculated from many-particle shell-model wave functions in a truncated $1d_{\frac{5}{2}}\,2s_{\frac{1}{2}}\,1d_{\frac{3}{2}}$ configuration space, with a maximum of four holes in the $1d_{\frac{5}{2}}$ subshell. The electric quadrupole transition strengths and moments are reproduced very well in a least-squares fit to 74 experimental data with one parameter, for the isoscalar effective charge, yielding the values $e_p = 1.6\,e$ and $e_n = 0.6\,e$. The results for magnetic dipole transition strengths and moments follow from adjusting two effective reduced single-particle matrix elements in separate least-squares fits to 17 experimental data in $A = 27$ nuclei and 21 data in $A = 29$ nuclei. The average absolute deviations between theory and experiment for E2 and M1 transition strengths are 3.0 and 0.05 W.u., while the average measured strengths are 7.7 and 0.08 W.u., respectively. Transitions from excited states above $E_x = 4.8$ MeV in ^{27}Al and from some low-lying states in ^{27}Al and ^{28}Si are poorly reproduced by the present model. Calculated strengths of transitions from analogue states are given. Previous conclusions about the single-particle character of M1 transitions and the collective behaviour of E2 transitions are confirmed. The experimental data of seven $A = 27$–29 nuclei are well reproduced in one general treatment with an appreciably lower number of free parameters than are required to obtain comparable results in collective model calculations.

1. Introduction

A possible rotational-like structure of the nuclei around mass 28 has been discussed by several authors [1-6]. Since many-particle shell-model calculations in the mass region $A = 30$–34 have met with considerable success [7,8], it was thought worthwhile to extend these calculations to the slightly lighter $A = 27$–29 nuclei. The electromagnetic properties are reported here. The excitation energies and spectroscopic factors are discussed in another paper [9]. The electric quadrupole moments of ^{27}Al and ^{28}Si as found in a previous calculation have already been published [10]. Similar calculations for $A = 23$–27 nuclei of which some have an established deformed character are in progress [11].

These calculations are feasible since a wealth of experimental information on $A = 27$–29 nuclei became available recently (see table 1). The wave functions have been calculated [9]) with the Oak Ridge-Rochester shell-model computer programs [12]. The configuration space is given by: $(1s)^4(1p)^{12}(1d_{\frac{5}{2}})^{n_1}(2s_{\frac{1}{2}})^{n_2}(1d_{\frac{3}{2}})^{n_3}$ with $n_1+n_2+n_3$

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Decays of the Even-Even Lead Isomers: ^{202m}Pb and ^{204m}Pb

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The decays of the 9$^-$ isomers, ^{202m}Pb and ^{204m}Pb, have been investigated using Ge(Li) detectors in a variety of singles and coincidence configurations. Improved conversion coefficients were obtained for two of the transitions following the decay of ^{204m}Pb, but no new, weak transitions were seen. Considerable improvement and enlargement of the ^{202m}Pb decay scheme was possible. We have been able to make unambiguous multipolarity assignments for 15 of the 18 transitions following its decay and to place all 18 in a consistent decay scheme. States in ^{202}Pb were established (following the 90.5% isomeric-transition decay) at 0 ($J^\pi = 0^+$), 960.70 (2^+), and 1382.82 (4^+), 1623.1 (4^+), 1915.2 (4^+), 2040.3 (5^-), and 2169.8 keV (9^-). Those in ^{202}Tl (following the 9.5% electron-capture decay) lie at 0 (2^-), 490.47 (4^-), 950.19 (7^+), 1098.7 (6^+, 7^+, 8^+), 1340.1 (8^+), 1552.1 ($8^+[9^+]$), and 1675.6 keV (9^+, 8^+). Interpretation is made concerning the nature of the states in ^{202}Pb and even-even Pb isotopes and also in ^{202}Tl and odd-odd Tl isotopes on the basis of the simple shell-model plus pairing forces.

I. INTRODUCTION

The Pb isomers were the first case of even-even isomerism to be observed. Besides being interesting in their own right, they also provided (and still provide) an advance opportunity to study some of the lower-lying states in the Pb isotopes, states that presumably should be amenable to explanation in simple shell-model terms. ^{204m}Pb and ^{202m}Pb, especially, have proven useful for building up skeletal level schemes for ^{204}Pb and ^{202}Pb before these could be studied by transfer reactions or the much more complicated decays of ^{204}Bi and ^{202}Bi. In the present work we reexamine the decays of ^{204m}Pb and ^{202m}Pb, using Ge(Li) γ-ray detectors for the first time. We then correlate our findings with those from other types of experiments when possible and examine the trends in the even-even Pb isotopes not too far from stability. We are also able to make arguments concerning the structures of some of the odd-odd ^{202}Tl states populated by the electron-capture (ϵ) decay branch of ^{202m}Pb.

The decay scheme of 66.9-min ^{204m}Pb has been the subject of many previous studies, beginning with Sunyar *et al.* in 1950.[1] An excellent summary of the intervening work is to be found in Hyde, Perlman, and Seaborg[2] and thus will not be repeated. It should be mentioned, however, that the decay scheme remains essentially that proposed by Fritsch in 1956.[3] Our study was aimed chiefly at finding weak, previously unobserved transitions. None was found, but we were able to obtain better values for some of the internal-conversion coefficients, using a unique single-crystal Ge(Li) "conversion-coefficient spectrometer" developed in this laboratory.[4]

The existence of an isomer associated with ^{202}Pb was first reported by Maeder and Wapstra in 1954.[5] They produced this isomer by bombarding

2.L

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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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^{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.) ⊗ $1d_{5/2}$ 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(^{3}He, $p)^{20}$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(^{3}He, $p\gamma)^{20}$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$(p, ^3$He)-^{20}F.[18] Studies of the reactions ^{18}O(^{3}He, $p)^{20}$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-

A SEARCH FOR QUARKS AT THE CERN INTERSECTING STORAGE RINGS

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No quark candidates have been seen among 0.6×10^9 charged particles at the ISR. The corresponding cross-section limit for charge $\frac{1}{2}$ ($\frac{2}{3}$) is $\lesssim 3(6) \times 10^{-34}$ cm^2 for quark masses up to 22(13) GeV, assuming $\langle P_T \rangle = 0.4$ GeV/c.

The Intersecting Storage Rings provide, for the first time, the possibility of producing in a controlled way pairs of heavy objects of masses up to ~25 GeV each. Thus the range of the search for heavy, stable, "fundamental" particles has been considerably extended beyond the ~ 5 GeV Serpukhov limit [1]. We report in this letter first results‡ from a search for quarks now in progress at the ISR. We give here flux limits on charge $\frac{1}{3}$ and charge $\frac{2}{3}$ quarks relative to the flux of normal charged particles, and we derive cross-section limits on the basis of a simple production model.

The detector layout is shown in fig. 1. Six scintillation counter telescopes, interlaced with proportional chambers, sample laboratory production angles between 10 mrad and 75°. These telescopes accumulate data simultaneously and independently. Also shown are some of the counters used to monitor the luminosity and background conditions of the beams.

Each telescope consists of nine plastic scintillation counters, one plastic Čerenkov counter, and two or more anticounters (not shown in the figure). Six multiwire proportional chamber planes cover the solid angle of each telescope.

The scintillation counters provide nine independent samples of energy loss for each event. They are 2 cm thick and are designed to give between 20 and 50 photoelectrons for a relativistic charge $\frac{1}{3}$ quark. As a result, our pulse-height spectra for ordinary particles are dominated by fluctuations in energy loss rather than by photoelectron statistics.

Care must be taken to avoid simulation of the low pulse heights expected from a fractionally charged quark. For instance, the nine counters of each telescope are aligned in such a way that no more than three scintillator edges line up from any direction. Also, the light guides are made of scintillator material, to avoid production of low pulse heights from Čerenkov radiation in conventional plexiglas light guides.

The Čerenkov counter for each telescope is made of 5 cm thick Pilot 425 plastic. Its pulse height has a velocity dependence different from that of the scintillators, and this it gives independent information in the search for anomalous charge values.

The anticounters detect any particles which could generate a signal directly in the telescope photomultipliers (56 DVP's). In addition, they tag any particles traversing the telescope light guides.

Multiwire proportional chambers [3] with a total of 5000 wires spaced at 2 mm, cover the solid angle subtended by the telescopes. The chambers are run with a 300 nsec strobe width for maximum quark detection efficiency. For relativistic particles, their efficiency is greater than 99.98%, as measured at the ISR. The chambers provide a means of track recognition and background suppression.

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‡ Our results, obtained previously with an old model (thick-walled) of the ISR vacuum chamber in our intersection, have already been reported, most recently by Sens [2].

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 $\nu + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$ 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.

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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-

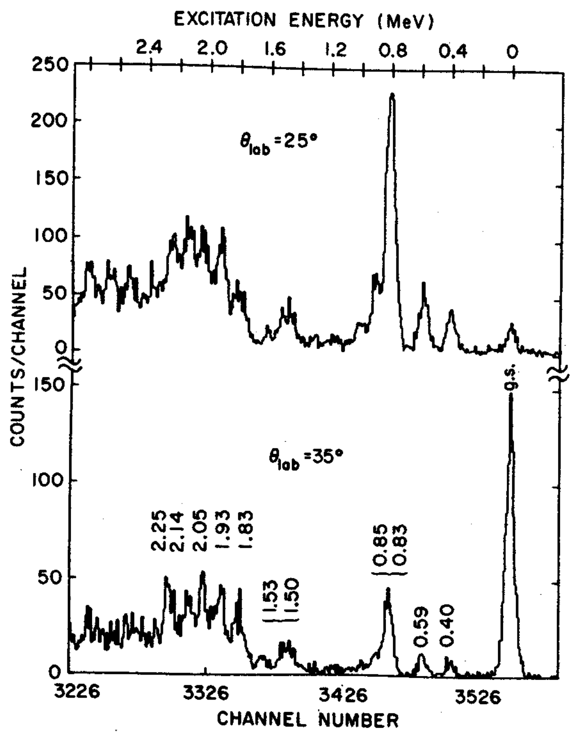

FIG. 1. Two spectra (θ_{lab} = 25 and 35°) of tritons from the ^{141}Pr(p,t) reaction at 40 MeV.

DATA ACQUISITION FROM SIMULTANEOUS EXPERIMENTS USING THE MSU SIGMA-7 COMPUTER*

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The large size of the nuclear spectroscopy group at Michigan State University and the relative ease and efficiency with which experiments can be performed using the MSU Sector-Focused Cyclotron make it imperative that simultaneous data acquisition and analysis be possible. The Sigma-7 computer at the MSU Cyclotron Laboratory forms the basis of a flexible real-time, time-sharing system that meets the requirements for performing simultaneous spectroscopic experiments or spectroscopic experiments simultaneously with nuclear scattering experiments, all the while allowing data analyses to be performed.

The computer consists of 32*K* of 32-bit core memory plus a 1.5-megabyte (8 bits = 1 byte) RAD (rapid access disk) for file storage and a 3.0-megabyte RAD for memory swapping during computation. [During this fall a 5.3-megabyte RAD (transfer rate = 3 megabytes/sec) will be added for memory swapping and both current RAD's (transfer rate = 0.19 megabytes/sec) will be used for file storage.] It has standard peripherals such as teletypes (with and without paper tape), card reader, card punch, 600 lines/sec line printer, two 9-track magnetic tape units, and a CalComp plotter.

*Work supported in part by the U.S. National Science Foundation.

A NaI(T1) SPLIT ANNULUS FOR COINCIDENCE, ANTICOINCIDENCE, TRIPLE COINCIDENCE, AND PAIR SPECTROMETRY–

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During the last three years we have been using an 8 x8-in. NaI (T1) split annulus more or less routinely as a counterpart to Ge(Li) detectors in various coincidence and anticoincidence configurations.[1] Its most common use has been for Compton suppression (external, collimted source) and simple anticoincidence experiments (internal source), most often with the insertion of an additional 3 x3-in. NaI (T1) detector at the end of its tunnel opposite the Ge(Li) detector in order to reduce Compton edges further. In fact, we have found it advisable to perform such experiments at the very outset of study of a new decay scheme so as to pinpoint immediately any delayed transitions or primarily β-fed ground-state transitions. The split feature of the annulus has made it very useful for other, more exotic experiments as well. Among these have been triple coincidence experiments involving short-lived nuclides or weak transitions, made possible only because of the high efficiency of the annulus. It has also been used as part of an efficient pair spectrometer for obtaining β^+ feedings and /or double-escape spectra, and it has been used to enhance the background reduction of a "Compton" or "duode" spectrometer.[2] As examples of its use in coincidence and triple coincidence experiments are straightforward and already appear in the literature,[1,3] here we

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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-

Energy Dependence of Proton Inelastic Scattering from ^{40}Ca†

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Inelastic proton scattering from ^{40}Ca has been measured at beam energies of 24.93, 30.04, 34.78, 34.78, and 39.83 MeV. Angular distributions from 13 to 97° for about 40 inelastic states were obtained. Analyses with both microscopic and macroscopic theories are presented.

I. INTRODUCTION

The double magic nuclei, such as ^{40}Ca, have been studied in great detail both experimentally and theoretically. The degree of deviation from a simple double-closed-shell structure is of great interest. Recent advances in the theories of nuclear shell models [random-phase approximation (RPA) and deformed], the effective nucleon-nucleon force, and the distorted-wave treatment of direct reaction enable one to formulate a microscopic description of the inelastic scattering of protons by nuclei.[1-6] The ^{40}Ca nucleus was chosen as a target to test the (p,p') reaction as a probe of nuclear structure because of the following points: First, it is a target which allows the (p,p') reaction to examine all the components of the proton-nucleus force. Second, it is a target in which the eigenvectors describing the excited states are relatively well established both experimentally and theoretically. Third, it is a target for which good optical-model parameters exist.

The structure of ^{40}Ca has also been investigated in other experiments such as (α,α'),[7,8] (e,e'),[9,10] $(^3He,d)$,[11] (d,n),[12] and $(p,p'\gamma)$.[13] The (α,α') reaction is a predominantly surface-dominated reaction and it leads to diffraction scattering. It measures L transfer for the excited normal-parity states, and the isoscalar component of the projectile-nucleon force. The (e,e') reaction gives reduced electromagnetic transition probabilities and multipolarities. The $(^3He,d)$ and (d,n) proton stripping reactions allow one to study individual components of the vectors of the excited states. The $(p,p'\gamma)$ reactions have been used primarily to determine the spins and parities of the excited states; whereas, the (p,p') reaction is useful in probing various components of the effective interaction and testing microscopic wave function.

By studying the energy dependence of the reaction, in many cases, one is able to remove ambiguities due to reaction mechanism problems. The present experiment studies proton inelastic scattering from ^{40}Ca at bombarding energies of 24.93, 30.04, 34.78, and 39.83 MeV. Spectra were taken simultaneously by two surface-barrier Ge(Li) detectors with an over-all resolution of 30 keV [full width at half maximum (FWHM)]. Angular distributions for inelastic scattering to approximately 50 excited states were obtained over the angular range from 13 to 97° (lab). The data were analyzed using both a collective model to extract L transfers and nuclear deformations and a microscopic model employing a realistic force, RPA wave functions, and approximate exchange.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

The data were obtained using protons from the Michigan State University sector-focused cyclotron.[14-16] The beam was energy-analyzed using two 45° bending magnets with image and object slits set to pass beam with fractional energy spread of $\pm1.25\times10^{-4}$. Detailed discussions of the optical properties of the beam and of the energy-analysis system are given elsewhere.[17-19] The absolute energies of the proton beams were obtained from nuclear-magnetic-resonance calibrations of the magnets. The uncertainty in this absolute scale was ±0.1%.[17] The absolute beam energies for this experiment were 24.93 ± 0.03, 30.04 ± 0.03, 34.78 ± 0.04, and 39.83 ± 0.04 MeV.

The beam on the target was monitored using both a Faraday cup and a Ge(Li) proton detector placed at 45° with respect to the beam. The scattering chamber[20] used in this experiment consisted of a target chamber which was viewed through ports in a sliding seal. Two ports separated by 14.7° were coupled such that a pair of Ge(Li) proton detectors could be used. The solid angles of the two detectors were $1.38\pm0.04\times10^{-4}$ and $0.786\pm0.024\times10^{-4}$ sr for detectors 1 and 2, respectively. The angular range of detection was from 12 to 97° in 5° steps. Data were taken twice at 27 and 72° by each detector for the relative normalization. Details concerning these detectors are given in a previous publication.[21] The target was a rolled, self-supported 2-mg/cm²

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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 co-workers[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

The $^{48}Ca(p,t)^{46}Ca$ Reaction at Ep=39 MeV*

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1. INTRODUCTION

There has been considerable interest in using a comparison of (p,t) and (t,p) reactions to the same final states, especially 0^+ states, to compare wave functions for a series of nuclei.[1] Such a study in the calcium isotopes would benefit from a more thorough study of the $^{48}Ca(p,t)$ reaction. The complementary $^{44}Ca(t,p)$ reaction has been carried out in various laboratories[2,3] and strongly populates states of $J^{\pi}=0^+$ at excitation energies between 5 MeV and 7 MeV. The $^{48}Ca(p,t)$ has also been studied previously but at fairly low energies[4,5] or with poor resolution[6] so that the states of interest could not be resolved. In addition discrepancies between the (t,p) experiments serves as an additional motivation for the (p,t) experiment. The present paper is a preliminary report of this work.

2. EXPERIMENTAL

The experiment was carried out in two stages using the Michigan State University Cyclotron at a proton beam energy of 39 MeV. A high resolution study was carried out using the Enge split-pole spectrograph and the resolution was peaked using the focal plane speculator system.[7] A resolution of 11 keV FWHM was obtained where these data were recorded on photographic emulsions. The second stage was run with intermediate resolution (∿50 keV) using a pair of single wire proportional counters in the focal plane of the spectrograph. Angular distributions were

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THE (p,t) REACTION ON ^{24}Mg AND ^{26}Mg*

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ABSTRACT

The ^{24}Mg(p,t)^{22}Mg and ^{26}Mg(p,t)^{24}Mg reactions have been studied at proton energies of 42.0 and 40.0 MeV respectively. Angular distributions were obtained for the ground and first excited states of ^{22}Mg and for the ground and five lowest excited states in ^{24}Mg. Measured reaction strengths are compared to predictions of the DWBA made with shell-model wave functions.

1. INTRODUCTION

Shell model calculations of nuclear structure[1,2] can now successfully account for many of the characteristics of the low-lying energy levels of sd-shell nuclei. Phenomena such as excitation energy spectra, single nucleon transfer strengths, electromagnetic decay rates and beta decay have been treated in some detail. In addition, several studies in the last few years have used shell model wave functions to analyze two-nucleon transfer between sd-shell nuclei.[3-7] These studies offer the possibility of examining the nuclear wave functions from a viewpoint quite different from those that are available in other kinds of observations.[8] Hence, if the experimental data are amenable to an unambiguous analysis with respect to the reaction process, conclusions from two-nucleon transfer experiments should be vital to extending our comprehension of nuclear structure in this region. In the present work we study ^{22}Mg and ^{24}Mg, nuclei for which wave functions successful in essentially all other areas of phenomena are available,[9] via the (p,t) reaction from ^{24}Mg and ^{26}Mg.

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EFFECT OF COMPLEX COUPLING IN INELASTIC CROSS SECTIONS, ASYMMETRIES AND SPIN FLIP IN THE DWA

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Abstract: The effects of adding an effective imaginary part to real inelastic microscopic form factors in DWA are investigated. Calculations are compared to data for the proton differential cross sections and asymmetries of the lowest-lying states of ^{120}Sn, ^{58}Ni, and ^{208}Pb. Proton spin flip is calculated for ^{120}Sn. Both collective imaginary and effective microscopic imaginary contributions were considered. The most substantial improvements were in fits to asymmetry data. Collective-model calculations indicate the effects of complex coupling are comparable to those of the deformed spin-orbit well.

1. Introduction

A number of authors have pointed out that when the collective model is applied to inelastic proton-nucleus scattering it is important to deform the imaginary and spin-orbit wells in addition to deforming the real well [1]). Satchler recently proposed a semi-phenomenological model for the imaginary form factor in microscopic (p, p′) calculations [2]). Also, it is now possible to include a two-body spin-orbit term in microscopic calculations [3,4]).

In view of this it is useful to study the effects of complex coupling on cross sections and asymmetries and to compare the results with those of similar calculations which include a spin-orbit term.

We performed calculations for the lowest-lying excited states in ^{58}Ni, ^{120}Sn, and ^{208}Pb using in each case a microscopic real form factor and each of two models for the imaginary form factor. Spin-orbit contributions were calculated with the collective model.

The calculations were done in DWA for 30 MeV incident protons using the optical parameters of ref. [5]). Exchange effects were included using a zero-range pseudopotential [6]). Angular distribution and asymmetry data are from ref. [7]), the spin-flip data from ref. [8]).

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V. Ph.D. Thesis Titles (July 1971-June 1972)

Department of Physics

Howell, Richard	Proton Spin-Flip Probability in Inelastic Scattering on ^{120}Sn and ^{124}Sn at 30 MeV
Laumer, Helmut	Proton Induced Reactions on ^{14}N and ^{16}O and the Creaction of Elements Lithium, Beryllium, and Boron
Todd, Richard	Gamma-Ray Spectroscopic Studies of Members of the A=141 Decay Chain

Department of Chemistry

Black, Jerry	Nuclear Spectroscopic Studies of Members of the A=141 Decay Chain
Giesler, Gregg	Nuclear Spectroscopic Studies of Some Short-Lived and Neutron Deficient Ga and Zn Isotopes
Goles, Ronald	The (p,t) Reactions on Rare Earth Nuclei