PHYSICAL REVIEW VOLUME 163, NUMBER 4 20 NOVEMBER 1967

Neutron Pickup Reactions on Si^{30}†

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(Received 19 June 1967)

The neutron pickup reactions Si$^{30}(d,t)$Si^{29} and Si^{30}(He^3,α)Si^{29} have been studied. The results indicate that the neutron configuration of Si^{30} contains about equal components of $1d_{3/2}$ and $2s_{1/2}$ neutrons. A small f-wave neutron component in the ground-state wave function was also found. Strong transitions with $l=2$, $J^\pi=\frac{5}{2}^+$ were observed to levels at 2.03, 4.89, 6.72, and 8.32 MeV. The latter is probably the isobaric analog to the ground state of Al^{29}. The level at 4.08 MeV was not excited. The results are compared with the neutron stripping reaction Si$^{28}(d,p)$Si^{29} and with experiments on the γ decay of the states of Si^{29}.

I. INTRODUCTION

THE locations of the levels of Si^{29} are well known from several experiments. The spins and parities of the levels below 4 MeV have been obtained from the $(p,p'\gamma)$ work of Bromley *et al.*,[1] the Mg$^{26}(\alpha,n)$Si^{29} work of Litherland and McCallum,[2] and the particle-γ angular-correlation experiment of Becker, Chase, and MacDonald.[3] Of the levels in this region, the only one whose spin may be considered somewhat uncertain is the 3.07-MeV level for which spin assignments of $\frac{5}{2}^+$ and $\frac{3}{2}^+$ have been proposed. Earlier work has been summarized by Endt and Van der Leun.[4] A partial level scheme of Si^{29} is shown in Fig. 1.

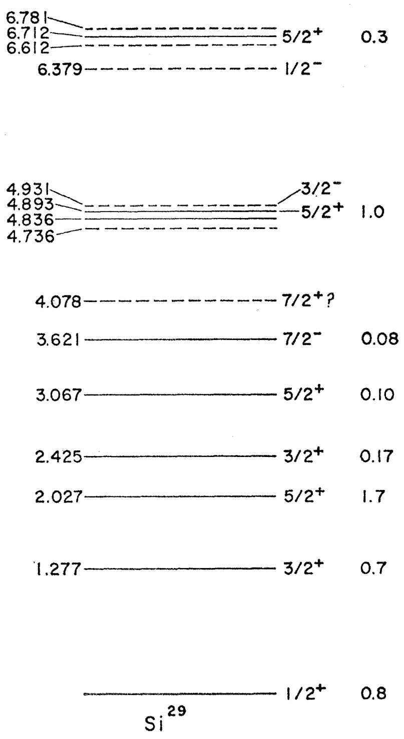

FIG. 1. Partial level scheme of Si^{29}. The levels not observed in the neutron pickup experiments are shown dashed. The number to the right of the spin is the experimental spectroscopic factor for the Si$^{30}(d,t)$Si^{29} experiment.

The investigation of the Si$^{30}(d,t)^{29}$ and Si^{30}(He,α)Si^{29} reactions will yield information on the ground-state wave function of Si^{30}. In particular, since the spins of the low-lying levels are known, it is possible to obtain a good occupation number for the $1d_{3/2}$ and $2s_{1/2}$ levels up to 4.8 MeV. This allows one to obtain some information on possible core excitation in Si^{30}. In addition, the distribution of the strength of the $l=2$ transitions among the excited states may give information on the validity of the use of the collective model as a description of Si^{29}. Such a description has been successful for nuclei with $A=25$ but appears to be inadequate for nuclei with $A=29$.

In the experimental investigation of theMg^{26}(He^3,α)-Mg^{25} reaction,[5] the $\frac{7}{2}^+$ and $\frac{9}{2}^+$ levels were relatively strongly excited. It has been proposed that these levels were not primarily excited by simple nucleon transfer, and a comparison with the excitation of the possible $\frac{7}{2}^+$ state at 4.08 MeV in Si^{29} was suggested. In the Mg^{26}-(He^3,α)Mg^{25} experiment, the observation of a very strong transition to the isobaric analog of the ground state of Na^{25} suggests strongly that the $d_{5/2}$ transition to other possible $\frac{5}{2}^+$ states with $T=\frac{3}{2}$ would have negligible strength. It is of interest to compare this transition with the transitions from states of Si^{30} to the isobaric analog of the ground state of Al^{29}.

II. EXPERIMENT

The 22.5-MeV deuteron beam and the 33.0-MeV He^3 beam of the Argonne 60-in. cyclotron were used to bombard self-supporting SiO$_2$ enriched to 95.5% in Si^{30}. The amount of oxygen in the target was not very well known, because the SiO$_2$ was partly reduced to SiO in the evaporation process. This impeded determining the target thickness by weighing. Instead, the target thickness was determined indirectly. In the (He^3,α) experiment, the elastic scattering of the He^3 particles was measured simultaneously. The yield was

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† Work performed under the auspices of the U. S. Atomic Energy Commission.

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[1] D. A. Bromley, H. E. Gove, E. B. Paul, A. E. Litherland, and E. Almqvist, Can. J. Phys. 35, 1042 (1957).

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then compared with the He^3 elastic scattering on a Mg^{26} target of known thickness. Assuming the elastic scattering to be the same within 10% for the two targets at forward angles, we arrived at a Si^{30} target thickness of 320 $\mu g/cm^2$. Since the Mg^{26} target thickness was known to approximately 10%, we believe that the cross section for the (He^3,α) reaction was determined with an uncertainty less than 20%.

In the (d,t) experiment another target was used, and this required a new determination of the thickness. It was found simply by comparing the elastic-deuteron-scattering cross sections with predicted values obtained by an optical-model calculation. In this case we computed a target thickness of 90 $\mu g/cm^2$—again with an uncertainty of 20%.

Particles were identified by use of an $E-dE/dx$ counter telescope consisting of a transmission-mounted totally-depleted surface-barrier detector of 163 μ thickness in combination with a 1-mm surface-barrier detector. For better resolution, several spectra of the (He^3,α) reaction were taken with a single detector. A typical spectrum is shown in Fig. 2. The use of a particle-identification system in the (He^3,α) reaction was nevertheless advisable because at several angles the energy of the He^3 elastically scattered from a heavy contaminant in the target coincided with that of the a group from the transition to the 8.3-MeV state.

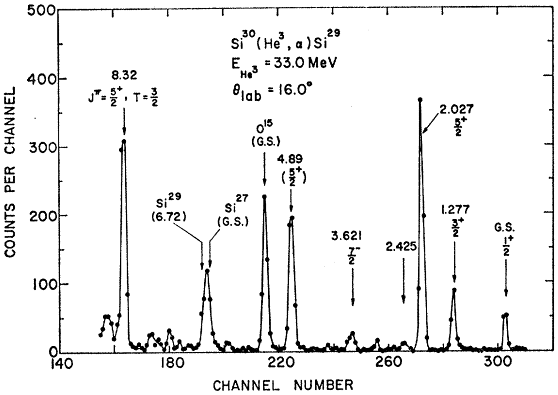

FIG. 2. α-particle spectrum from the $Si^{30}(He^3,\alpha)Si^{29}$ experiment at 33 MeV at $\theta_{lab}=10°$.

Obviously all the (d,t) spectra had to be taken with the $E-dE/dx$ detector system. Figure 3 shows the $Si^{30}(d,t)Si^{29}$ triton spectrum obtained at 24°. The α-particle spectra were measured at 60° and in steps of 2.0° or 2.5° between 10° and 55°. Triton spectra were obtained in steps of 3° between 12° and 30°. An aperture placed in front of the detectors was 3.18 mm in diameter and 200 mm from the target.

III. RESULTS

The α-particle spectrum (Fig. 2) shows strong transitions only to states at 2.027, 4.90, and 8.32 MeV. The state or group of states near 6.7-MeV excitation was not resolved from the $Si^{28}(He^3,\alpha)Si^{27}$ ground-state transition. The ground-state $l=0$ transition is only very weakly excited because of the often mentioned inhibition of $l=0$ transitions in a (He^3,α) reaction. The (d,t) spectrum (Fig. 3) shows a rather large yield for the ground-state transition at 24.° In the (d,t) reaction, the cross section for excitation of the 8.32-MeV state $(T=\frac{3}{2})$ is much less than the high value observed in the (He^3,α) reaction. This is due to the rather strong Q dependence of the (d,t) absolute cross section. For an excitation energy of 8.3 MeV, the c.m. energy of the outcoming triton ($E_t=8.5$ MeV) is already rather close to the Coulomb barrier when the deuterons are incident at 22.5 MeV. In the (He^3,α) reaction, however, the α energy is still well above the Coulomb barrier; because of the large positive Q value, the c.m. energy of the α particles is 32 MeV for the 8.3-MeV state. Another convenient feature of the (He^3,α) reaction is that the high momentum mismatch decreases with increasing excitation energy. As a result, (He^3,α) reactions show approximately the same yield for transitions of the same strength over a wide energy range. This behavior is correctly predicted by the distorted-wave (DW) theory. Therefore, the (He^3,α) reaction is quite suitable for the study of isobaric analog states.

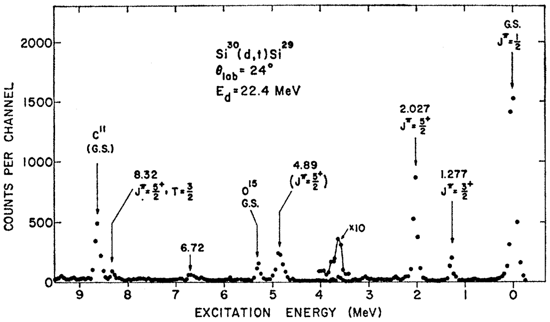

FIG. 3. Triton spectrum of the $Si^{30}(d,t)Si^{29}$ experiment at 22.4 MeV at $\theta_{lab}=24°$.

Angular distributions of the (He^3,α) and (d,t) reactions are shown in Figs. 4 and 5, respectively. Quantitative information on the strength S of the various transitions was obtained in the usual fashion by comparing experimental and calculated differential cross sections as related in the expression

$$\left(\frac{d\sigma}{d\omega}\right)_{\text{expt}}=NS\left(\frac{d\sigma}{d\omega}\right)_{\text{DW}}.$$

The distorted-wave curves, also shown in Figs. 4 and 5, were calculated with the code JULIE[6] by use of the optical-model parameters listed in Table I. Absolute spectroscopic factors (listed in Table II) were extracted from the (d,t) reaction by use of the $N(d,t)$ normaliza-

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[6] We are indebted to Dr. R. M. Drisko for making this program available to us.

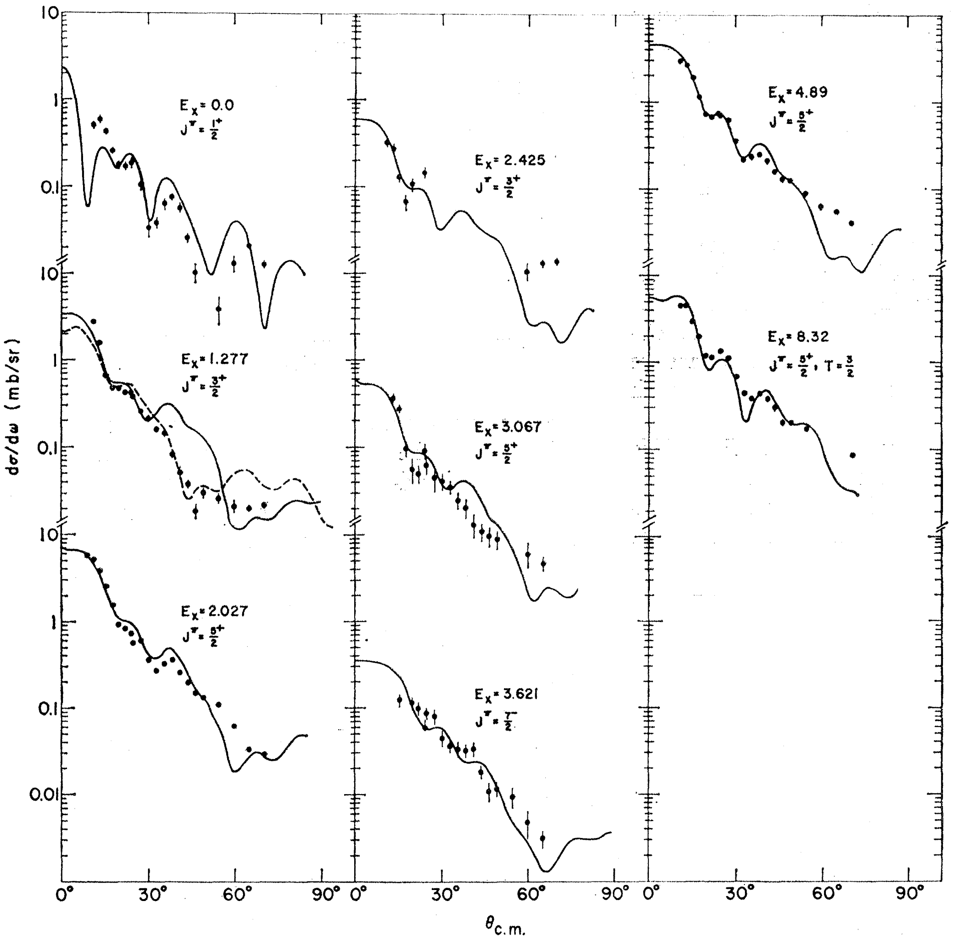

FIG. 4. Angular distributions and distorted-wave curves of the $Si^{30}(He^3,\alpha)Si^{29}$ reaction.

tion constant given by Bassel.[7] Because of the low yield of the ground-state $l=0$ transition in the (He^3,α) reaction and the uncertainty of the $l=0$ cross sections predicted by the distorted-wave calculations, the spectroscopic factors of the (He^3,α) reaction were normalized to the strength of the (d,t) reaction to the strongly excited $J^\pi = \frac{5}{2}^+$ state at 2.027 MeV. A (He^3,α) normalization factor $N(He^3,\alpha) = 13$ was obtained from this comparison. The value is very close to the normalization factor extracted in the same way from a comparison of the (d,t) and (He^3,α) reactions on Mg^{26}.

In the extraction of the spectroscopic factors in the (d,t) reaction, the deuteron optical-model-potential parameters do not quite reproduce the experimentally observed diffraction pattern of the elastically scattered deuterons, as shown in Fig. 6. This discrepancy does not appear to be as strong in the calculated triton angular distributions and it does not seriously affect the uncertainty in the absolute spectroscopic factors extracted from a comparison of the observed and calculated angular distributions. The uncertainty in the absolute spectroscopic factors for strong transitions is estimated to be about 20%. In the case of the level at 8.32 MeV, the uncertainty is estimated at 40%,

TABLE I. Optical-model parameters.

Set	Channel	V_0 (MeV)	W (MeV)	W_D (MeV)	r_0 (F)	a_0 (F)	r_i (F)	a_i (F)	r_c (F)	$V_s{}^0$ (MeV)
1	$Si^{30}+He^3$	155.1	20.1	0.0	1.22	0.69	1.6	0.75	1.4	8.0
2	$Si^{29}\pm He^4$	200.8	16.5	0.0	1.411	0.553	1.411	0.553	1.4	0.0
3	$Si^{30}+He^3$	167.1	20.5	0.0	1.10	0.688	1.688	0.75	1.4	8.0
4	$Si^{29}+He^4$	84.7	12.92	0.0	1.52	0.606	1.80	0.538	1.52	0.0
5	$Si^{30}+d$	61.2	0.0	69.6	1.416	0.571	1.088	0.847	1.4	8.0
6	$Si^{29}+t$	172.6	33.5	0.0	1.4	0.603	1.4	0.603	1.4	8.0

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[7] R. H. Bassel, Phys. Rev. **149**, 791 (1966).

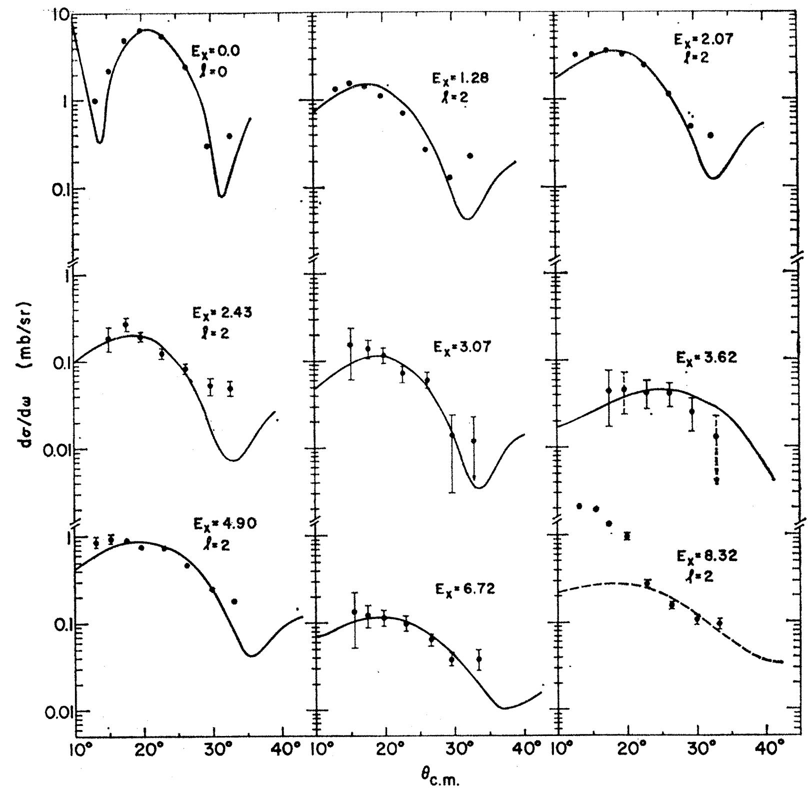

FIG. 5. Angular distributions and distorted-wave curves of the $Si^{30}(d,t)Si^{29}$ reaction. At angles smaller than 20° the $C^{12}(d,t)C^{11}$ ground-state transition is not separated from the 8.32-MeV transition. (See Fig. 3.)

since the experimental angular distribution in the region of the maximum could not be obtained. The relative uncertainties are obviously much smaller.

In the (He^3,α) reactions a j dependence is observed for transitions to the $\frac{5}{2}^+$ and $\frac{3}{2}^+$ states. A characteristic feature of the $J^\pi = \frac{5}{2}^+$ transitions is the oscillation around 40°, which is missing in the $J^\pi = \frac{3}{2}^+$ transition. Similar effects were observed in (He^3,α), and (α,t) reactions on Mg isotopes. The present experiment seems to show one exception to this j dependence: The angular distribution of the weak transition to the state at $E_x = 3.067$ MeV looks very much like the $J^\pi = \frac{3}{2}^+$ angular distributions, although recent angular-correlation work on the $Si^{27}(d,p\gamma)Si^{29}$ reaction[3] rather strongly suggests a spin of $J^\pi = \frac{5}{2}^+$. A similar discrepancy between the rules of j dependence and the stated spin of this state exists in the $Si^{28}(d,p)Si^{29}$ reaction.[8] Since this state is rather weakly excited in both stripping and pickup reactions and thus contains only a small amount of the $id_{5/2}$ neutron single-particle strength, the possible violation of the j-dependence rules may be explained by a more complex structure of this state.

The distorted-wave calculation has failed so far to reproduce the observed j dependence. Using a spin-orbit term in the form-factor calculation and in the He³ optical-model parameters affected the absolute cross

TABLE II. Absolute spectroscopic factors S for neutron pickup from Si³⁰.

E_x (Si²⁹) (MeV)	J^π	Spectroscopic factor, S (d,t)	(He^3,a)
0.0	$\frac{1}{2}^+$	0.8	(0.7)
1.277	$\frac{3}{2}^+$	0.7	1.2
2.027	$\frac{5}{2}^+$	1.7	1.7[a]
2.425	$\frac{3}{2}^+$	0.17	0.21
3.067	$(\frac{5}{2}^+)$	0.10	0.18
3.621	$\frac{7}{2}^-$	0.08	0.11
4.893 (+4.836)	$\frac{5}{2}^+$	1.0	1.0
6.72	$\frac{5}{2}^+$	0.3	
8.32	$\frac{5}{2}^+(T=\frac{3}{2})$	2.0	1.7

[a] Normalized to the (d,t) spectroscopic factor.

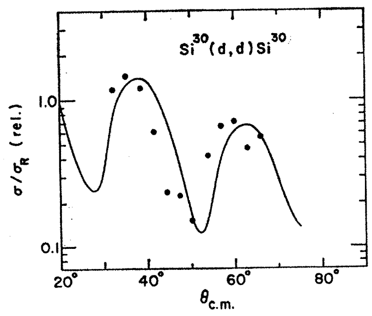

FIG. 6. Comparison of the experimentally observed angular distribution of deuterons elastically scattered from Si³⁰ with the angular distribution predicted by the optical-model-potential parameters used in the distorted-wave calculations.

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[8] J. P. Schiffer, L. L. Lee, Jr., A. Marinov, and C. Mayer-Böricke, Phys. Rev. 147, 829 (1966).

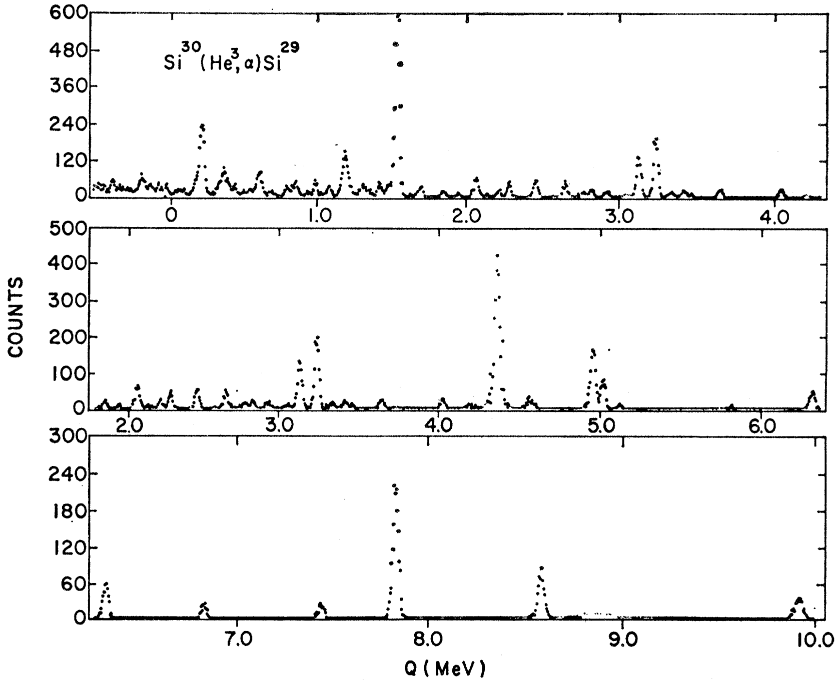

FIG. 7. α-particle spectrum from the $Si^{30}(He^3,\alpha)Si^{29}$ experiment at 12.0 MeV. $\theta_{lab}=30°$.

section but not the shape. The calculated curves always gave reasonable fits to the $J^\pi=\frac{5}{2}^+$ transitions. The relatively poor fit to the $J^\pi=\frac{3}{2}^+$ distributions could be improved quite considerably by applying a cutoff radius of 3.0 F (Fig. 4; broken line).

It was difficult to obtain a satisfactory fit to the $l=0$ ground-state transition. Optical-model parameter sets 3 and 4 (Table I) with a lower cutoff radius of 4.2 F were somewhat more successful than parameter sets 1 and 2, which were used in the calculations of the other distributions. Because of the poorer fit to the $J^\pi=\frac{3}{2}^+$ state, the uncertainty in the relative strength from the (He^3,α) reaction is larger for the $J^\pi=\frac{3}{2}^+$ transitions than for the $J^\pi=\frac{5}{2}^+$ transitions.

IV. DISCUSSION

Si^{30} has eight neutrons outside the O^{16} core. It is apparent from the sum of the observed transition strengths given in Table II that the $d_{5/2}$ shell is fairly well filled and that the remaining two particles are about equally distributed among the $2s_{1/2}$ and $1d_{3/2}$ shells. It is rather surprising that the transition to the level at 3.621 MeV, which has a rather well-established $\frac{7}{2}^-$ spin, is observed. The $f_{7/2}$ admixture in the ground state of Si^{30} is considerably larger than would be expected on the basis of the simple shell model. In the present cyclotron experiments, the transition to the 4.93-MeV level could not be separated from the levels at 4.89 and 4.84 MeV. However, the angular distribution shows no sign of any $l=1$ contribution in either reaction. This is consistent with magnetic-spectrograph data from the (He^3,α) reaction at 12 MeV. A spectrum obtained in this experiment (Fig. 7) indicates transitions to both the 4.89- and 4.84-MeV levels but not to the 4.93-MeV level which is strongly excited in the $Si^{28}(d,p)Si^{29}$ reaction. The angular distributions (Figs. 4 and 5) of the transitions to the 4.89-MeV level therefore presumably contain the sum of these two states, and both states appear to be excited by $l=2$ neutron transfer. It is estimated that more than 70% of the cross section comes from the 4.89-MeV level. A state is known to exist near 4.08 MeV. The work of Becker *et al.*[3] allows spins of $\frac{3}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$—with the $\frac{3}{2}$ spin somewhat less likely. This state was not excited in either the (d,t) or (He^3,α) reaction. In the mirror nucleus P^{29}, there is a level near 4.08 MeV which is thought to be a $\frac{7}{2}^+$ level.[9] In the $Mg^{26}(He^3,\alpha)Mg^{25}$ reaction, the $\frac{7}{2}^+$ level at 1.61 MeV was fairly strongly excited. This excitation is presumably a multiple-excitation process rather than pickup of a $g_{7/2}$ neutron. In the $Si^{30}(He^3,\alpha)Si^{29}$ reaction, neither excitation process appears to occur.

The transition strength to the 8.32-MeV state, the isobaric analog of the ground state of Al^{29}, is approximately the total $d_{5/2}$ strength to the $T=\frac{3}{2}$ state. It is therefore unlikely that there is another $d_{5/2}$, $T=\frac{3}{2}$ state with appreciable single-particle strength. This is consistent with result of the $Si^{30}(d,He^3)Al^{29}$ ground-state strength of 5.6 obtained by Bearse and Youngblood.[10] A similar result was observed in the $Mg^{26}(He^3,\alpha)Mg^{25}$ transition to the isobaric analog of the Na^{25} ground state. The cyclotron experiments did not permit an

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investigation of the isobaric analog of the 1.4-MeV $\frac{1}{2}^+$ level in Al^{29}.

The distribution of the $d_{5/2}$ strength over a number of $T=\frac{1}{2}$ states, two of which are strongly excited, is in rather sharp contrast to the apparently very good overlap between the wave functions of the Si^{30} ground state and the Al^{29} ground state plus a $d_{5/2}$ proton.

On the basis of both the $\mathrm{Si}^{30}(d,t)\mathrm{Si}^{29}$ and the $\mathrm{Si}^{28}(d,p)\mathrm{Si}^{29}$ experiments, the $\frac{3}{2}^+$ state at 1.28 MeV can be expected to have a large component of the $d_{3/2}$ single-particle neutron state. This is not inconsistent with the γ decay.[3,11] The absence of an appreciable γ transition to the ground state suggests that the 3.067-MeV level is not a strongly collective state based on the ground state. The (d,t) experiment indicates that it does not have a large single-particle neutron-hole component. However, there appears to be a discrepancy between the observed very fast γ transitions from the 2.027-MeV level (which suggests a very strong collective component for the wave function of that state) and the $\mathrm{Si}^{30}(d,t)\mathrm{Si}^{29}$ result (which requires an appreciable component of $d_{5/2}$ neutron-hole configuration).

ACKNOWLEDGMENTS

We are indebted to R. D. Lawson and R. E. Segel for several helpful discussions on the comparison between the neutron-pickup results and the γ-ray work. The technical assistance of J. Bicek and the cyclotron group is gratefully acknowledged.

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PHYSICAL REVIEW VOLUME 163, NUMBER 4 20 NOVEMBER 1967

Nuclear Structure of the Nickel Isotopes*

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(Received 10 July 1967)

The nickel isotopes are described in terms of strongly admixed spherical shell-model configurations of neutrons occupying the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbits. A set of effective-interaction matrix elements is deduced which accurately reproduces the spectra of the Ni isotopes from Ni^{58} to Ni^{67}. The wave functions resulting from the calculation of the energy levels are then used to calculate the single-nucleon spectroscopic factors. These are in fairly good agreement with the experimental spectroscopic factors found in pickup and stripping experiments. In addition, some of the results from two-nucleon transfer reactions are compared with the predictions of the present model. Using the wave functions obtained and an effective charge for the neutron, the $E2$ transition probabilities in the even-mass isotopes of Ni are calculated and found to be in agreement with experimental facts.

I. INTRODUCTION

In the past few years a great deal of experimental work has been performed in the region of the nickel isotopes[1–8] and few theoretical investigations were devoted to the study of this region.[9–16] Usually the theoretical studies were restricted to only a few nuclei in this region [11,12] or were hampered by the approximation schemes used in the different calculations.[9,10] Only very recently were detailed shell-model calculations performed for the Ni isotopes.[16] The new experimental results and in particular the data from stripping[1–3,7,8] and pickup [4,5] reactions make possible a closer examination of the structure of the nickel isotopes.

It is the purpose of the present work to give a detailed description of these nuclei which will be consistent with the new experimental facts. We will be concerned mainly with the spectra of the different isotopes as well as with the results obtained in various transfer reactions. The $B(E2)$ transition probabilities and quadrupole moments in the even-mass isotopes will also be considered.

The present calculation is based on the method of effective interactions in which the two-body matrix

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* Work supported by the U. S. Atomic Energy Commission.

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