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Study of the Low-Lying Excited States of Al^{29}. I. $Si^{30}(t, \alpha)Al^{29}$ Direct-Reaction Investigation*

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The $Si^{30}(t, \alpha)Al^{29}$ reaction at a bombarding energy of 11.8 MeV has been used to investigate the states of Al^{29} up to 4.5-MeV excitation energy. From the deduced l values of the picked-up protons, the spin parity of the 1.40-MeV state is confirmed as $\frac{1}{2}^+$ and an assignment of $J^\pi = \frac{1}{2}^+$ is made to the 3.43-MeV level. The states at 2.88, 3.07, 3.65, 3.68, and 4.23 MeV are assigned $J^\pi = (\frac{3}{2}, \frac{5}{2})^+$. Tentative assignments of $(\frac{5}{2}^-, \frac{7}{2}^-)$ are made for both the 3.19-and 3.99-MeV states which are weakly excited in the experiment. Assuming that most of the proton pickup strength has been observed, the percentage occupation of protons in the Si^{30} ground state is deduced to be $(1d_{5/2})^2 = 82\%$, $(2s_{1/2})^2 = 7\%$, $(1d_{3/2})^2 = 7\%$, and $(1f_{7/2})^2 \leq 4\%$.

I. INTRODUCTION

FOR a considerable time Al^{29} has remained one of the accessible nuclei of medium mass for which very little spin-parity information is available. The energy levels of this nucleus up to 6.8-MeV excitation energy were reported by Jaffe *et al.*,[1] who measured the differential cross section of the $Al^{27}(t, p)Al^{29}$ reaction at an incident triton energy of 5.5 MeV. In this study the angular momentum L transferred by the two neutrons was obtained for two states: the ground state for which an $L = 0$ transfer confirmed the $J^\pi = \frac{5}{2}^+$ assignment already inferred from β-decay considerations[2]; and the 3.58-MeV level for which an $L = 2$ transfer determined the state to have even parity and limited the spin to lie between $\frac{1}{2}$ and $\frac{9}{2}$.

Recently, a study of the differential cross section of the $Si^{30}(d, He^3)Al^{29}$ reaction at 23.4-MeV incident deuteron energy has been reported.[3] An $l = 2$ pattern observed for the ground-state angular distribution is consistent with the previous assignment of $J^\pi = \frac{5}{2}^+$, and an $l = 0$ distribution observed for the 1.40-MeV level determined the state to have spin-parity $\frac{1}{2}^+$. In the same work, the $Mg^{26}(\alpha, p)Al^{29}$ reaction was employed to excite the higher states that were not studied by the d, He^3 reaction. The measured energies of the states obtained were in close agreement with those reported by Jaffe. As far as can be ascertained, this is the only published information on excited states of Al^{29} although two other studies[4,5] are presently in progress.

In this paper, the results of a study of the charged particle angular distributions observed in a study of the $Si^{30}(t, \alpha)Al^{29}$ reaction at an incident triton energy of 11.8 MeV are presented. In Sec. II, we present an account of the experimental method, followed, in Sec. III, by the presentation of angular distributions and details of the extraction of l values and spectroscopic factors. In Sec. IV, we attempt to interpret the results in terms of the theoretical wave functions of Glaudemans *et al.*,[6] and we extract occupation numbers of protons in the Si^{30} ground state.

States in Al^{29} have also been studied in this laboratory by measuring γ-ray angular distributions in a colinear geometry, using both the $Al^{27}(t, p\gamma)Al^{29}$ and $Si^{30}(t, \alpha\gamma)Al^{29}$ reactions to populate the levels. Results of this investigation are described in a subsequent paper.[7]

II. EXPERIMENTAL METHOD

A beam of tritons of 11.8 MeV, accelerated by the Atomic Weapons Research Establishment, Aldermaston, United Kingdom, tandem Van de Graaff was used to bombard a 75-μg/cm^2 target of 95.55% enriched $Si^{30}O_2$ evaporated on to a 15-μg/cm^2 carbon film. Outgoing α particles were detected in 25-μ Ilford "K minus one" nuclear emulsions placed in the first 18 channels (5°–130° laboratory angle) of a multichannel spectrograph.[8] A total integrated charge of 2500 μC was collected in the Faraday cup during the bombardment. After processing, the nuclear plates were scanned in $\frac{1}{4}$-mm intervals for α tracks. We show in Fig. 1 a spectrum obtained from the spectrograph channel at 27.5° laboratory angle. The Al^{29} groups were identified by their kinematic motion at several angles. It was not found possible to obtain any information from the spectrograph channel at 5° laboratory angle because so many scattered triton tracks were present on the emulsion that the identification of α tracks amidst them was not possible. Evaluated energies for the Al^{29} levels are consistent with previous measurements of Jaffe *et al.*[1] and Bearse *et al.*[3]

III. ANGULAR DISTRIBUTIONS

In Figs. 2–18 we show the experimental angular distributions. No absolute cross section was measured in this experiment, and the abscissas are marked in

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[1] A. A. Jaffe, F. DeS. Barros, P. D. Forsyth, J. Muto, I. J. Taylor, and S. Ramavataram, Proc. Phys. Soc. (London) **76**, 914 (1960).

[2] P. M. Endt and C. van der Leun, Nucl. Phys. **A105**, 1 (1967).

[3] R. C. Bearse, D. H. Youngblood, and J. L. Yntema, Phys. Rev. **167**, 1043 (1968).

[4] R. G. Hirko (private communication).

[5] D. R. Tilley (private communication).

[6] P. W. M. Glaudemans, G. Wiechers, and P. J. Brussaard, Nucl. Phys. **56**, 548 (1964).

[7] A. D. W. Jones, J. A. Becker, and R. E. McDonald, Bull. Am. Phys. Soc. **13**, 1372 (1968); and (to be published).

[8] R. Middleton and S. Hinds, Nucl. Phys. **34**, 404 (1962).

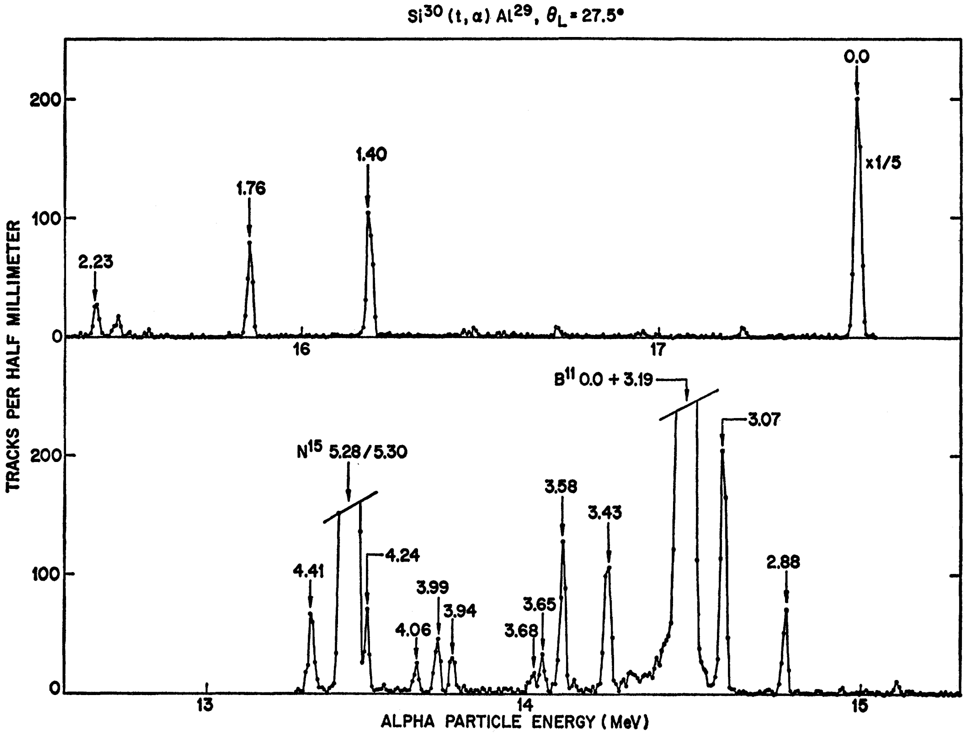

FIG. 1. α-particle spectrum obtained at 27.5° laboratory angle from the $Si^{30}(t,\alpha)Al^{29}$ reaction at $E_t = 11.8$ MeV. The levels of Al^{29} shown in the diagram are labeled in MeV and were identified from the variation of the energies of the peaks as a function of detection angle. The weak unmarked groups can be attributed to the $Si^{28}(t,\alpha)Al^{27}$ reaction from the 3.8% Si^{28} impurity in the target. At this angle the $C^{13}(t,\alpha)B^{12}$ ground-state group arising from the 1.1% C^{13} present in the target backing lies underneath the 4.41-MeV level. Due allowance for its presence has been made in extracting the angular distribution of this level, illustrated in Fig. 18.

number of counts observed. The strengths of the distributions presented are correct relative to each other.

Distorted wave fits were made to the angular distributions employing a code written by Yates[9] based on the work of Buck and Hodgson.[10] This code assumes that the mechanism of the t, α reaction is single-particle pickup and uses the zero-range assumption for the triton-proton interaction in the α particle. The bound proton is considered to move in a Saxon-Woods well whose depth is adjusted to reproduce the correct binding energy of the particle.[11]

The initial procedure adopted was to find a parameter set such that a fit could be obtained to the known $l=2$ transition to the ground state of Al^{29} using the triton parameters of Glover and Jones[12] and the α parameters of McFadden and Satchler.[13] This distribution was fitted well when parameters corresponding to deep wells were used in accordance with the current practice for the treatment of complex particles. When these same parameters were applied to the excited states, the fits were not good. The fit to the angular distribution of the α group populating the 3.07-MeV level is typical and is illustrated in Fig. 7. Here we show $l=1$, 2, and 3 predictions using parameters a, c, and e of Table I. There is little doubt that this distribution is best fitted by the $l=2$ curve as the $l=3$ prediction is certainly too wide and the $l=1$ curve, apart from any other considerations, does not correctly reproduce the second and third maxima at 42° and 65°, which the $l=2$ prediction does. Introducing a lower cutoff radius in the radial integral makes the $l=2$ fit narrower, but it is still wider than the experimental peak. Varying the parameters of the bound state resulted in significant changes in the predicted cross section but not in the shape of the fit. An acceptable fit was finally obtained to this distribution with parameters a, b, and d of Table I as shown in Fig. 8. Note that with these parameters, the introduction of a lower radial cutoff has no noticeable effect on its shape. These same parameters gave a fit to the ground-state distribution as shown in Fig. 2. This fit is narrower than the pickup peak but is still acceptable. For states at a higher excitation than the 3.07-MeV level, the $l=2$ predictions

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[9] M. J. L. Yates, Atomic Weapons Research Establishment, Aldermaston, United Kingdom (private communication).

[10] B. Buck and P. E. Hodgson, Phil. Mag. **6**, 1371 (1961).

[11] Calculations were carried out with a version of the code modified by R. W. Nightingale to run on the Univac-1108 computer of the Lockheed Missiles and Space Company.

[12] R. N. Glover and A. D. W. Jones, Nucl. Phys. **81**, 268 (1966); R. N. Glover (private communication).

[13] L. McFadden and G. R. Satchler, Nucl. Phys. **84**, 177 (1966).

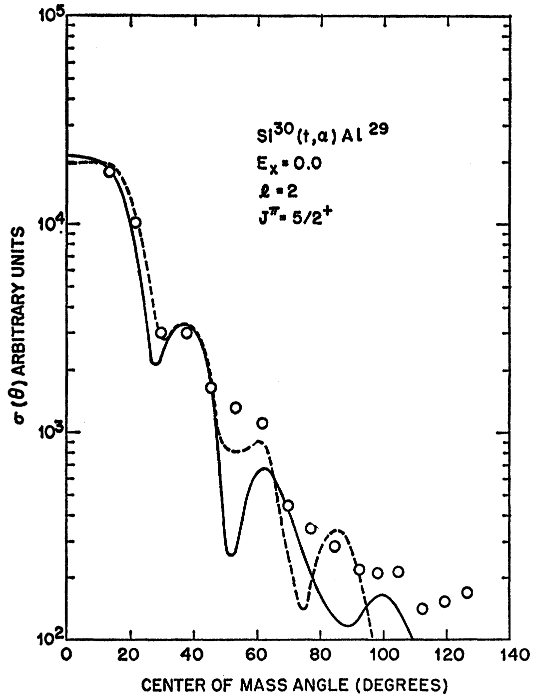

FIG. 2. Angular distribution of α particles to the ground state of Al^{29}. The dotted line is an $l=2$ fit employing parameters a, c, and e of Table I. The continuous line is a similar fit with parameters a, b, and d.

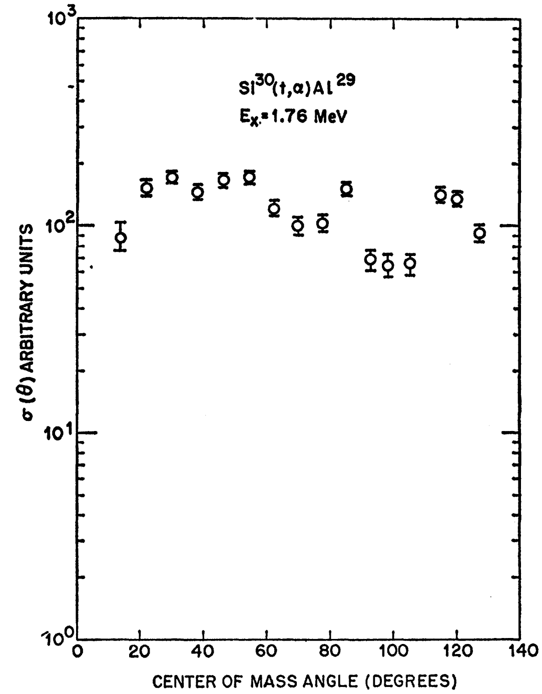

FIG. 4. Angular distribution of α particles to the Al^{29} state at 1.76 MeV.

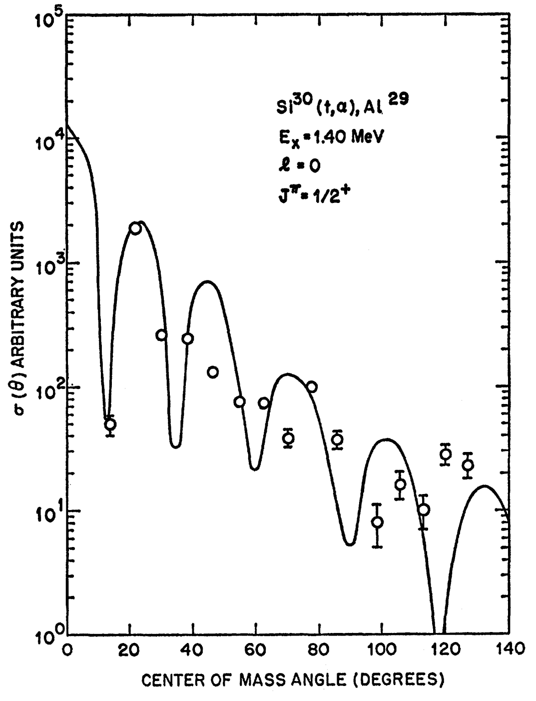

FIG. 3. Angular distribution of α particles to the Al^{29} state at 1.40 MeV. The fit shown is an $l=0$ prediction employing parameters a, b, and d of Table I.

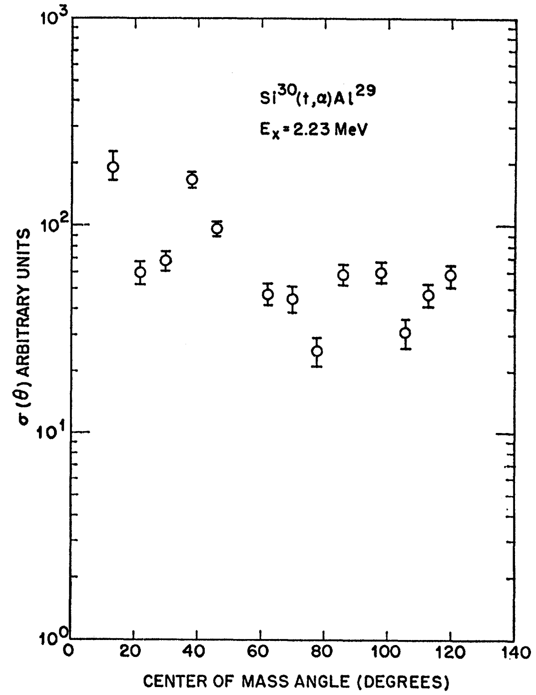

FIG. 5. Angular distribution of α particles to the Al^{29} state at 2.23 MeV.

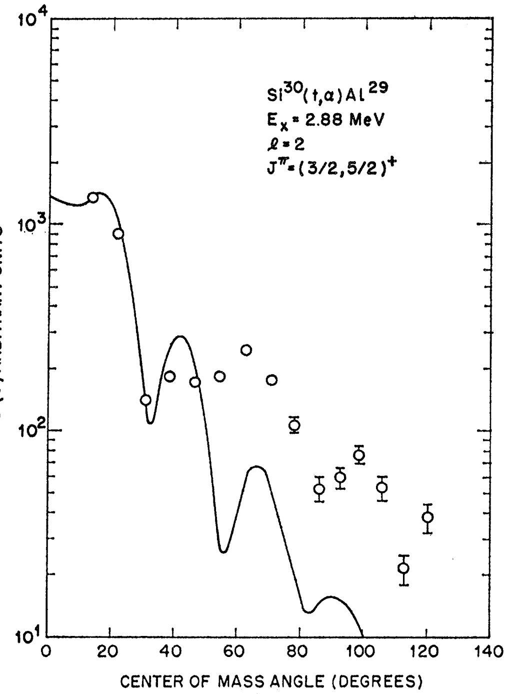

FIG. 6. Angular distribution of α particles to the Al^{29} state at 2.88 MeV. The fit shown is an $l=2$ prediction employing parameters a, b, and d of Table I.

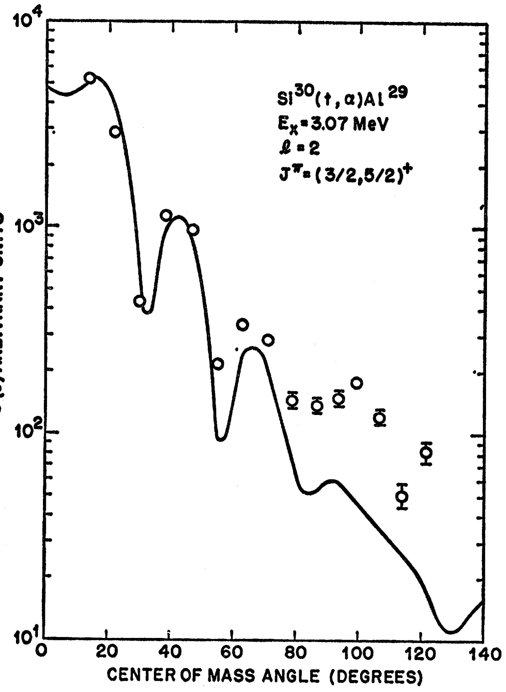

FIG. 8. Angular distribution of α particles to the Al^{29} state at 3.07 MeV. The fit shown is an $l=2$ prediction employing parameters a, b, and d of Table I.

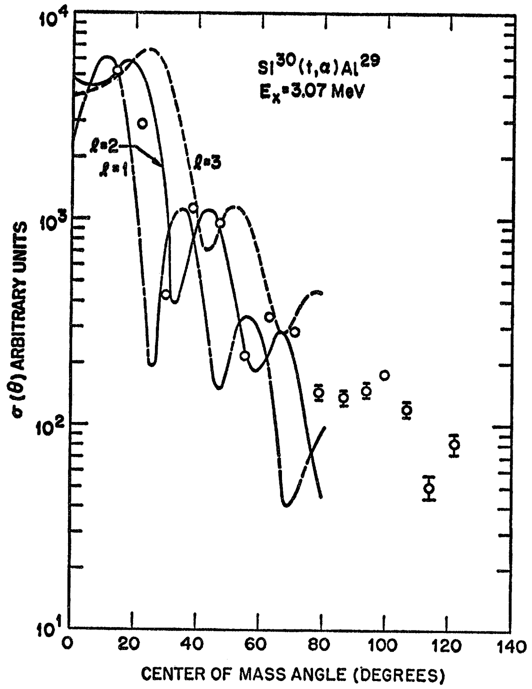

FIG. 7. Angular distribution of α particles to the Al^{29} state at 3.07 MeV. The fits shown are $l=1$, 2, and 3 predictions with parameters a, c, and e of Table I.

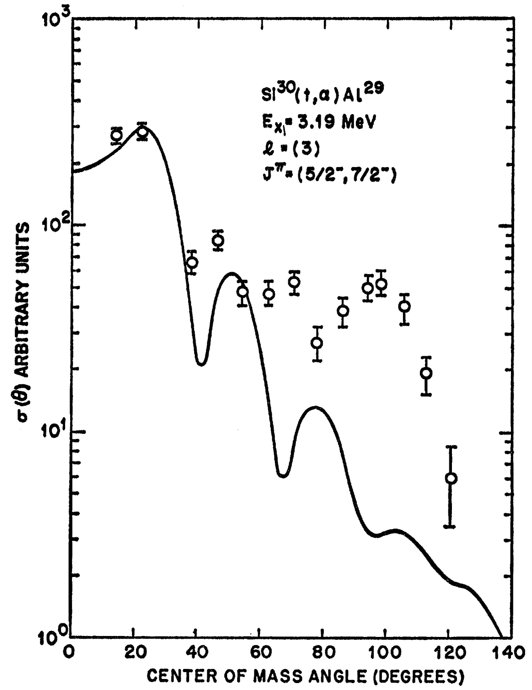

FIG. 9. Angular distribution of α particles to the Al^{29} state at 3.19 MeV. The fit shown is an $l=3$ prediction employing parameters a, b, and d of Table I.

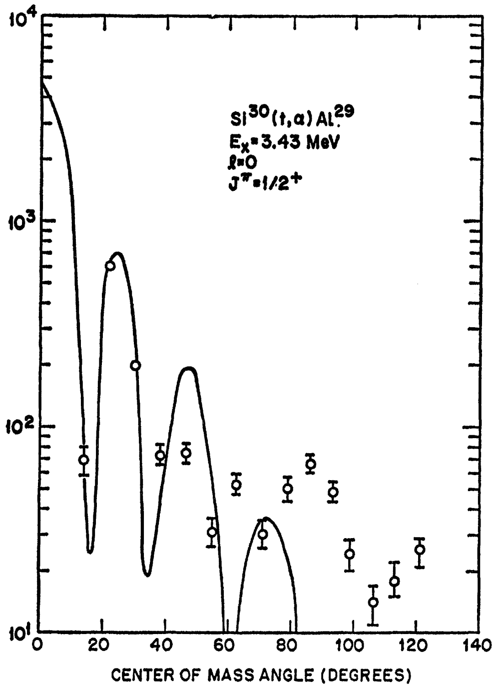

FIG. 10. Angular distribution of α particles to the Al^{29} state at 3.43 MeV. The fit shown is an $l=0$ prediction employing parameters a, b, and d of Table I.

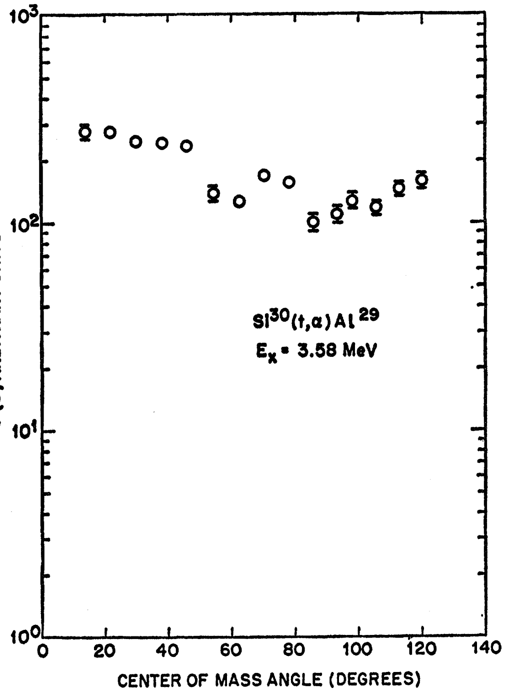

FIG. 11. Angular distribution of α particles to the Al^{29} state at 3.58 MeV.

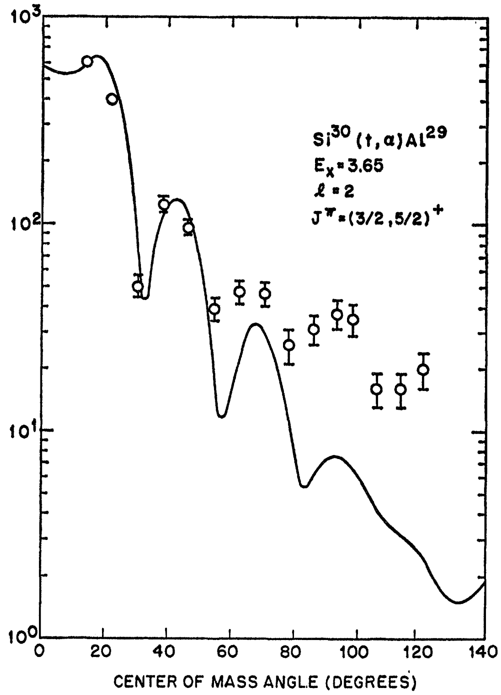

FIG. 12. Angular distribution of α particles to the Al^{29} state at 3.65 MeV. The fit shown is an $l=2$ prediction employing parameters a, b, and d of Table I.

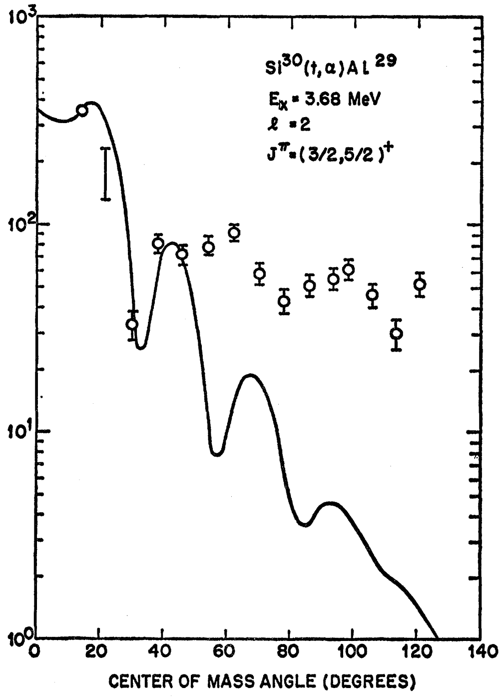

FIG. 13. Angular distribution of α particles to the Al^{29} state at 3.68 MeV. The fit shown is an $l=2$ prediction employing parameters a, b, and d of Table I. The estimate for the experimental point at a c.m. angle of 22.1° is obtained as discussed in the text.

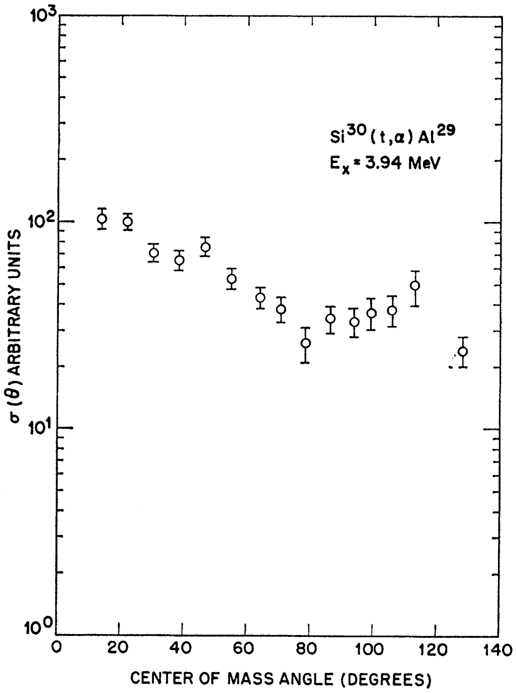

FIG. 14. Angular distribution of α particles to the Al^{29} state at 3.94 MeV.

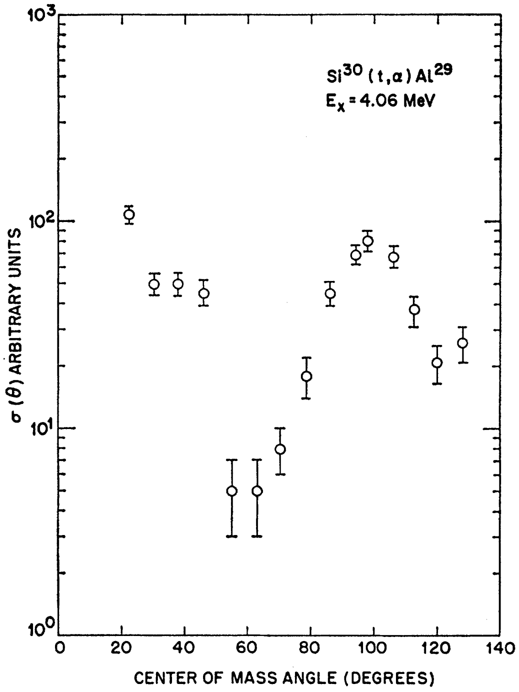

FIG. 16. Angular distribution of α particles to the Al^{29} state at 4.06 MeV. No interpretation of this distribution is made because of the loss of the data point from the spectrograph channel at 12.5° laboratory angle.

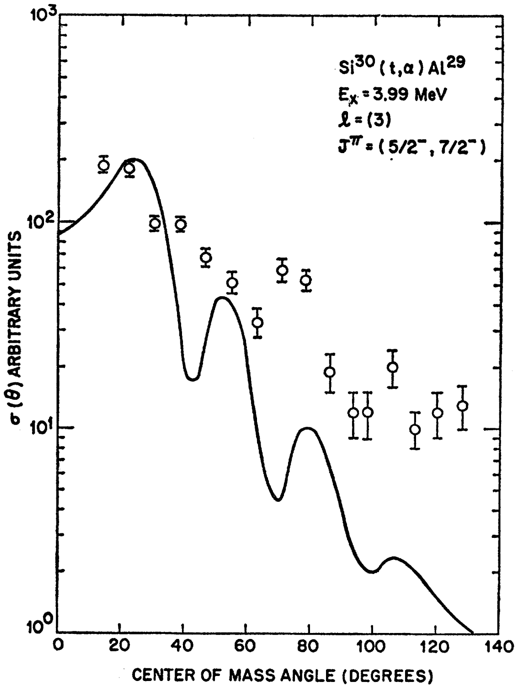

FIG. 15. Angular distribution of α particles to the Al^{29} state at 3.99 MeV. The fit shown is an $l=3$ prediction employing parameters a, b, and d of Table I.

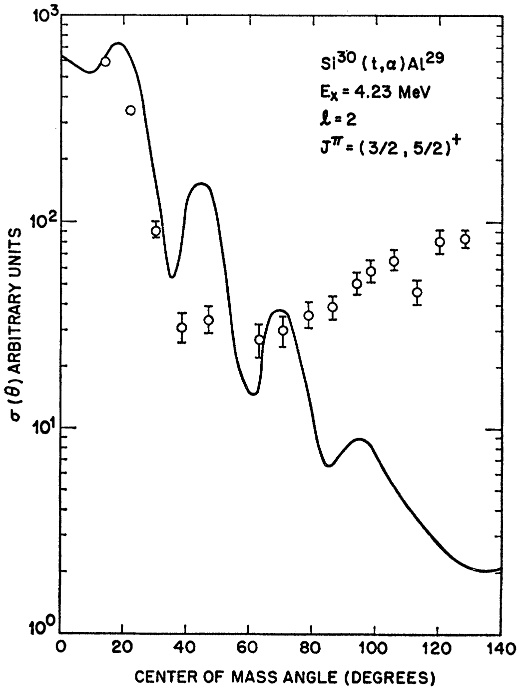

FIG. 17. Angular distribution of α particles to the Al^{29} state at 4.23 MeV. The fit shown is an $l=2$ prediction employing parameters a, b, and d of Table I.

TABLE I. Optical-model parameters.

		U (MeV)	W_v (MeV)	a_u (F)	r_u (F)	a_w (F)	r_w (F)	Reference
Tritons	(a)	148.1	36.8	0.657	1.240	0.742	1.420	a
α particles	(b)	24.9	9.0	0.54	1.802	0.54	1.802	b
	(c)	197.1	17.0	0.592	1.349	0.559	1.349	b
Bound state	(d)			0.65	1.25			
	(e)			0.65	1.20			

[a] Reference 12. [b] Reference 13.

with parameters a, b, and d are again broader than the peak of the experimental angular distributions as seen in Figs. 12, 13, and 17. Even so, we have taken parameters a, b, and d as the basis of our calculations, as they give the best overall fits to the angular distributions.

Such difficulties as these in fitting t, α angular distributions have been previously observed in a study of the $Zr^{92}(t, \alpha)Y^{91}$ reaction,[14] but there are no reported t, α distorted wave fits in the $A=30$ mass region for comparison. In contrast, it has been observed[15] that in the $1f_{7/2}$ shell, such distributions were reasonably predicted without having recourse to either cutoff radii or unphysical parameters, as needed here.

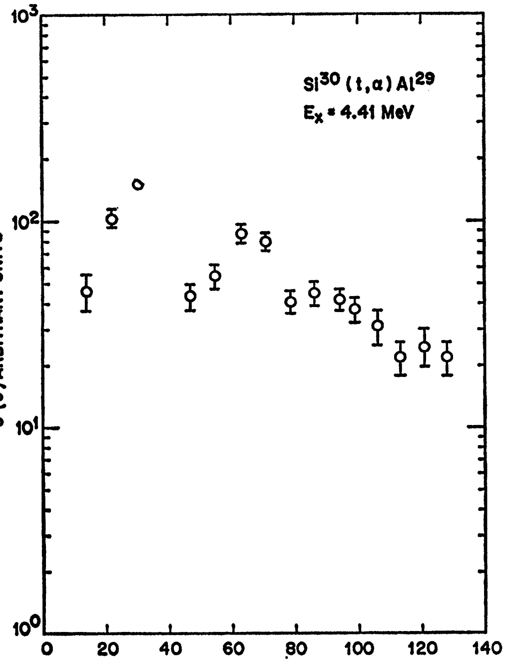

FIG. 18. Angular distribution of α particles to the Al^{29} state at 4.41 MeV.

Despite these drawbacks, two important criteria of direct reaction spectroscopy are basically unaffected: first, the prediction of relative cross sections and extraction of spectroscopic factors, and second, the assignment of l values. Relative cross sections of the distributions predicted with different parameter sets are very similar and are of the order of the 20% uncertainty typical for relative spectroscopic factors. The results of a sample calculation are shown in Table II.

As regards l-value extraction, four distributions are very similar to the ground-state pattern, in that the ratio of the measured intensity of the 12.5° to 20° laboratory angle data points is approximately constant, and the intensity at 27.5° is consistently almost an order of magnitude less than the intensity at the peak of the distribution. As discussed above, these trends are reproduced by the calculations; thus the transitions to the 2.88-, 3.07-, 3.65-, and 4.23-MeV states are assigned $l=2$.

For the 3.68-MeV state, the data point at 20° laboratory angle falls on the gap between the two nuclear plates used for each spectrograph angle so that some of the counts are lost. We can estimate the yield at 20° by fitting a line shape to the tails of the group observed on the two plates. In this way we extract the estimate shown in Fig. 13. The resulting distribution is consistent with an $l=2$ pattern and therefore this transition is also assigned $l=2$.

TABLE II. Relative peak cross sections resulting from calculations carried out with parameters of Table I.

		Relative peak cross sections[a]	
E_x (MeV)	l	Parameters a, b, and d[b]	Parameters a, c, and e[b]
0	2	1.00 (0°)	1.00 (10°)
1.40	0	0.90 (25°)	0.95 (25°)
2.88	2	0.62 (15°)	0.73 (15°)
3.19	3	0.31 (25°)	0.38 (25°)
3.68	2	0.52 (15°)	0.65 (15°)

[a] Intensity at second maximum taken for $l=0$ transition.
[b] See Table I.

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[14] J. C. Hardy, W. G. Davies, and W. Darcey, Nucl. Phys. **A121**, 103 (1968); and (private communication).

[15] A. D. W. Jones and R. N. Glover (to be published).

TABLE III. Spectroscopic factors for $Si^{30}(t, \alpha)Al^{29}$.

E_x (MeV)	l	J^π	Relative C^2S [a]	Normalized C^2S [b]	Relative (d, He^3) C^2S [c]
0	2	$\frac{5}{2}^+$	1.000	3.264	1.000
1.40	0	$\frac{1}{2}^+$	0.095	0.310	0.143
1.76	...	...			
2.23	...	...			
2.88	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.099	0.323	
3.07	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.405	1.322	
3.19	(3)	$(\frac{5}{2}^-, \frac{7}{2}^-)$	(0.046)	(0.150)	
3.43	0	$\frac{1}{2}^+$	0.034	0.111	
3.58	...	...			
3.65	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.053	0.173	
3.68	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.031	0.101	
3.94	...	...			
3.99	(3)	$(\frac{5}{2}^-, \frac{7}{2}^-)$	(0.025)	(0.082)	
4.06	...	...			
4.23	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.050	0.163	
4.41	...	...			

[a] Obtained with parameters a, b, and d of Table I.
[b] Normalized so that $\Sigma_l S = 6.0$.
[c] Reference 3.

With the same parameters, (a, b, and d of Table I) unambiguous $l=0$ fits are obtained for the 1.40- and 3.43-MeV states. After fitting the $l=2$ and $l=0$ patterns, two characteristic direct reaction distributions remain, those for the 3.19- and 3.99-MeV states. It is unfortunate that for the 3.19-MeV state the point at 27.5° laboratory angle is lost because a B^{11} impurity group is coincident in energy with the group at this angle (see Fig. 1). The first two points in the distribution favor a higher l value than 2, but an $l=3$ fit is not very good, and the loss of the 27.5° point becomes crucial to the assignment.

The 3.99-MeV state is very weakly excited, and the peak cross section is of the same order of magnitude as the cross section observed for some of the other states that show no direct reaction pattern. The pattern over the peak, however, is very similar to the 3.19-MeV distribution, but again the $l=3$ fit is too wide. In this energy region, as discussed above, the $l=2$ fits are also wider than the experimental peaks, and so we tentatively describe these two transitions as being due to an $l=3$ proton pickup.

A summary of these assignments, together with the deduced spin parity values and relative spectroscopic factors are shown in Table III. Also shown in Table III are the $Si^{30}(d, He^3)Al^{29}$ spectroscopic factors obtained from Ref. 3.

There are six states to which we can make no l value assignments as either the angular distributions are

TABLE IV. Application of the $2J+1$ rule to the integrated cross section for the 1.76-, 2.23-, 3.58-, and 3.94-MeV states in Al^{29}.

E_x (MeV)	Integrated cross section[a]	$J(2.23) = 1/2$	$J(2.23) = 3/2$	$J(2.23) = 5/2$
1.76	1.93	3/2	7/2	11/2
2.23	1.0	1/2	3/2	5/2
3.58	2.74	3/2, 5/2	9/2, 11/2	15/2
3.94	0.91	1/2	3/2	5/2

[a] The cross section is normalized to 1.0 for the 2.23-MeV level.

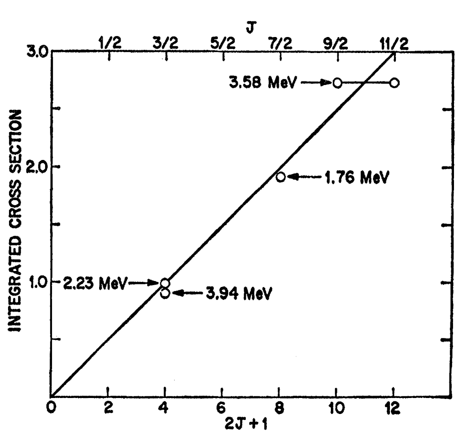

FIG. 19. The application of the $(2J+1)$ rule to the states shown. The normalization is to a spin of $\frac{1}{2}$ for the 2.23-MeV level.

TABLE V. Proton occupation numbers for Si^{30} and Si^{28}.[a]

	Si^{30} [b] $J^\pi(3.07)=5/2^+$	Si^{30} [b] $J^\pi(3.07)=3/2^+$	Si^{28} [c]	Si^{28} [d]
$(1d_{5/2})^2$	4.92 (82%)	3.60 (60%)	4.22 (73%)	4.72 (82%)
$(2s_{1/2})^2$	0.42 (7%)	0.42 (7%)	0.79 (14%)	0.49 (8%)
$(1d_{3/2})^2$	0.42 (7%)	1.75 (29%)	≥0.75 (13%) ≤0.99 (17%)	≥0.56 (10%) ≤0.96 (16%)

[a] In these evaluations it is assumed that all the pickup spectroscopic strength is observed in the experiment.

[b] Total strength is less than 100% because of the excitation of states with $l=3$ distributions.

[c] For the purpose of evaluating the percentage occupation of the $1d_{5/2}$ and $2s_{1/2}$ shells, the lower limit of the $1d_{3/2}$ strength is taken. See Ref. 18.

[d] For the purpose of evaluating the percentage occupation of the $1d_{5/2}$ and $2s_{1/2}$ shells, the lower limit of the $1d_{3/2}$ strength is taken. See Ref. 19.

almost isotropic, or the states are so weakly excited that they show no interpretable forward angle peak to which one may attempt to fit a theoretical curve. These are the α-particle distributions for the 1.76-, 2.23-, 3.58-, 3.94-, 4.06-, and 4.41-MeV states. We may conclude that the dominant method of formation of these states, with the possible exception of the 4.06- and 4.41-MeV states, is not through a direct reaction. Loss of the first two data points for the 4.06-MeV level distribution makes the interpretation of its structure difficult and the 4.41-MeV level distribution cannot be reconciled with any calculated fit. If, however, the formation of the states were by a compound nucleus process the conditions[16] are such that the total cross section would be proportional to $(2J+1)$, where J is the spin of the state. In Table IV we show the results of an integration of the 1.76-, 2.23-, 3.58-, and 3.94-MeV angular distributions from 0°–90°. Such a procedure includes contributions from any direct process, if present, and this is one of the limiting factors in this analysis. We also show in Table IV possible J values for the states assuming $J=\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ for the 2.23-MeV level. We see from Table IV that assuming $J=\frac{5}{2}$ for the 2.23-MeV level requires the 3.58-MeV level to have $J=\frac{15}{2}$, which is inconsistent with Jaffe's work.[1] Results presented elsewhere[6] rule out $J=\frac{1}{2}$ for the 2.23-MeV state because of the anisotropy in the angular distribution of the 2.23→0 MeV γ ray observed in the angular correlation investigation. Thus, this analysis is consistent only with the following assignments: 1.76 MeV, $J=\frac{7}{2}$; 2.23 MeV, $J=\frac{3}{2}$; 3.58 MeV, $J=\frac{9}{2}$; and 3.94 MeV, $J=\frac{3}{2}$. The results are shown graphically in Fig. 19. The rigor of such assumptions and analysis leaves a lot to be desired, and we regard the above values more as guides to future experiments than as tentative assignments.

IV. DISCUSSION

Theoretical predictions for the wave functions of Si^{30} states have been given by Glaudemans, Wiechers, and Brussaard.[7] Their basic assumption is that the $1d_{5/2}$ shell is closed at Si^{28} and that the nucleons occupy only the $1d_{3/2}$ and $2s_{1/2}$ shells. Their ground-state wave function for Si^{30} is as follows:

$$\psi(\text{g.s.}, J=0^+) = -\sqrt{(0.73)}\,(\nu 2s_{1/2})_0{}^2 + \sqrt{(0.27)}\,(\nu 1d_{3/2})_0{}^2 \cdots, \quad (1)$$

where ν denotes neutron occupation.

If such a wave function were a good representation of the Si^{30} ground state, one would expect to observe in the t, α reaction, at most, two $l=2$ transitions corresponding to the pickup of $d_{5/2}$ protons and forming states in Al^{29} whose structure could be considered basically as a $d_{5/2}$ proton hole coupled separately to the two components of the wave function written above. As can be seen from Table III, in the energy range covered, we observe six $l=2$ distributions. The two $l=0$ patterns observed at these low excitations are also not consistent with the predicted wave function and constitute direct evidence for some measure of proton occupation of the $2s_{1/2}$ shell. It is then a reasonable assumption that some of the $l=2$ strength observed comes from proton occupation of the $1d_{3/2}$ shell. This investigation does not directly distinguish between the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ states formed this way, but from γ-ray angular correlation work[6] the 2.88-MeV state is identified as $\frac{3}{2}$. No selection, however, is made between the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ assignment to the 3.07-MeV state. We can obtain more information from the spectroscopic sum rule[17] and by evaluation of the proton shell occupation numbers. In column 5 of Table III, we show a set of normalized spectroscopic factors. The normalization is such that the total strength of the transitions is 6.0, the same as would be observed if the $1d_{5/2}$ shell were completely closed. The basic assumption here is that most of the pickup strength has been observed in the range of excitation covered and that none of the strength observed comes from a deeper shell than the $1d_{5/2}$. Calculated occupation numbers for the $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$-proton shells are shown in Table V, assuming that the 3.07-MeV state has $J^\pi=\frac{3}{2}^+$ and $\frac{5}{2}^+$, in turn. In these evaluations we have taken the 3.65- and 4.23-MeV states to have $J^\pi=\frac{5}{2}^+$ and the 3.68-MeV state to have $J^\pi=\frac{3}{2}^+$. Such assignments are not inconsistent

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[16] N. MacDonald, Nucl. Phys. **33**, 110 (1962).

[17] J. B. French and M. H. MacFarlane, Nucl. Phys. **26**, 168 (1961).

with the γ decay of the 3.65- and 3.68-MeV states,[6] but we have no such information on the 4.23-MeV state. The spectroscopic factors for these states are small, however, and the values are not significant in the calculations. Incorrect assignments would only slightly alter the quoted percentages. We also show in Table V the results of similar calculations[18,19] for Si^{28}. In this case, the spins of the Al^{27} levels are well known,[2] and ambiguities of the kind experienced in this work were not encountered. Both experiments, however, investigate the closure of the $1d_{5/2}$ proton shell, and we expect the occupation numbers to be similar.

If we assume the 3.07-MeV state to be $\frac{5}{2}^+$, then the $1d_{3/2}$ and $2s_{1/2}$ shells have approximately equal populations, the same as is observed for Si^{28} as shown in columns 4 and 5 of Table V. The upper $1d_{3/2}$ limit shown in column 5 must be treated with reserve as Wildenthal and Newman[19] were unable to resolve the $\frac{3}{2}^+$ state at 2.976 MeV in Al^{27} from a $\frac{9}{2}^+$ state at 3.001 MeV. Their spectroscopic factor was extracted after fitting a combination of $l=2+4$ to the observed doublet distribution. Gove *et al.*[18] show that such a procedure is far from rigorous as the 3.001-MeV state, similarly formed in their experiment, did not show a pattern that could be reconciled with an $l=4$ distorted wave fit.

In view of these results, as well as the fact that the ground states of Si^{29} and P^{29} have $J^\pi=\frac{1}{2}^+$, indicating that in this region the $2s_{1/2}$ shell is lower in energy than the $1d_{3/2}$, it is unlikely that the occupation of the $1d_{3/2}$ shell would be four times that of the $2s_{1/2}$ shell which would be the case if the 3.07-MeV state had $J^\pi=\frac{3}{2}^+$. Faced with this evidence, we conclude that a $J^\pi=\frac{5}{2}^+$ assignment is favored for the 3.07-MeV level.

Two possible $l=3$ transitions have been observed in the energy region covered in the present experiment. We are unable to distinguish between the spin parity possibilities of $\frac{5}{2}^-$ and $\frac{7}{2}^-$, but the strength of these states is 4% of the total. We can regard this as an upper limit on the $(1f_{7/2})^2$ proton configuration in the Si^{30} ground state.

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[18] H. E. Gove, K. H. Purser, J. J. Schwartz, W. P. Alford, and D. Cline, Nucl. Phys. **A116**, 369 (1968).

[19] B. H. Wildenthal and E. Newman, Phys. Rev. **167**, 1027 (1968).

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Spin Flip in the Inelastic Scattering of Protons*†

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Proton spin-flip probabilities and differential inelastic scattering cross sections were measured over a large angular region for the following 2^+ excitations: 4.44 MeV in $^{12}\mathrm{C}$ at 12, 13, 14, 15, and 20 MeV; 1.45 MeV in $^{58}\mathrm{Ni}$ at 9.25, 10.46, 15, and 20 MeV; 1.33 MeV in $^{60}\mathrm{Ni}$ at 10.5 and 14 MeV; and 1.34 MeV in $^{64}\mathrm{Ni}$ at 10.5 and 14 MeV. The results were analyzed in the distorted-wave Born approximation, with collective-model form factors derived from the optical-model potential. The deformed spin-dependent part of the coupling potential was of the full Thomas form, and the data are best described when $\beta_2^{\mathrm{SO}}>\beta_2$. Good fits are obtained for elastic polarization data (obtained elsewhere) when the depth of the spin-orbit potential is determined from spin-flip probability measurements.

I. INTRODUCTION

NUMEROUS experiments involving the scattering of polarized protons have been performed in order to investigate spin-dependent forces in nuclei.[1-3] An alternative and complementary approach, and one which seems particularly attractive since it does not require the use of a polarized beam, is the measurement of spin flip in the inelastic scattering of protons from even-even nuclei. The method has been described in a

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[1] *Proceedings of the Second International Symposium on Polarization Phenomena of Nucleons, Karlsruhe, 1965*, edited by P. Huber and H. Schopper (Birkhauser Verlag, Basel, Germany, 1966).

[2] M. P. Fricke, E. E. Gross, and A. Zucker, Phys. Rev. **163**, 1153 (1967).

[3] C. Glashausser, R. de Swiniarski, J. Thirion, and A. D. Hill, Phys. Rev. **164**, 1437 (1967). This and Refs. 1 and 2 contain many references to earlier work.