Spin Assignments in the $2p$ Shell from J Dependence in (d,p) Angular Distributions*

L. L. LEE, JR.,† AND J. P. SCHIFFER
Argonne National Laboratory, Argonne, Illinois
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The empirically established J dependence in (d,p) angular distributions is used to assign spin values to energy levels in the nuclei Ti^{47}, Ti^{49}, Ti^{51}, Cr^{51}, Fe^{59}, and Ni^{65}—most of which are populated by $l=1$ (d,p) transitions with large cross sections. The results are in general agreement with available nuclear-structure calculations.

INTRODUCTION

IN a series of recent papers[1] we have discussed the experimental evidence that the proton angular distribution from a (d,p) reaction may show a systematic dependence on the total angular-momentum transfer ΔJ, in addition to the dependence of the angular distribution on the orbital-angular-momentum transfer.[2] The J dependence in the $2p$ shell, which is illustrated in Fig. 1 for 10-MeV deuterons, is quite firmly established experimentally. For $l_n=1$ transitions in the $2p$ shell, it is evident[1] that the proton angular distributions (for zero-spin targets) for final states of spin $J=\frac{1}{2}$ exhibit a sharp minimum in the angular range $90°<\theta<150°$, while those for final spin-$\frac{3}{2}$ states exhibit a smooth gradual decrease with increasing angle. Although this effect is not understood theoretically, no exceptions have been found for states with spectroscopic factors 0.1 or greater. It thus seems appropriate to use this effect to determine spins for states not already studied by angular-correlation techniques or other more firmly established methods of spin measurement.[3] It must be remembered, however, that we are using an empirical rule, whose application must be regarded with proper caution.

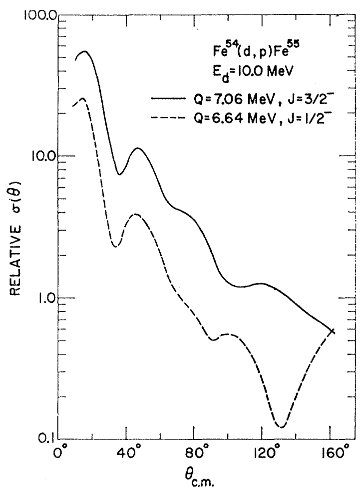

FIG. 1. Example of (d,p) J dependence for $l=1$ transitions in the $2p$ shell. Taken from Ref. 1.

The present paper[4] reports results for final states of previously undetermined spin in several nuclei in the mass range $47\leqslant A\leqslant 65$. In all cases studied except Fe^{59}, orbital-angular-momentum transfers $l_n=1$ (and usually the spectroscopic factors) have been determined for the states of interest in previous experiments, as noted below. The results obtained give spin values which, along with those obtained by other means, can be compared with predictions based on models for nuclear structure in this mass region.

In order to make possible a quantitative analysis of the angular distribution, we have determined the quantity $R=(\bar{\sigma}_{\max}-\sigma_{\min})/\frac{1}{2}(\bar{\sigma}_{\max}+\sigma_{\min})$ as a measure of the strength of the dip at backward angles. Here $\bar{\sigma}_{\max}$ is the average of the maximum cross sections on either side of the dip (or just the maximum behind the minimum if no clear maximum is observed within 30°–40° forward of the dip), and $\sigma_{\min}$ is the cross section at the minimum. For the cases in Ref. 1, the dip for $\Delta J=\frac{3}{2}$ transitions was usually absent, although a small dip with $R\leqslant 0.3$ was observed in a few cases; for the $\Delta J=\frac{1}{2}$ cases, all transitions had $R\geqslant 0.8$. In the present case we observe several angular distributions with $0.3\leqslant R\leqslant 0.8$. The dividing line between the two spins was therefore, somewhat arbitrarily, set at $R=0.5$. The validity of spin assignments then depends on how much R differs from this value as well as on the strength of the transition; a spin assignment is regarded as questionable for any transition with $R=0.5\pm 0.1$ or with a spectroscopic factor $S<0.1$.

EXPERIMENT

The measurements reported here were made in an 18-in.-diam scattering chamber[5] at the Argonne tandem accelerator. The bombarding energy $E_d=10$ MeV was chosen since earlier results[1] indicated that the J dependence was most prominent at this energy. Reaction

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† Present address: State University of New York at Stony Brook, Stony Brook, New York.

[1] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. Letters **12**, 108 (1964); L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. **136**, B405 (1964); J. P. Schiffer, L. L. Lee, Jr., A. Marinov, and C. Mayer-Böricke, *ibid.* **147**, 829 (1966).

[2] See, for example, S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).

[3] See, for example, *Nuclear Spin-Parity Assignments*, edited by N. B. Gove (Academic Press Inc., New York, 1966).

[4] A preliminary report of these results was given at the Washington meeting of the American Physical Society, April 1964 [Bull. Am. Phys. Soc. **9**, 457 (1964)].

[5] J. T. Heinrich and T. H. Braid (to be published).

protons were detected in Si surface-barrier detectors; the over-all energy resolution width was about 60 keV but varied with target thickness. Measurements were normalized to a monitor counter fixed at 90°. Pulse-height spectra were recorded in multichannel analyzers and punched on IBM cards for further reduction. The targets were self-supporting foils enriched in the isotope of interest, except that the Ni^{64} target was prepared by evaporating enriched Ni^{64} onto a thin carbon backing.

As mentioned earlier, the J dependence of interest in the present study appears in the backward part of the proton angular distribution. Therefore, except for the $Fe^{58}(d,p)Fe^{59}$ reaction for which no earlier angular distributions existed,[6] all measurements were confined to the angular range $90° \leqslant \theta \leqslant 160°$. Also, since the primary interest was in the shape of the angular distribution, no attempt was made to obtain absolute values of the cross section.

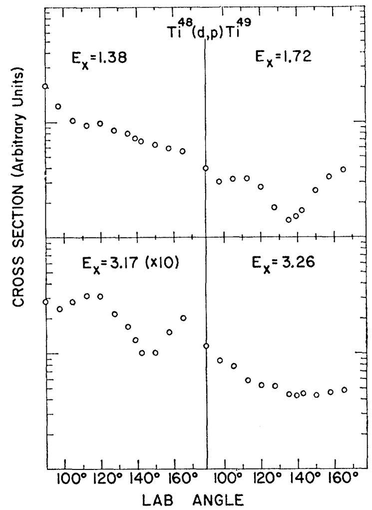

FIG. 3. Backward-quadrant angular distributions from the reaction $Ti^{48}(d,p)Ti^{49}$ to the final states indicated. Previous experiments have measured $l_n=1$ for these transitions. As indicated, the data points for the 3.17-MeV state are displaced upward by one decade relative to those for the other states.

RESULTS

$Ti^{46}(d,p)Ti^{47}$: Angular distributions of the prominent $l_n=1$ proton groups from this reaction are shown in Fig. 2. The excitation energies indicated are taken from the work of Rapaport, Sperduto, and Buechner,[7] who also made the measurement for $l_n=1$. It is evident that the angular distributions for the states at 1.79 and 2.54 MeV excitation both show pronounced dips at $\theta \approx 137°$. This indicates a spin of $\frac{1}{2}$ for these states. The fact that the other $l=1$ states studied have little structure in their back-angle distributions suggests that these are spin-$\frac{3}{2}$ states.

$Ti^{48}(d,p)Ti^{49}$: Back-angle $l_n=1$ angular distributions for this reaction are shown in Fig. 3. The excitation energies and l_n values are taken from the work of Rietjens, Bilaniuk, and Macfarlane.[8] There are pronounced dips for both the 1.72- and 3.17-MeV states while the angular distributions for the other states fall off smoothly with increasing angle. On this basis we can assign spin $\frac{1}{2}$ to the 1.72- and 3.17-MeV states and $J=\frac{3}{2}$ to the states at 1.38- and 3.26-MeV excitation. These assignments of the two lower-lying states are in agreement with the more definitive $(n,\gamma\gamma)$ angular-correlation work of Knowles *et al.*[9] and were among those used in our earlier papers[1] to establish the empirical J dependence.

$Ti^{50}(d,p)Ti^{51}$: For this reaction, measurements were made only for the strong $l_n=1$ transitions to the Ti^{51} ground state and the first excited state at 1.16-MeV excitation. The Q values and l_n have been determined for these levels by Ramavataram[10] and by Barnes *et al.*[11] Our results are shown in Fig. 4; they indicate spin $\frac{1}{2}$ for the 1.16-MeV state and $\frac{3}{2}$ for the ground state.

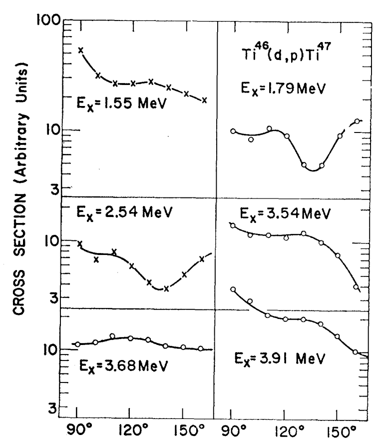

FIG. 2. Proton angular distributions in the backward quadrant from the reaction $Ti^{46}(d,p)Ti^{47}$. Excitation energies of the various states are indicated on the figure; $l_n=1$ has previously been determined for all of the states shown. In this and subsequent figures, the solid lines are to guide the eye and do not represent theoretical fits.

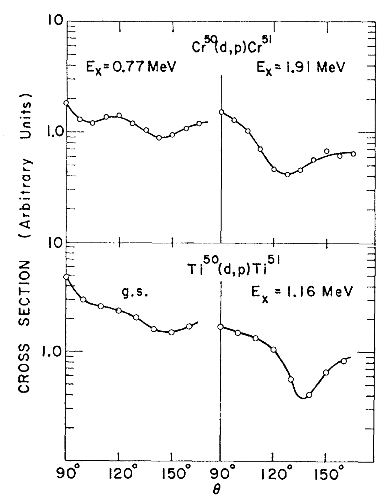

FIG. 4. Backward-quadrant angular distributions from the reactions $Ti^{50}(d,p)Ti^{51}$ and $Cr^{50}(d,p)Cr^{51}$ to the final states indicated. Previous experiments, cited in the text, have determined $l_n=1$ for these transitions.

[6] Q values to various states in Fe^{59} have been measured by A. Sperduto and W. W. Buechner [Phys. Rev. **134**, B142 (1964)].
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[9] J. W. Knowles, G. Manning, G. A. Bartholomew, and P. J. Campion, Phys. Rev. **114**, 1065 (1959).
[10] K. Ramavataram, Phys. Rev. **132**, 2255 (1963).
[11] P. D. Barnes, C. K. Bockelman, O. Hansen, and A. Sperduto, Phys. Rev. **136**, B438 (1964).

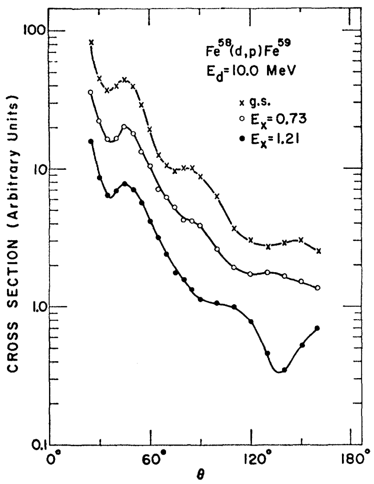

FIG. 5. Angular distributions from the reaction $Fe^{58}(d,p)Fe^{59}$ to the final states indicated. The data are displaced vertically for clarity of presentation. The $l_n=1$ character of these transitions is evident from the present data and the work of Ref. 14.

$Cr^{50}(d,p)Cr^{51}$: Angular distributions were obtained only for the strong $l_n=1$ groups from states of 0.77- and 1.91-MeV excitation; the results are also shown in Fig. 4. The value $l_n=1$ for these groups comes from the work of Bochin *et al.*[12] Our results indicate spin $\frac{3}{2}^-$ for the 0.77-MeV state and a doubtful $\frac{3}{2}^-$ for the 1.91-MeV state, although a minimum with $R=0.47$ is observed in this case. More recent high-resolution work[13] has shown that the 0.77-MeV level is in fact a doublet. From their observed J dependence, the authors of Ref. 13 assign $J=\frac{3}{2}^-$ to a state at 0.769-MeV excitation and $\frac{1}{2}^-$ to a state at 0.795-MeV excitation. Their measured yield to the 0.769-MeV state is about three times that to the 0.795-MeV state. It is thus likely that our angular distribution is dominated by the $\frac{3}{2}^-$ state.

$Fe^{58}(d,p)Fe^{59}$: Since no previous (d,p) angular-distribution results were available for this reaction, it was

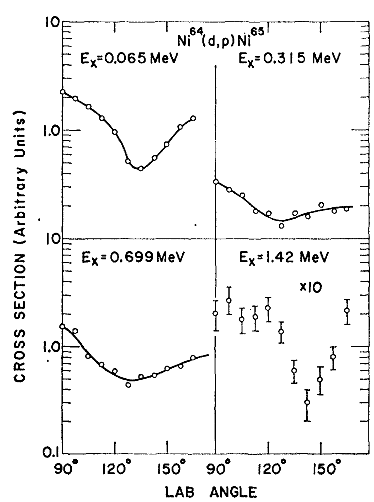

FIG. 6. Backward-quadrant angular distributions from the reaction $Ni^{64}(d,p)Ni^{65}$ to the final states indicated. Previous experiments have determined $l_n=1$ for all of these transitions. As indicated, the data points for the 1.42-MeV state are displaced upward by one decade relative to those for the other states.

TABLE I. Spin assignments for the states indicated. They are based on the observed J dependence as discussed in the text for each case.

Final nucleus	Excitation (MeV)	Approximate spectroscopic factor	R^a	Spin[b]
Ti^{47}	1.55	0.59[c]	0.04	$\frac{3}{2}$
	1.79	0.36	0.78+	$\frac{1}{2}$
	2.54	0.16	0.70+	$\frac{1}{2}$
	3.27	0.05	No dip	($\frac{3}{2}$)
	3.67	0.12	No dip	$\frac{3}{2}$
	3.91	0.21	No dip	$\frac{3}{2}$
Ti^{49}	1.38	0.7[d]	No dip	$\frac{3}{2}$[e]
	1.72	0.6	0.88+	$\frac{1}{2}$[e]
	3.17	0.3	0.87+	$\frac{1}{2}$
	3.26	0.3	0.04	$\frac{3}{2}$
Ti^{51}	0	0.9[f]	0.31	$\frac{3}{2}$
	1.16	0.85	1.03+	$\frac{1}{2}$
Cr^{51}	0.77[g]	0.3[h]	0.38	$\frac{3}{2}$[g]
	1.91	0.2	0.47	($\frac{3}{2}$)[i]
Fe^{59}	0	0.51[j]	0.11	$\frac{3}{2}$
	0.73	0.16	0.06	$\frac{3}{2}$
	1.21	0.74	0.88+	$\frac{1}{2}$
Ni^{65}	0.065	0.6[k]	1.14+	$\frac{1}{2}$
	0.315	0.04	0.31	($\frac{3}{2}$)
	0.699	0.15	0.45	($\frac{3}{2}$)
	1.42	0.07	1.50	($\frac{1}{2}$)

[a] R is a measure of the depth of the minimum as defined in the text. A plus sign is used to indicate that the cross section is still clearly rising at back angles and that the value of R is larger than the number given.
[b] Parentheses indicate doubtful assignments.
[c] Reference 7, distorted-wave Born approximation (DWBA). The spectroscopic factor quoted in this reference for the 3.27-MeV state seems to be low by an order of magnitude, possibly because of a misprint.
[d] Reference 8, from normalized plane-wave stripping theory.
[e] Spin assignment consistent with Ref. 9.
[f] Reference 11, DWBA.
[g] Doublet. See Ref. 13 and text.
[h] Reference 12, normalized by the present authors.
[i] Spin assignment confirmed in Ref. 18.
[j] Reference 14, DWBA.
[k] Reference 15, DWBA.

necessary to extendour measurements to forward angles to locate the strong $l_n=1$ transitions. Our results are shown in Fig. 5, in which the data are displaced vertically for clarity of presentation. Although our measurements do not cover the first maximum of the angular distribution, $l_n=1$ is clearly indicated for all of the angular distributions shown.[14] The observed J dependence clearly indicates $J=\frac{1}{2}^-$ for the level at 1.21-MeV excitation and $\frac{3}{2}^-$ for the other levels shown.

$Ni^{64}(d,p)Ni^{65}$: Angular distributions for this reaction were obtained at forward angles by Fulmer and McCarthy.[15] Our back-angle distributions corresponding to four transitions for which they identify $l_n=1$ are shown in Fig. 6. $J=\frac{1}{2}^-$ is clearly indicated for the strong transition to the state at 0.065-MeV excitation in Ni^{65}.

[12] V. P. Bochin, K. I. Zherebtsova, V. S. Zolotarev, V. A. Komarov, L. V. Krasnov, V. G. Litvin, Yu. A. Nemilov, B. G. Novatsky, and Sh. Piskorzh, Nucl. Phys. **51**, 161 (1964).

[13] J. E. Robertshaw, A. Sperduto, and W. W. Buechner, Bull. Am. Phys. Soc. **11**, 318 (1966).

[14] A more complete study of the reaction $Fe^{58}(d,p)Fe^{59}$, including DWBA analysis, is being prepared for publication by E. D. Klema and the present authors.

[15] R. H. Fulmer and A. L. McCarthy, Phys. Rev. **131**, 2133 (1963).

We think that the dip observed for the 0.699-MeV state is too slight ($R=0.45$) to be $J=\frac{1}{2}^-$ and suggest $\frac{3}{2}^-$ for that state, although this is certainly questionable. The other two states observed have small (d,p) cross sections ($S<0.1$), so the indications here are unreliable. In particular, the sharp dip observed for the 1.42-MeV state predicts $\frac{1}{2}^-$, in contrast to a study[16] of the Cu^{65} analog to this state which suggested $\frac{3}{2}^-$.

All of the results above are summarized in Table I, in which values of spectroscopic factors are also given. Since these values have been determined by different workers using different methods, they should be regarded as comparable only within a given reaction.

DISCUSSION

Some of the results presented above can be directly compared with other experiments and with available nuclear-structure calculations. Alty *et al.*[17] used 9.15-MeV deuterons in J-dependence measurements of the type employed here. Their results include the Ti^{47}, Ti^{49}, and Cr^{51} states reported here and many more. They agree with our results except for the 2.54-MeV state in Ti^{47} and the 3.17-MeV state in Ti^{49}. Since they do not show angular distributions for these states, we are not able to comment on this discrepancy. From their observations of J dependence in (d,p) reactions, Robertshaw *et al.*[13] report $J=\frac{1}{2}^-$ for the 1.91-MeV level in Cr^{51}, in disagreement with our $(\frac{3}{2}^-)$ assignment. For this level, however, the $(n,\gamma\gamma)$ results of Bartholomew *et al.*[18] indicate $\frac{3}{2}^-$ from an unambiguous measurement of the γ-γ angular correlation through this state. It must be noted that the levels in question are among those for which the backward minima in the angular distributions are less pronounced than in the well-established $J=\frac{1}{2}$ cases.[1]

Several other authors[8,15,19] have reported spin assignments based on relative cross sections in stripping and pickup reactions, (d,p) spectroscopic factors, and nuclear systematics. These assignments are, of course, highly tentative and must be regarded with some caution. For instance, the present spin assignments in Ti^{47} and Ti^{49} disagree strongly with those of Ref. 8, and in one of these cases our assignment is supported by angular-correlation results.[9] Similarly, our results for Ni^{65} disagree with the assignments of Ref. 15, particularly for the strong transition to the 0.065-MeV state.

In several cases, the spin values suggested by the present work can be compared with predictions based on various nuclear models. Ti^{51} especially, with 29 neutrons, has been extensively studied by several workers. The most recent and detailed treatment is that of Vervier,[20] who has made a detailed shell-model calculation in the $N=29$ and $N=30$ nuclei. His paper contains a full comparison with experiment and with earlier calculations.[10,21] All three of the pertinent calculations predict $\frac{3}{2}^-$ for the Ti^{51} ground state and $\frac{1}{2}^-$ for the 1.16-MeV excited state, in agreement with the spins determined in the present experiment.

The states of Ni^{65} and other Ni isotopes have been calculated by use of the pairing-force approximation by Kisslinger and Sorenson[22] and by Kerman, Lawson, and Macfarlane,[23] and by use of shell-model techniques by Auerbach[24] (who considered only seniority-1 states) and by Cohen, Lawson, Macfarlane, Pandya, and Soga.[25] The predictions of these papers are in general agreement with each other and with our results for Ni^{65}: $\frac{1}{2}$ for the 0.065-MeV state, $\frac{3}{2}^-$ for the states at 0.315- and 0.699-MeV excitation. It is also worth noting that this level order is, as expected, virtually the same[26] as in the isotonic nucleus Zn^{67}.

Fe^{59} (with five neutrons outside the closed $f_{7/2}$ shell and two $f_{7/2}$ proton holes) and the nuclei Cr^{51} and $Ti^{47,49}$ (with the $f_{7/2}$ shell unfilled for both protons and neutrons) present more difficult problems of calculation. We are unaware of any predictions in which the $p_{3/2}$ and $p_{1/2}$ orbitals are included. In all of these latter nuclei, our results and those of Ref. 13 suggest low-lying $\frac{3}{2}^-$, $\frac{1}{2}^-$ doublets with separations of at most 350 keV. The appearance of such doublets in other nuclei in this region (Cr^{53},Fe^{55},Ni^{59},Ni^{61}) has been noted some time ago.[27] The separation is much less than the known $p_{3/2}$-$p_{1/2}$ spin-orbit splitting for the single particle energies of ~ 2 MeV. Our results also suggest possible $\frac{1}{2}^-$ states at higher excitation, but this has not been confirmed by other experiments. It would be interesting to obtain angular-correlation results for the more highly excited p states in the Ti nuclei.

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