In actual calculations the N-d phase shifts of van Oers and Brockmann[6] were used. The interference terms between the graphs shown in Fig. 2 were also taken into account. The result of the calculations normalized by $N = 0.093$ for $E_d = 10.0$ MeV are shown in Fig. 1. The model describes the general behavior of the coincidence spectra rather well, although the calculated spectral shape is broader than the measured one. The quasifree scattering model for the reaction $p+d \rightarrow p+p+n$ also predicted slightly broader spectral shapes than were measured.[3]

Figure 3 shows the dependence with bombarding energy of the normalization constant necessary for the calculated cross section to reproduce the measured d-p peak cross sections. As the bombarding energy decreases the disagreement between the absolute values of the calculated and measured cross section increases.

In conclusion it might be said that nucleon-deuteron quasifree scattering in the reaction $d+d \rightarrow d+p+n$ dominates the measured d-n and d-p coincidence spectra. This is a surprising result, since at these low bombarding energies the de Broglie wavelength of a deuteron is rather large, which makes it difficult for a deuteron to interact with only one nucleon in the other deuteron. The equality of the d-n and d-p peak cross section indicates that the FSI modifications of the observed QFS peaks are not significant. However, the constructed model for deuteron-nucleon quasifree scattering in the reaction $d+d \rightarrow d+p+n$ at low bombarding energies predicts a cross section an order of magnitude too high. Furthermore, the limitations of the simple quasifree scattering model are revealed by the fact that the calculated curves are broader than the measured spectra and that the normalization constant to the measured peak cross section is energy dependent. Further experiments[7] are being performed to investigate the angular distributions of the QFS peaks and compare them with the simple model.

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[1] V. Valković, W. von Witsch, D. Rendić, and G. C. Phillips, Phys. Letters 33B, 208 (1970).

[2] V. Valković, D. Rendić, V. A. Otte, W. von Witsch, and G. C. Phillips, Phys. Rev. Letters 26, 394 (1971).

[3] V. Valković, D. Rendić, V. A. Otte, W. von Witsch, and G. C. Phillips, Nucl. Phys. A166, 547 (1971).

[4] A. S. Wilson, M. C. Taylor, J. C. Lett, and G. C. Phillips, Nucl. Phys. A126, 193 (1969).

[5] I. M. Duck, V. Valković, and G. C. Phillips, to be published.

[6] W. T. H. van Oers and K. W. Brockmann, Nucl. Phys. 92, 561 (1967).

[7] E. Andrade, V. Valković, D. Rendić, W. E. Sweeney, Jr., and G. C. Phillips, Bull. Am. Phys. Soc. 16, 54 (1971).

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J Dependence for $L=2$ (α, p) Transitions in s-d Shell Nuclei

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The J dependence for $L=2$ transfer has been studied at $E_\alpha = 28.8$ MeV for the (α, p) reactions on ^{32}S and ^{24}Mg. The results are compared with previous $^{28}Si(\alpha, p)^{31}P$ data where no J dependence is observed for $L=2$ transfer.

Previous J-dependence studies on even-even target nuclei leading to states of presumably well-established spins and parities for both (α, p) and (p, α) reactions have shown a large and persistent difference in shape of the angular distributions for $L=1$ transfer to $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states. Earlier work by Lee *et al.*,[1] who interpreted the data of Yamazaki, Kondo, and Yamabe[2] for $L=2$ transfer reactions in $^{28}Si(\alpha, p)^{31}P$ and $^{32}S(\alpha, p)^{35}Cl$ at $E_\alpha = 22.2$ MeV, also indicated a fairly large J dependence in these cases as well. However, recent experiments[3,4] at the Naval Research Laboratory (NRL) at 28.8 and 39.5 MeV showed that the $^{28}Si(\alpha, p)^{31}P$ reaction exhibited essentially no J dependence for the same

TABLE I. Optical-model parameters for DWBA calculations.

Channel	V_S (MeV)	W_S (MeV)	W_D (MeV)	r_{0S} (fm)	r_{0I} (fm)	r_C (fm)	a_S (fm)	a_I (fm)	V_{so} (MeV)
$^{32}S+\alpha$	182	16.9	...	1.63	1.63	1.30	0.421	0.421	...
$^{35}Cl+p$	42.8	...	13.5	1.25	1.25	1.25	0.650	0.470	7.50

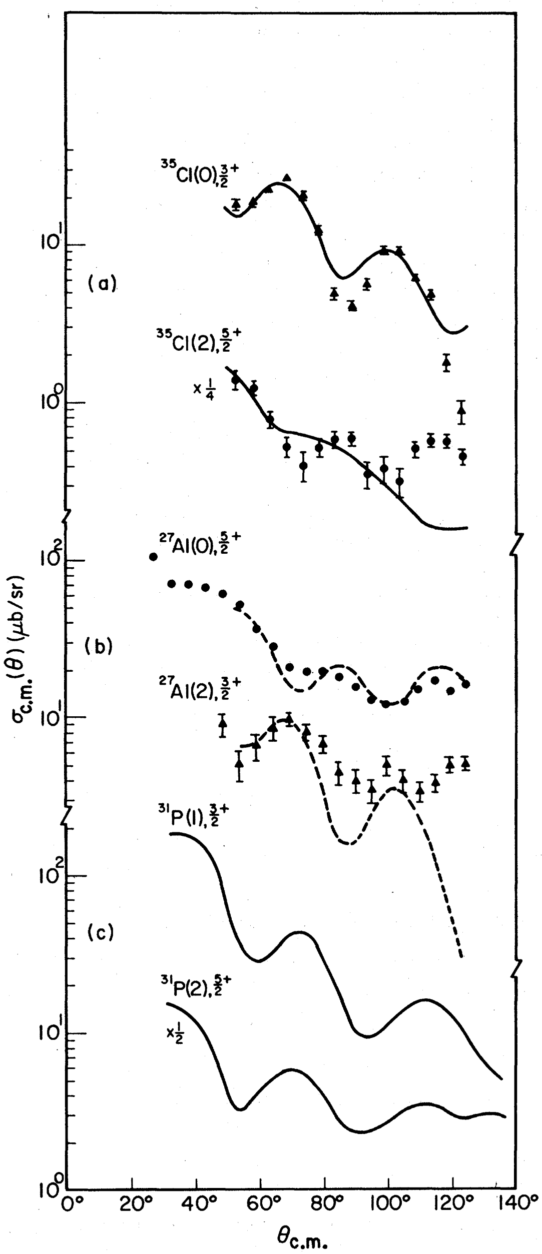

FIG. 1. Proton angular distributions for $L=2$ transfer obtained at $E_\alpha=28.8$ MeV for the reactions: (a) $^{32}S(\alpha,p)$-^{35}Cl; (b) $^{24}Mg(\alpha,p)^{27}Al$; and (c) $^{28}Si(\alpha,p)^{31}P$. In those cases where error bars are not shown they are equal to or smaller than the data points.

$L=2$ transitions discussed by Lee *et al.* It was, therefore, a matter of considerable interest to study (α, p) J dependence for $L=2$ transfer on target nuclei "similar" to ^{28}Si, i.e., even-even, $N=Z$, and not very different A. In this note we report on the results for $L=2$ transfer in the (α, p) reactions on ^{32}S and ^{24}Mg at 28.8 MeV, and compare these data and distorted-wave Born-approximation (DWBA) calculations with the earlier work on the $^{28}Si(\alpha, p)^{31}P$ reaction.

The 28.8-MeV α beam was obtained from the NRL isochronous cyclotron, and the beam currents utilized ranged from 0.1 to 0.5 μA. Two counter telescopes were employed in this work, and particle identification was done digitally. The sulfur target was made by evaporating natural PbS onto a 30-$\mu g/cm^2$ carbon foil, and the effective ^{32}S thickness was 163 $\mu g/cm^2$. The over-all resolution for the $^{32}S(\alpha, p)$ work was approximately 250-keV full width at half maximum (FWHM). The ^{24}Mg target was a 418-$\mu g/cm^2$ self-supporting foil of isotopically enriched ^{24}Mg of greater than 99% purity that was obtained from the Isotopes Division of the Oak Ridge National Laboratory. The over-all resolution was about 100-keV FWHM for the $^{24}Mg(\alpha, p)$ experiment.

In Figs. 1(a) and 1(b) we see evidence for J dependence in the reactions $^{32}S(\alpha, p)^{35}Cl$ and ^{24}Mg-$(\alpha, p)^{27}Al$ at $E_\alpha=28.8$ MeV for $L=2$ transfer. The proton angular distributions for the $^{32}S(\alpha, p)$ reaction are for the $\frac{3}{2}^+$ ground state and the $\frac{5}{2}^+$ second excited state at 1.763 MeV in ^{35}Cl. The J dependence manifests itself primarily by the two angular distributions being out of phase. The $\frac{5}{2}^+$ distribution appears to be less oscillatory than that for the $\frac{3}{2}^+$ state, but because of possible compound-nucleus effects and the indicated errors, extremely close comparison cannot be made. The solid curves that have been arbitrarily normalized to the appropriate $^{32}S(\alpha, p)$ distributions are local zero-range DWBA calculations that have been made using the code DWUCK.[5] The form factor utilized in the calculations is that for a triton cluster bound in a Woods-Saxon well. The optical-model parameters for the $\alpha+{}^{32}S$ channel were obtained by searching with the code SEEK[6] on elastic scattering data found in the literature,[7] and for the $p+{}^{35}Cl$ channel the average parameters suggested by

Perey[8] were employed. The parameters are given in Table I, and the nomenclature is consistent with that used by Perey.

The *J* dependence for the $^{24}Mg(\alpha, p)$ reaction shown in Fig. 1(b) for $L=2$ transfer to the $\frac{5}{2}^+$ ground state and the $\frac{3}{2}^+$ second excited state at 1.013 MeV in ^{27}Al again manifests itself primarily by the two distributions being out of phase. The dashed distributions that have been arbitrarily normalized to the experimental data were obtained by drawing smooth curves through the data for the corresponding states in ^{35}Cl. As far as where the maxima and minima occur, the comparisons show that the results for states of the same spin and parity in ^{35}Cl and ^{27}Al are indeed similar. Again we emphasize the importance that should be attached to possible compound-nucleus effects and error assignments in making such comparisons.

In Fig. 1(c) a representation of some previous NRL data[3] also obtained at $E_\alpha = 28.8$ MeV is shown for convenience of comparison. The proton angular distributions are for $L=2$ transfer for the $\frac{3}{2}^+$, 1.27-MeV first excited and the $\frac{5}{2}^+$, 2.23-MeV second excited states of ^{31}P that are populated by the reaction $^{28}Si(\alpha, p)^{31}P$. In marked contrast to the other data in the figure, the $^{28}Si(\alpha, p)$ reaction exhibits essentially no *J* dependence, as manifested by the two distributions being in phase and the amplitude of the oscillations being the same. There also appears to be a significant compound-nucleus contribution to the $\frac{5}{2}^+$ distribution. Data[4,9] taken at incident energies of 35.5 and 39.5 MeV for these same transitions yield distributions that are more forward-peaked, and, consequently, they exhibit even greater similarity than is seen in Fig. 1(c).

To summarize, we see that the (α, p) *J* dependence for $L=2$ transfer in the reactions $^{32}S(\alpha, p)$-^{35}Cl and $^{24}Mg(\alpha, p)^{27}Al$ are, at least qualitatively, similar and about what would be expected on the basis of the simple DWBA calculations shown in Fig. 1(a). The failure to observe a *J* dependence in the reaction $^{28}Si(\alpha, p)^{31}P$ for $L=2$ transfer remains a problem. It might be suspected that the J^π assignment for the second excited state of ^{31}P is $\frac{3}{2}^+$, but recent experiments,[10,11] as well as previous ones,[12] are consistent with a $\frac{5}{2}^+$ assignment for this state.

On the basis of these observations, either of two conclusions could be reached. In one view, it can be argued that (α, p) *J* dependence for $L=2$ transfer is an unreliable spectroscopic technique and should be rejected completely. Alternatively, it is possible to postulate that the failure to observe *J* dependence in the reaction $^{28}Si(\alpha, p)^{31}P$ is peculiar to the mass region $A \approx 28$, perhaps owing to structure effects of some sort, and that the *J* dependence for $L=2$ transfer can be reliably employed as a spectroscopic tool elsewhere. Considering the very small amount of data that have been obtained by systematically studying well-understood states, both possible conclusions are premature. It is hoped that this work will stimulate further study of the questions raised. It would be especially worthwhile to investigate well-substantiated $\frac{3}{2}^+$ and $\frac{5}{2}^+$ states in heavier nuclei, where the problems associated with direct-reaction studies on light nuclei are absent.

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[1] L. L. Lee, Jr., A. Marinov, C. Mayer-Böricke, J. P. Schiffer, R. H. Bassel, R. M. Drisko, and G. R. Satchler, Phys. Rev. Letters 14, 261 (1965).

[2] T. Yamazaki, M. Kondo, and S. Yamabe, J. Phys. Soc. Japan 18, 620 (1963).

[3] L. S. August, P. Shapiro, and L. R. Cooper, Phys. Rev. Letters 23, 537 (1969).

[4] L. R. Cooper, L. S. August, P. Shapiro, and J. J. Kolata, Bull. Am. Phys. Soc. II, 15, 630 (1970).

[5] DWBA code DWUCK by P. D. Kunz, 1967 (unpublished).

[6] Search code SEEK by M. A. Melkanoff, J. Raynal, and T. Sawada, 1966 (unpublished).

[7] A. Bobrowska, A. Budzanowski, K. Grotowski, L. Jarczyk, S. Micek, H. Niewodniczanski, A. Strzalkowski, and Z. Wrobel, Institute of Nuclear Physics, Cracow, Report No. 624/PL, 1968 (unpublished).

[8] F. G. Perey, Phys. Rev. 131, 745 (1963).

[9] J. E. Glenn, C. D. Zafiratos, and C. S. Zaidins, Phys. Rev. Letters 26, 328 (1971).

[10] C. E. Moss, R. V. Poore, N. R. Roberson, and D. R. Tilley, Nucl. Phys. A144, 577 (1970).

[11] B. Mertens, C. Mayer-Böricke, and H. Kattenborn, Nucl. Phys. A158, 97 (1970).

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