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Measurements of vector analyzing power in the $(\vec{d},t)$ reaction on ^{54}Cr, ^{56}Fe, and ^{64}Ni at 15, 16, and 18 MeV

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Measurements of vector analyzing power have been carried out for the $(\vec{d},t)$ reaction on targets of ^{54}Cr, ^{56}Fe, and ^{64}Ni at deuteron energies of 15, 16, and 18 MeV. Data were taken over the angular range 10°–55° for transitions to low-lying states of $J^\pi=(\frac{1}{2},\frac{3}{2},\frac{5}{2},\frac{7}{2})^-$ using a position-sensitive counter telescope in the focal plane of an Enge spectrograph. Transitions to states of $j^\pi=\frac{3}{2}^-$ or $\frac{7}{2}^-$ show only slight dependence on incident energy, while those to states of $j^\pi=\frac{1}{2}^-$ or $\frac{5}{2}^-$ show a greater dependence, and greater variations between different states. Distorted-wave Born approximation calculations show at best qualitative agreement with the data. The results indicate that measurements of VAP for the $(\vec{d},t)$ reaction at low energies will not provide accurate estimates of j mixing for transitions on odd-A targets.

INTRODUCTION

Measurements of angular distributions of cross sections in single-particle transfer reactions have long been used to determine the orbital angular momentum l and the parity of the transferred particle, and hence to investigate the shell-model structure of nuclei. While the determination of l is usually unambiguous as long as particle energies are well above the Coulomb barrier, cross sections show little sensitivity to the total angular momentum transfer $j=l\pm\frac{1}{2}$. In contrast to this, measurements of analyzing power in reactions initiated with a polarized beam are found to have a strong and often characteristic dependence on j.

Extensive studies of analyzing powers in polarized $(\mathbf{d},p)$ stripping reactions have been carried out by Haeberli and co-workers [1,2]. This work has shown that at beam energies near the Coulomb barrier height, analyzing powers are large and of opposite sign for the two possible j values associated with a given l. The experimental results do not show strong sensitivity to A of the target or reaction Q value, and are fitted quite well with standard distorted-wave Born approximation (DWBA) calculations. At somewhat higher energies, which provide better discrimination of l, DW calculations of analyzing power may not fit the data as well, but the j of the transferred neutron is readily determined. In the case of stripping of an odd-A target for which $J_i\neq 0$, there may be two or more allowed values of j for the transferred neutron. Kocher and Haeberli [3] have shown that, in this case, measurements of analyzing power may also be used to determine the relative contributions of different transfer j values.

It is expected that polarized pickup reactions such as $(\vec{p},d)$ or $(\vec{d},t)$ will also show a j dependence in their analyzing powers, and this has also been extensively investigated. Initial measurements of A_y in the $(\vec{d},t)$ reaction were carried out at sub-Coulomb energies for the outgoing tritons [4,5], and results similar to those for $(\vec{d},p)$ reactions were observed. At somewhat higher energies, however, the j discrimination is not as clear for $(\vec{d},t)$ reactions [6–8] and DWBA fits to the data are often poor. It has also been found [9] that the analyzing power for a given j depends sensitively on the reaction Q value and that the DW calculations usually model the Q dependence better for $j=l+\frac{1}{2}$ than for $j=l-\frac{1}{2}$ transitions. This last observation implies the influence of some specifically spin-dependent interaction in the reaction, and it has been suggested that this may arise from the D-state component of the deuteron wave function or from a tensor term in the deuteron optical potential. Studies [10–12] have shown, however, that while these factors are essential for understanding tensor analyzing powers, they have almost no influence on the vector analyzing power.

In spite of these problems with the interpretation of analyzing power measurements in $(\vec{d},t)$ reactions, the relatively small negative Q values for this reaction make it attractive for pickup studies with low-energy accelerators, and numerous spectroscopic studies have been reported [7,13–19]. The present study was initiated as part of an effort to use the $(\vec{d},t)$ reaction for quantitative spectroscopic studies of (fp) shell nuclei. Given the difficulties with analyzing power measurements mentioned earlier, it is important to establish better the dependence of the analyzing power for given j on target

TABLE I. Target specifications.

Target	Thickness (mg/cm^2)	Enrichment (%)	$Q_{\mathrm{g.s.}}(d,t)$ (MeV)
^{54}Cr	1.2	94	−3.46
^{56}Fe	1.5	91.7 (natural)	−4.95
^{64}Ni	1.0	>97.9	−3.40

mass, reaction Q value, and incident beam energy. In order to avoid possible problems from nondirect or second-order processes in the reaction mechanism, we have confined our attention to strong transitions leading to well-resolved states of known spin and parity in ^{53}Cr, ^{55}Fe, and ^{63}Ni.

The measurements reported here were carried out using the polarized deuteron beam from the FN tandem Van de Graaf accelerator at the Tandem Accelerator Laboratory of McMaster University. Beam currents were typically up to 50 nA, with polarization about $p = 0.7$, as measured by the quench ratio method [20]. Reaction products were analyzed using an Enge split-pole magnetic spectrograph with a position-sensitive detector and particle identification system similar to that developed by Markham and Robertson [21]. Energy resolution was about 25 keV, permitting clear identification of triton groups of interest and excellent discrimination of impurity groups. Triton spectra were measured over the angular range 10°–55° at beam energies of 15, 16, and 18 MeV, except that scattered deuterons obscured some triton groups of interest at energies and angles, as noted below.

TABLE II. States observed in $(\vec{d},t)$ measurements.

Residual nucleus	E_x (MeV)	J^π	C^2S	Reference
^{53}Cr	0.0	$\frac{3}{2}^-$	0.66	
	0.564	$\frac{1}{2}^-$	0.24	
	1.008	$\frac{5}{2}^-$	0.54	b
	1.29	$\frac{7}{2}^-$	0.68	
	1.54	$\frac{7}{2}^-$	1.8	
^{55}Fe	0.0	$\frac{3}{2}^-$	0.67,0.90[a]	
	0.411	$\frac{1}{2}^-$	0.25,0.28	
	0.941	$\frac{5}{2}^-$	0.35,0.40	c
	1.32	$\frac{7}{2}^-$	0.73,0.84	
	1.40	$\frac{7}{2}^-$	2.91,3.48	
^{63}Ni	0.0	$\frac{1}{2}^-$	0.47	
	0.087	$\frac{5}{2}^-$	3.43	
	0.155	$\frac{3}{2}^-$	2.42	d
	0.530	$\frac{3}{2}^-$	0.82	
	1.00	$\frac{1}{2}^-$	0.52	

[a] Different values of C^2S result from different choices of optical potentials and normalizations in the DWBA analysis.
[b] Reference [23].
[c] Reference [24].
[d] Reference [25].

Targets were self-supporting metal foils with thicknesses of about 1 mg/cm^2. Specifications of individual targets are shown in Table I.

For measurements of vector analyzing power (VAP), cross sections were measured for incident beam polariza-

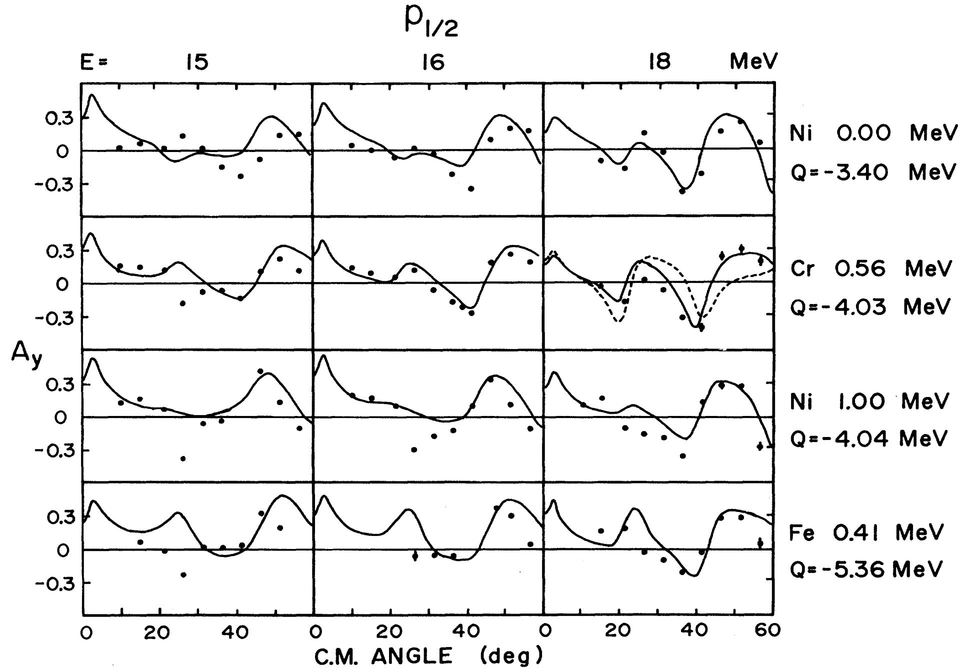

FIG. 1. Comparison between data and DWBA calculations for $p_{1/2}$ transitions at beam energies of 15, 16, and 18 MeV. Each transition is identified by its excitation energy in the final nucleus.

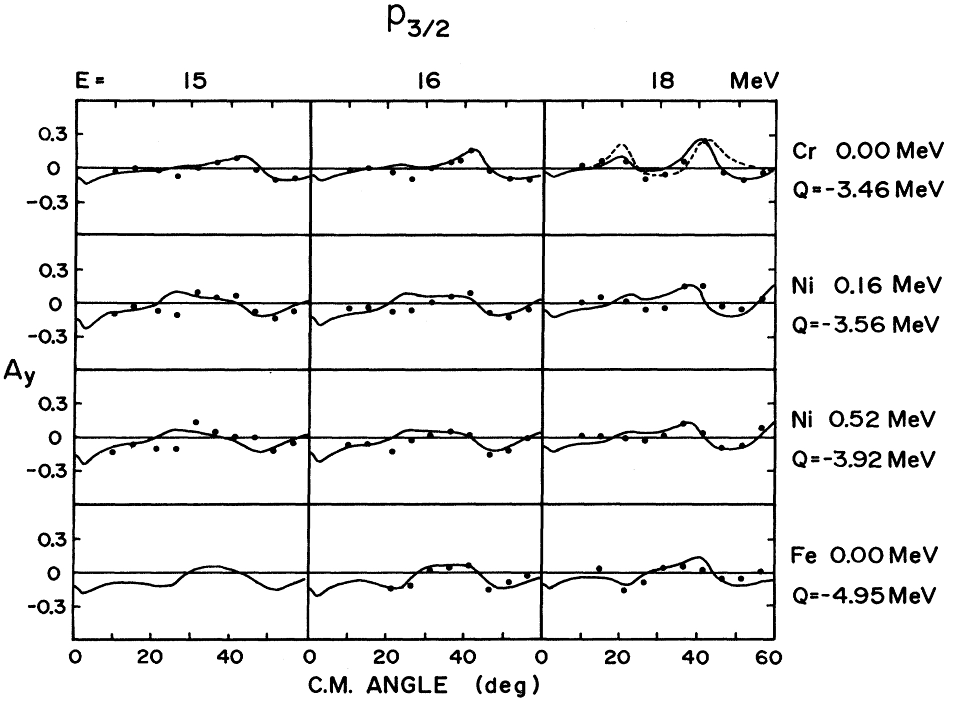

FIG. 2. Comparison between data and DWBA calculations for $p_{3/2}$ transitions.

tion $m_I = \pm 1$ and for an unpolarized beam. The Madison convention [22] was used in calculating analyzing powers. Measurements were carried out only for strong transitions to low-lying states of the residual nuclei involved. Earlier studies of the (d,t) reaction on ^{54}Cr [23], ^{56}Fe [24], and ^{64}Ni [25] have shown that the triton angular distributions to the states of interest have shapes characteristic of the known l transfer involved and are satisfactorily fitted by DWBA calculations. Strong transitions to states at higher excitations are known, but were not studied in these measurements because of interference from elastically or inelastically scattered deuterons. The states involved in these measurements, along with spins, parities, and spectroscopic factors, are listed in Table II.

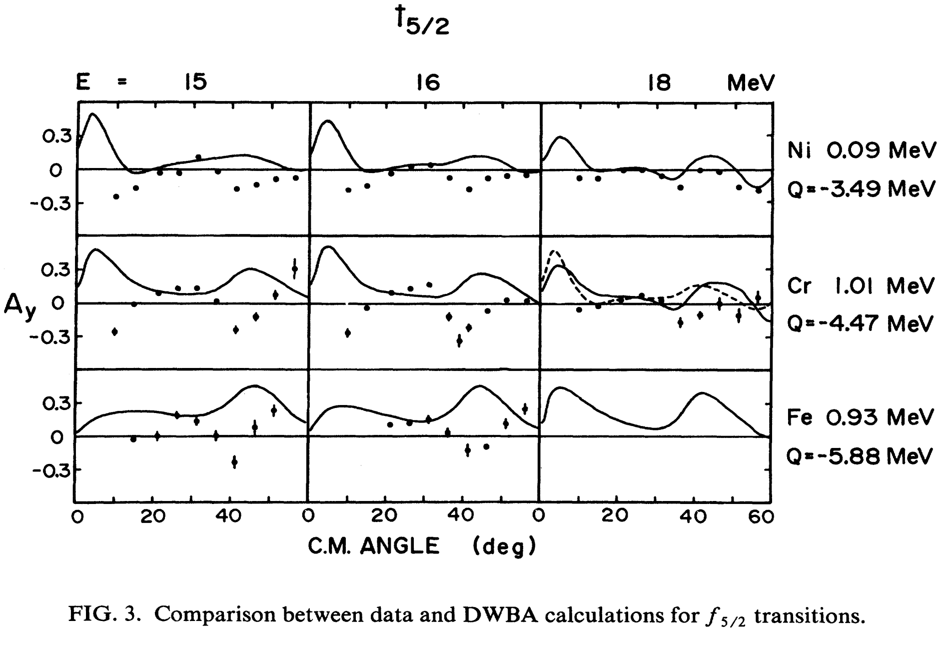

FIG. 3. Comparison between data and DWBA calculations for $f_{5/2}$ transitions.

RESULTS

The measured vector analyzing powers are shown in Figs. 1–4. Each figure shows results for transfers of a given j^π at each of the incident energies. Within each figure, the results are identified by the excitation energy of the final state involved. Measurements were made at 5° intervals between 10° and 55° in the laboratory for most states. Missing data points indicate that the state of interest was obscured by deuteron groups at the angle and beam energy involved. Error bars on the data points are uncertainties arising from counting statistics and from uncertainties in incident beam polarization as measured by the quench ratio method.

Predicted asymmetries calculated using DWBA are shown as curves on these figures and are discussed in the following section.

DWBA COMPARISON

In order to use VAP measurements to deduce j mixing in transfer reactions, the angular distributions should be clearly characteristic of the j^π value involved and independent of other details of the particular state. It is expected that these distributions will depend on beam energy, target mass, and reaction Q value, but that the dependence will be simple enough to be modeled by DWBA calculations.

The results shown in Figs. 1–4 do show generally similar angular distributions for all transitions of a given j^π. There are, however, significant differences among such transitions at a given beam energy, which may signal a simple dependence on reaction Q value or target mass, or a more complex dependence on nuclear wave functions. For a given transition there is also a dependence on beam energy, which should be reproduced by DWBA calculations if the $(\vec{d},t)$ reaction is adequately described by the simple one-step direct reaction model.

DWBA calculations for comparison with these data were carried out with the code DWUCK4 [26] using the standard deuteron and triton parameter sets derived by Daehnick, Childs, and Vrcelj [27] and Hardekopf *et al.* [28] from elastic-scattering and VAP data for deuterons and tritons, respectively (Table III). The global variations with deuteron energy and target mass suggested in Ref. [27] are small over the limited range studied here. Little change in the quality of the fit to the data results from large variations in the triton parameters (from those of Ref. [28] to those of Ref. [29], for instance) or from 10% to 20% variations in the deuteron parameters. An exception is the real central potential for the deuterons, for which a 10% alteration produces a significant change in the $(\vec{d},t)$ reaction VAP. In Figs. 1 and 2, for $l=1$ transfers with $j=\frac{1}{2}$ and $\frac{3}{2}$, respectively, a fixed $V_0=-100$ MeV was used, and a single example with $V_0=-90$ MeV is shown for the appropriate Cr transition at $E_d=18$ MeV. For the $l=3$ transfers of Figs. 3 and 4 for $j=\frac{5}{2}$ and $\frac{7}{2}$, respectively, a fixed $V_0=-90$ MeV is used and the variation to $V_0=-100$ MeV is shown for a Cr transition at $E_d=18$ MeV. The difference presumably reflects a small deficiency either in the parameter set (though a modest search has failed to reveal one) or in the approximations of DWBA.

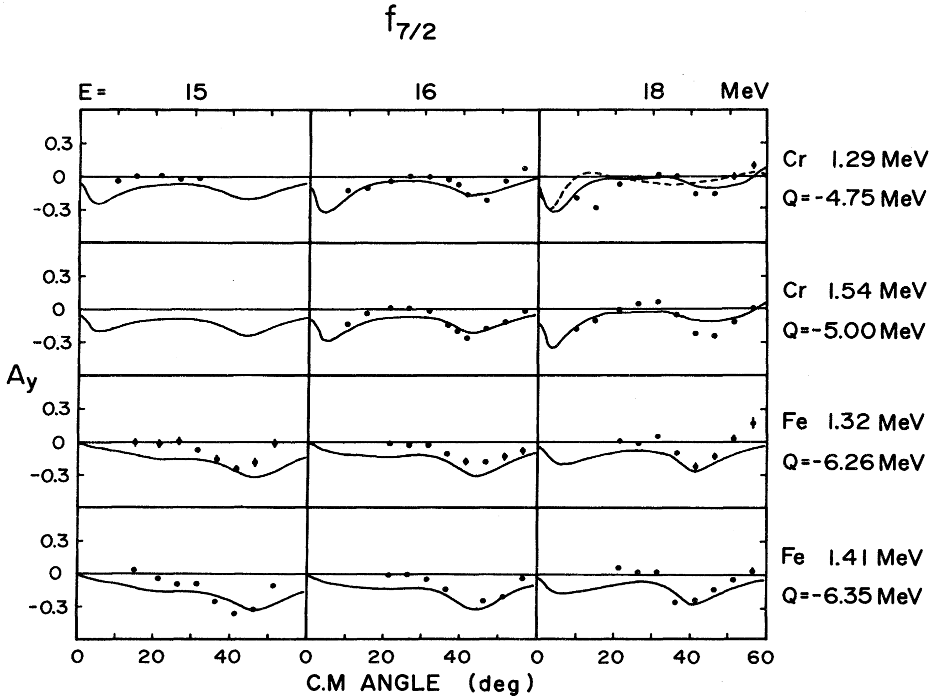

FIG. 4. Comparison between data and DWBA calculations for $f_{7/2}$ transitions.

TABLE III. Optical model parameters: $V = Vf(R_R,a_R) + 4iWf(R_I,a_I) + (4iW_s/r)(df/dr)(R_s,a_s) - (V_{\mathrm{s.o.}}/r)(df/dr)(R_{\mathrm{s.o.}},a_{\mathrm{s.o.}})\mathbf{L}\cdot\mathbf{S} + V_{\mathrm{Coul}}$, $R = r_0 A^{1/3}$, and $f(R,a) = \{1+\exp[(r-R)/a]\}^{-1}$.

	V (MeV)	r_{0R} (fm)	a_R (fm)	W (MeV)	r_{0I} (fm)	a_I (fm)	W_s (MeV)	r_{0s} (fm)	a_s (fm)	$V_{\mathrm{s.o.}}$ (MeV)	$r_{0\mathrm{s.o.}}$ (fm)	$a_{\mathrm{s.o.}}$ (fm)
Deuteron	−90, −100	1.17	0.735	0			12.3	1.325	0.78	−13.8	1.07	0.66
Triton	−150	1.2	0.72	−8.75	1.4	0.84	0			−10	1.2	0.80
Neutron	a	1.3	0.7									

[a] Fitted to binding energy: Coulomb radius parameter $r_{0C} = 1.25$ fm, nonlocality parameter 0.54 fm, and finite range parameter 0.845 fm.

A number of further observations may be made which may have a similar significance or, alternatively, may be related to structural details of the states involved.

(a) The fits would be improved, particularly in the case of $j = \frac{1}{2}$, if V increased slightly with increasingly negative Q value.

(b) The fits for $j = \frac{5}{2}$ are generally poor. The calculations display the usual approximate rule [29]

$$A_y(j = l + \tfrac{1}{2}) / A_y(j = l - \tfrac{1}{2}) = -l/(l+1) \ .$$

This behavior is seen in the data for $l = 1$, but not for $l = 3$.

(c) The similarity between the experimental and calculated analyzing powers is greater at larger reaction angles than at the forward angles.

DISCUSSION

For transitions with $j^\pi = \frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{7}{2}^-$, the DWBA calculations reproduce the general behavior of the data reasonably well. For $j^\pi = \frac{5}{2}^-$, the calculations fail to fit even the qualitative features of the measured angular distributions. More specific comments are as follows.

(i) $j^\pi = \frac{1}{2}^-$: The data all show a relatively large positive VAP at angles greater than 40°. This feature of the data is reproduced fairly well by the DWBA calculations at 16 and 18 MeV, but rather poorly at 15 MeV. As noted above, the fit could be improved if the depth of the central well is increased with increasingly negative Q value. At forward angles (10°–20°), the calculations also show generally good agreement with the data at all energies. At angles of 25° and 30°, the data are not fitted by the calculations and frequently have the opposite sign. As a summary of this comparison, we may say that the DWBA calculations reproduce the data best at angles greater than 40° and at the highest energy studied here of 18 MeV.

(ii) $j^\pi = \frac{3}{2}^-$: For these transitions, VAP is small, rarely exceeding a value of ±0.15. A consistent feature of the data is a small positive VAP at angles 30°–35° with a shallow minimum at an angle of about 45°. This behavior is reproduced fairly well by the calculations. As with the data for $j^\pi = \frac{1}{2}^-$, the largest disagreement between the data and DWBA occurs near 25°.

(iii) $j^\pi = \frac{5}{2}^-$: At 15 and 16 MeV, the data show a clear minimum in the VAP near 40° and negative values at forward angles. The calculations are almost out of phase with these results, predicting maximum VAP near 40° and positive values at forward angles. It is now in the region near 25° that the data show best agreement with the small positive VAP predicted by the DWBA. Only two distributions could be measured at 18 MeV. The overall quality of the fit to calculations is considerably better than at lower energies, though the maximum predicted near 40° is not clearly seen in the data.

(iv) $j^\pi = \frac{7}{2}^-$: For all transitions measured, the data show a clear minimum in the VAP near 40°, which is reproduced fairly well by the calculations. At more forward angles, the VAP is predicted to remain negative, but of smaller magnitude than near 40°. This general behavior is seen in the data, though in most measurements the VAP is larger than calculated by about 0.1.

For all the transitions studied, the angular distributions showed slight dependence on beam energy, and the dependence was modeled reasonably well by the calculations. Where there was disagreement between data and calculations, the disagreement was similar at all energies.

CONCLUSIONS

In order to provide good discrimination between the two possible j transfers for a given l transfer, the VAP should be large and opposite sign for the different j values.

For $l = 1$ transitions, the VAP's for $j = \frac{1}{2}$ and $\frac{3}{2}$ do consistently show opposite signs at angles greater than about 30°, especially at 18 MeV beam energy. The variations from state to state and the modest quality of DWBA fits to the data indicate that while mixing could be measured for components of comparable magnitude, reliable measurements would not be possible for components with an amplitude less than about 30% of the total wave function.

For $l = 3$ transitions, the VAP's for both $j = \frac{5}{2}$ and $\frac{7}{2}$ have a maximum magnitude, but the same sign at angles near 40°. It has also been noted that the data for $j = \frac{5}{2}$ are in almost total disagreement with DWBA calculations. In this situation, it is unlikely that reliable discrimination could be obtained for $\frac{5}{2}^-$ and $\frac{7}{2}^-$ transitions.

In a recent study [30] of the ^{15}Nd($\vec{d}$,t) reaction at 89 MeV, it was shown that $p_{1/2}$ and $p_{3/2}$ contributions to mixed transitions can be reliably identified. In spite of this encouraging result, our conclusion is that measurements of VAP in the $(\vec{d},t)$ reaction on (f,p) shell nuclei at low energies will be of limited interest in the study of j mixing in pickup reactions.

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[1] T. J. Yule and W. Haeberli, Nucl. Phys. **A117**, 1 (1968).
[2] D. C. Kocher and W. Haeberli, Nucl. Phys. **A196**, 225 (1972).
[3] D. C. Kocher and W. Haeberli, Nucl. Phys. **A252**, 381 (1975).
[4] H. S. Liers, R. D. Rathmell, S. E. Vigdor, and W. Haeberli, Phys. Rev. Lett. **26**, 261 (1971).
[5] S. E. Vigdor, R. D. Rathmell, H. S. Liers, and W. Haeberli, Nucl. Phys. **A210**, 70 (1972).
[6] S. Sen, S. E. Darden, W. A. Yoh, and E. D. Berners, Nucl. Phys. **A250**, 45 (1975).
[7] G. A. Huttlin, J. A. Aymar, J. A. Bieszk, S. Sen, and A. A. Rollefson, Nucl. Phys. **A263**, 445 (1976).
[8] M. E. Brandan and W. Haeberli, Nucl. Phys. **A287**, 205 (1977).
[9] J. A. Bieszk and S. E. Vigdor, Phys. Rev. C **23**, 1404 (1981).
[10] L. D. Knutson, P. C. Colby, and J. A. Bieszk, Phys. Lett. **85B**, 209 (1979).
[11] F. Merz, H. Clement, F. J. Eckle, A. M. Eiro, G. Graw, H. Kader, S. Roman, P. Schiemenz, and N. Seichert, Phys. Lett. B **183**, 144 (1987).
[12] R. Frick, H. Clement, G. Graw, P. Schiemenz, N. Siechert, and Sun Tsu-Hsun, Z. Phys. A **319**, 133 (1984).
[13] G. P. A. Berg and P. A. Quin, Nucl. Phys. **A274**, 141 (1976).
[14] M. E. Williams-Norton and R. Abegg, Nucl. Phys. **A291**, 419 (1977).
[15] R. R. Cadmus, Jr., T. B. Clegg, and E. J. Ludwig, Nucl. Phys. **A319**, 165 (1979).
[16] J. A. Bieszk, Luis Montrestruque, and S. E. Darden, Phys. Rev. C **16**, 1333 (1977).
[17] J. A. Cameron, E. Habib, A. A. Pilt, R. Schubank, and V. Janzen, Nucl. Phys. **A365**, 113 (1981).
[18] E. Habib, J. A. Cameron, G. U. Din, V. Jansen, and R. Schubank, Phys. Rev. C **26**, 834 (1982).
[19] J. Årdal, J. R. Lien, G. Lovhoiden, D. G. Burke, and J. C. Waddington, Can. J. Phys. **60**, 1534 (1982).
[20] G. A. Olsen, J. L. McKibben, P. W. Keaton, Jr., and D. D. Armstrong, Phys. Rev. Lett. **27**, 599 (1971).
[21] R. G. Markham and R. G. H. Robertson, Nucl. Instrum. Methods **129**, 131 (1975).
[22] G. R. Satchler *et al.*, in *Polarization Phenomena in Nuclear Reactions,* edited by H. H. Barschall and W. Haeberli (University of Wisconsin Press, Madison, 1971), p. xxv.
[23] M. Borsaru, J. Nurzynski, D. W. Gebbie, C. L. Hollas, S. Whineray, N. H. Merrill, Lio Barbopoulos, and A. R. Quinton, Nucl. Phys. **A237**, 93 (1975).
[24] M. A. Zaman, A. R. Majumder, M. S. Chowdhury, and H. M. Sen Gupta, Lett. Nuovo Cimento **30**, 279 (1981).
[25] R. H. Fulmer and W. W. Daehnick, Phys. Rev. **139**, B579 (1965).
[26] P. D. Kunz, computer code DWUCK4, University of Colorado (unpublished).
[27] W. W. Daehnick, J. D. Childs, and Z. Vrcelj, Phys. Rev. C **21**, 3353 (1980).
[28] R. A. Hardekopf, R. F. Haglund, Jr., G. G. Ohlsen, W. J. Thompson, and L. R. Veeser, Phys. Rev. C **21**, 906 (1980).
[29] F. D. Becchetti and G. W. Greenlees, in *Polarization Phenomena in Nuclear Reactions,* edited by H. H. Barschall and W. Haeberli (University of Wisconsin Press, Madison, 1971), p. 682.
[30] K. Swapan Saha *et al.*, Phys. Rev. C **42**, 922 (1991).