of Standards Miscellaneous Publication No. 273 (U.S. G.P.O., Washington, D. C., 1966).
[3]G. Reiter, to be published.
[4]H.-Y. Lau, L. M. Corliss, A. Delapalme, J. M. Hastings, R. Nathans, and A. Tucciarone, unpublished.
[5]G. S. Rushbrooke and P. J. Wood, Mol. Phys. 6, 409 (1963).
[6]M. F. Collins, Phys. Rev. B 2, 4552 (1970).
[7]A. Tucciarone, L. M. Corliss, and J. M. Hastings, to be published.
[8]M. Blume and J. Hubbard, Phys. Rev. B 1, 3815 (1970).

# $j$ Dependence in the Vector Analyzing Power for $^{208}$Pb$(d, t)^{207}$Pb

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(Received 9 November 1970)

A vector-polarized deuteron beam of energy 12.3 MeV has been used to measure differential cross sections and vector analyzing powers for the reaction $^{208}$Pb$(d,t)$, leading to the $p_{1/2}$ ground state, $f_{5/2}$ first excited state, and $p_{3/2}$ second excited state of $^{207}$Pb. The vector analyzing powers for the two $l=1$ transitions differ strikingly. This $j$ dependence is well reproduced by distorted-wave Born-approximation calculations.

It has been known for some time that the orbital angular momentum $l$ of the transferred nucleon in stripping and pickup reactions can be determined from the angular dependence of the differential cross section.[1] Recently, Yule and Haeberli[2] have shown that for a given $l$, there is a pronounced difference in the vector analyzing power for $(d,p)$ reactions between transitions of total angular momentum transfer $j=l+\frac{1}{2}$ and $j=l-\frac{1}{2}$. This $j$ dependence is well reproduced for intermediate[2] and heavy[3] nuclei by distorted-wave Born-approximation (DWBA) calculations. Measurements of $(d,p)$ vector analyzing powers thus often allow the unambiguous determination of $j$ and, in the case of spin-0 target nuclei, of the final-state spin.[4] A similar effect in the vector analyzing power for $(p,d)$ reactions has been observed.[5]

The present experiment was undertaken to investigate the existence of a $j$ dependence in the vector analyzing power for $(d,t)$ reactions. To demonstrate such an effect clearly, it is most desirable to initiate the reaction on a spin-0 target nucleus for which strong transitions, known to be of the same $l$ but different $j$, have been observed. The reaction $^{208}$Pb$(d,t)$ proceeding to the $p_{1/2}$ ground state and $p_{3/2}$ second excited state ($E_x=0.89$ MeV) of $^{207}$Pb was chosen for this study. Differential cross sections and vector analyzing powers were measured for these transitions as well as for the $f_{5/2}$ transition to the first excited state ($E_x=0.57$ MeV) of $^{207}$Pb. Cross-section measurements at deuteron energies of 14.8, 20.1, and 24.8 MeV have been reported previously.[6] The bombarding energy used in the present experiment ($E_d=12.3$ MeV) is near the Coulomb barrier, where it is expected that the DWBA gives a good representation of the transfer-reaction mechanism with little sensitivity to optical-model parameters.[7]

A beam of vector-polarized deuterons from a Lamb-shift polarized-ion source and tandem Van de Graaff accelerator was incident on an evaporated 1.5-mg/cm$^2$ lead target enriched in $^{208}$Pb. Four counter telescopes, located on one side of the incident beam direction, were used in conjunction with a particle identification scheme to distinguish tritons from other reaction products. At each detector angle a pair of measurements was made, with the incident deuteron spin parallel and antiparallel to $\vec{k}_d\times\vec{k}_t$. Absolute cross sections were determined by normalizing the counter-telescope yields to the yield of deuterons scattered elastically into two monitor detectors placed at $\theta_{lab}=\pm 13.05°$; the method is described by Loyd and Haeberli.[8] The incident-beam polarization was monitored continuously in a calibrated $^4$He polarimeter located at the back of the scattering chamber.

The measured cross sections and vector analyzing powers for the three $(d,t)$ transitions studied are shown in Fig. 1. The data extend from 30° to 150°. At angles $\theta \geqslant 45°$ the peaks of interest in the triton pulse-height spectra were clearly resolved and free from contamination. In the analysis of the peaks at 30° and 35°, however, it was necessary to subtract background which was caused by the very high deuteron counting rate. The errors shown include uncertainties from counting statistics and the estimated effects of

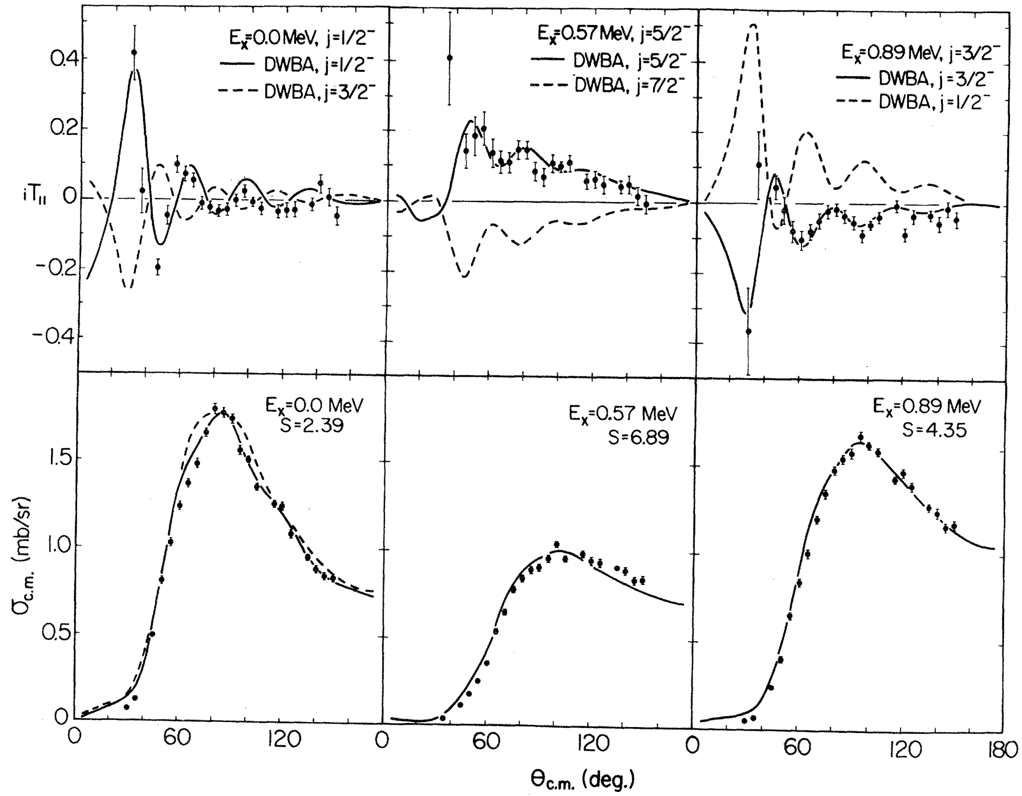


FIG. 1. Measured vector analyzing powers and cross sections for the reaction $^{208}$Pb$(d,t)^{207}$Pb at 12.3 MeV bombarding energy leading to states in $^{207}$Pb at $E_x = 0.0$, 0.57, and 0.89 MeV, having $j = \frac{1}{2}^-$, $\frac{5}{2}^-$, and $\frac{3}{2}^-$, respectively. The solid and dashed curves are DWBA predictions based on the parameters in Table I. The spectroscopic factor $S$ determined from this experiment is given for each transition.

uncertainties in the background. Errors in the cross section attributable to other sources are less than 3 %.

The solid and dashed curves in Fig. 1 are the results of DWBA calculations.[9] The optical-model and neutron-well parameters used are given in Table I. The deuteron parameters come from an analysis of the differential cross section for elastic scattering of 11.8-MeV deuterons from $^{208}$Pb (Satchler[10]). The triton parameters were taken from the parameters which Becchetti and Greenlees[11] obtained by fitting triton and $^3$He elastic-scattering data over a wide range of energy and target mass. Spin-orbit potentials[12,13] were added to both parameter sets. The DWBA predictions for the cross sections and for the vector analyzing powers agree very well with the data when the correct value of $j$ (solid curves) is used. The cross-section angular distributions are similar to those observed in $(d,p)$ reactions performed at energies near the Coulomb barrier.[14] The spectroscopic factors given in Fig. 1 were obtained by normalizing the DWBA predictions to the measured cross sections in the vicinity of the maxima; they are in reasonable agreement with those obtained previously[6] and with those expected $(S = 2j+1)$ for completely

Table I. Parameters used in DWBA calculations for $^{208}$Pb$(d,t)^{207}$Pb.[a]

| | Deuteron | Triton |
|---|---|---|
| $V_R$ (MeV) | 109.9 | 161.7 |
| $r_R$ (fm) | 1.063 | 1.20 |
| $a_R$ (fm) | 1.038 | 0.72 |
| $W_V$ (MeV) | 0 | 19.6 |
| $W_{SF}$ (MeV) | 9.8 | 0 |
| $r_I$ (fm) | 1.501 | 1.40 |
| $a_I$ (fm) | 0.728 | 0.86 |
| $V_{so}$ (MeV) | 5.25 | 2.0 |
| $r_{so}$ (fm) | 0.9 | 1.20 |
| $a_{so}$ (fm) | 0.6 | 0.72 |

[a]The notation is that of F. D. Becchetti, Jr., and G. W. Greenlees, Phys. Rev. 182, 1190 (1969). The bound-neutron potential used is that of Ref. 6, with radius $r_R = 1.225$ fm, diffuseness $a_R = 0.70$ fm, and spin-orbit factor $\lambda = 25.0$. The depth of the neutron well is adjusted to match the neutron binding energy to its empirical value.

filled neutron shells. Additional DWBA predictions demonstrated that omission of the spin-orbit potentials in the deuteron and triton channels caused no qualitative changes in the differential cross sections or vector analyzing powers.

It is clear from Fig. 1 that there is a pronounced $j$ dependence in the vector analyzing power for the two $l=1$ transitions, and that this effect is well reproduced by DWBA calculations. Although only a single $l=3$ transition was studied, it is worth noting that the DWBA predictions for the vector analyzing power are very different for $j=\frac{5}{2}^-$ and $j=\frac{7}{2}^-$, and that the former $j$ value is obviously favored by the data. Furthermore, a noticeable $j$ dependence in the predicted shape of the differential cross section, near the angular distribution peak, is observed for the ground-state transition, but not for the other transitions studied.

The analyzing powers and cross sections for the reaction $^{208}$Pb$(d,t)$ exhibit a strong dependence on $Q$ value, in contrast to the results obtained from $(d,p)$ reactions on intermediate-weight nuclei.[2,4] Between the ground-state and second-excited-state transitions there is a large change in the magnitude of the analyzing powers predicted for a given $j$ (see Fig. 1). In the absence of $Q$ dependence the cross sections for the $p_{1/2}$ and $p_{3/2}$ transitions would be in approximately the same ratio as the statistical weights, $(2j_1+1)/(2j_2+1)=\frac{1}{2}$, whereas the measured peak cross sections are nearly equal. The rapid variation of analyzing powers and cross sections with $Q$ value is characteristic of transfer reactions at sub-Coulomb energies.[7]

The present experiment has demonstrated that measurements of vector analyzing powers in $(d,t)$ reactions provide a useful method for determining nuclear spins. However, the strong $Q$ dependence observed here indicates that, at least for reactions performed at energies near the Coulomb barrier, purely empirical rules concerning the sign of the analyzing power may not be sufficient to determine $j$ unambiguously.

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

[1]S. T. Butler and O. H. Hittmair, *Nuclear Stripping Reactions* (Wiley, New York, 1957).

[2]T. J. Yule and W. Haeberli, Phys. Rev. Lett. 19, 756 (1967), and Nucl. Phys. A117, 1 (1968).

[3]A. A. Debenham, J. A. R. Griffith, M. Irshad, and S. Roman, Nucl. Phys. A151, 81 (1970).

[4]D. C. Kocher and W. Haeberli, Phys. Rev. Lett. 25, 36 (1970).

[5]J. L. Escudie, J. C. Faivre, J. Gosset, H. Kamitsubo, R. M. Lombard, and B. Mayer, Phys. Rev. Lett. 23, 1251 (1969).

[6]G. Muehllehner, A. S. Poltorak, W. C. Parkinson, and R. H. Bassel, Phys. Rev. 159, 1039 (1967).

[7]L. J. B. Goldfarb, Nucl. Phys. 72, 537 (1965), and in *Lectures in Theoretical Physics*, edited by P. D. Kunz and W. E. Brittin (Univ. of Colorado Press, Boulder, Colo., 1966), Vol. VIII C.

[8]D. H. Loyd and W. Haeberli, Nucl. Phys. A148, 236 (1970).

[9]The code DWUCK, obtained from P. D. Kunz, was used for the DWBA calculations.

[10]G. R. Satchler, private communication quoted in P. E. Hodgson, Advan. Phys. 15, 329 (1966).

[11]F. D. Becchetti, Jr., and G. W. Greenlees, John H. Williams Laboratory of Nuclear Physics Annual Progress Report, 1969 (unpublished), p. 116, and to be published.

[12]The deuteron spin-orbit potential is based on that obtained from a fit to vector analyzing power data for deuteron elastic scattering from $^{90}$Zr, at $E_d=11$ MeV: P. J. Bjorkholm, thesis, University of Wisconsin, 1969 (unpublished); P. J. Bjorkholm and W. Haeberli, to be published.

[13]The triton spin-orbit strength is taken to be roughly one-third of that for nucleon elastic scattering; see P. W. Keaton, in *Proceedings of the Symposium on Nuclear Reaction Mechanisms and Polarization Phenomena, Quebec, Canada, 1969* (Laval University Press, Quebec, Canada, 1970), p. 331.

[14]D. W. Miller, H. E. Wegner, and W. S. Hall, Phys. Rev. 125, 2054 (1962); J. J. van der Merwe and G. Heymann, Z. Phys. 220, 130 (1969).