ciently accurate to describe the analyzing powers for sub-Coulomb elastic scattering. In addition we have found that the predicted spin-orbit potential is consistent with the measured vector analyzing power at higher energies. Additional optical-model studies at higher energies (including tensor analyzing-power data) must be made before stronger conclusions can be drawn. These studies may eventually show the necessity for modifying the folding-model spin-dependent potentials. Should that be the case, the model would still provide a physically reasonable starting point for further optical-model analysis.

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

[1]S. Watanabe, Nucl. Phys. 8, 484 (1958).

[2]W. Haeberli, Rev. Brasil. Fis. 2, 187 (1972).

[3]J. Raynal, Phys. Lett. 29B, 93 (1969).

[4]G. R. Satchler, Nucl. Phys. 21, 116 (1960).

[5]The deuteron wave function used in this calculation was taken from T. Hamada and I. D. Johnston, Nucl. Phys. 34, 382 (1962). The neutron and proton optical-model potentials were obtained from F. D. Becchetti, Jr., and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).

[6]J. Raynal, Ph.D. thesis, Commissariat à l'Energie Atomique, Centre d'Etudes Nucléaires de Saclay, Report No. CEA-R 2511, 1965 (Argonne National Laboratory Report No. ANL-TRANS-258) (unpublished).

[7]S. E. Darden, in *Polarization Phenomena in Nuclear Reactions*, edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1970), p. 39.

[8]R. C. Johnson, in *Polarization Phenomena in Nuclear Reactions*, edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1970), p. 143.

[9]See, for example, P. Schwandt and W. Haeberli, Nucl. Phys. A123, 401 (1969); J. A. R. Griffith, M. Irshad, O. Karban, and S. Roman, Nucl. Phys. A146, 193 (1970), and A166, 675(E) (1971).

[10]H. S. Liers, R. D. Rathmell, S. E. Vigdor, and W. Haeberli, Phys. Rev. Lett. 26, 261 (1971).

[11]N. Rohrig and W. Haeberli, to be published.

[12]The analyzing powers are defined according to the Madison Convention, as found in *Polarization Phenomena in Nuclear Reactions*, edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1970).

[13]Becchetti and Greenlees, Ref. 5.

[14]This argument does not hold at higher energies for which the vector analyzing power is large in magnitude. See, for example, J. Raynal, Phys. Lett. 7, 281 (1963).

[15]The off-diagonal parts of the T_r potential were treated properly in the calculation. Tensor potentials of the T_L type (see Ref. 4) were not used. The tensor potential which arises from the interaction of the deuteron quadrupole moment with the Coulomb field of the nucleus was also included in the calculation. This potential is discussed in Ref. 2.

[16]P. W. Keaton and D. D. Armstrong, Bull. Amer. Phys. Soc. 17, 686 (1972).

[17]Further calculations have shown that the overall quality of the fits does not change significantly when the imaginary tensor term is omitted in the calculation. Thus the present work is unable to establish the existence of the imaginary tensor potential.

[18]J. M. Lohr and W. Haeberli, Bull. Amer. Phys. Soc. 17, 563 (1972), and to be published.

Analysis of the Anomaly in the Reaction ^{88}Sr(d, p_0)^{89}Sr Using Polarized Deuterons at the Threshold of the Neutron Analog Channel*

G. Graw, W. Stach, G. Gaul,† and C. Hategan‡
Physikalisches Institut der Universität Erlangen-Nürnberg, 8520 Erlangen, Germany
(Received 21 October 1971; revised manuscript received 10 April 1973)

The theory of Lane for the anomaly in the excitation function of the (d,p_0) reaction near the threshold of the analog (d,n) channel has been applied to polarized-beam measurements. The anomaly effects, observed at several angles in both cross section and analyzing power in the reaction ^{88}Sr$(d,p_0)^{89}$Sr, are reproduced by a distorted-wave Born-approximation calculation, if the radial matrix elements for the proton exit channel with $l=1$, $j=\frac{3}{2}$ are modified by a resonance term.

Anomalous effects in excitation curves of the (d,p_0) reaction near the threshold of the (d,n) analog channel have been observed with several spin-0^+ targets in the $A=90$ mass region[1,2] and pronounced effects have been found for the reaction ^{88}Sr$(d,p_0)^{89}$Sr$(\frac{5}{2}^+)$.[3] The anomaly is assumed to originate from the isospin coupling of the $3p$ neutron single-particle resonance to the proton analog channel.[1,4] For $A\approx 90$ nuclei the $3p$ resonance is near the neutron emission threshold.

For this case, it has been shown[1,4] that the $3p$ resonance is compressed in width and is moved very close to the threshold. This point has been discussed recently in more detail.[5] To reproduce the anomaly effects in differential cross sections, coupled-channels calculations have been performed[6]; however, no fits to the analyzing power data of polarized-beam experiments[7] have been presented.[8] In this Letter we show that the pronounced anomaly effects observed at several angles in both differential cross section $\sigma(\theta)$ and vector analyzing power $A(\theta)$ for the reaction $^{88}Sr(d,p_0)^{89}Sr$ can be reproduced quite well by the more phenomenological theory of Lane,[1] which has been used in a modified distorted-wave Born-approximation (DWBA) calculation.

According to Lane, the anomaly effect is described by a resonance term which is added to those scattering matrix elements that populate the $l=1$, $j=\frac{3}{2}$ proton exit channel. The giant resonance character of the analog $3p_{3/2}$ neutron resonance and the existence of the threshold are expressed in the appropriate energy dependence of the resonance denominator. Lane did not consider the dependence on the scattering angle. To obtain a good reproduction of the anomaly in $\sigma(\theta)$ at one scattering angle near $\theta=160°$, the background scattering was described by one complex number, chosen to give the appropriate relative phase with the resonant term.

In order to describe the angular dependence of the anomaly effect and to correlate the effects in $\sigma(\theta)$ and $A(\theta)$, we used the DWBA code DWUCK[9] for the background description. If we adjust the resonance terms to reproduce the excitation function of $\sigma(\theta)$ at $\theta=160°$—this corresponds to the adjustment of the relative phase between resonance term and background—we obtain at the same time a very good reproduction of the anomaly effects in $\sigma(\theta)$ at other angles and also a correct prediction of the anomaly effects in the analyzing power.

Figure 1 shows the excitation functions of $A(\theta)$ and $\sigma(\theta)$ for the reaction $^{88}Sr(d,p_0)^{89}Sr$ at scattering angles $\theta=160°$, 140°, 120°, and 90°. There are also indicated the cross-section data of Zaidi, Cocker, and Martin,[3] which cover a large energy range. The measurement has been performed with the purely vector polarized deuteron beam of the 12-MeV Erlangen tandem accelerator,[10] the experimental procedure being similar to the previous experiment on ^{90}Zr.[7] The excitation function has been measured at seven scattering angles from $E_d=6.5$ to 8.5 MeV with a tar-

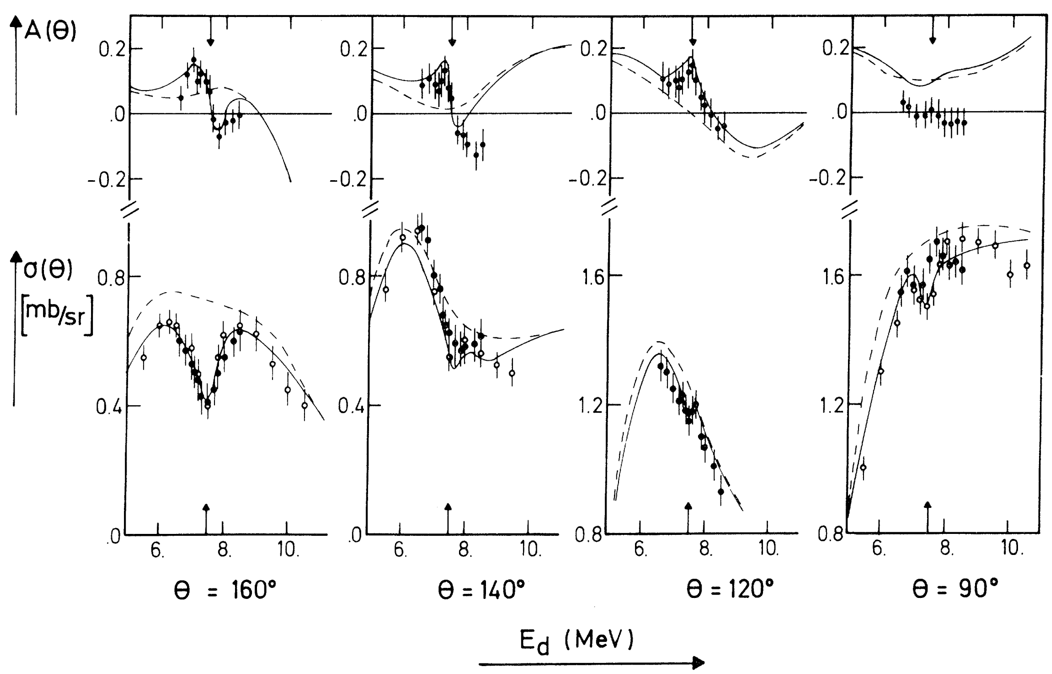

FIG. 1. Excitation functions of analyzing power A and differential cross section $\sigma(\theta)$ for the reaction $^{88}Sr(d,p_0)$ at scattering angles $\theta=160°$, 140°, 120°, and 90°. The open circles indicate data points of Zaidi, Cocker, and Martin (Ref. 3). Arrows indicate the position of the analog (d,n) threshold. The solid and dashed curves are DWBA calculations (spectroscopic factor $S=0.8$) with and without a resonance term.

get of isotopically enriched $^{88}Sr(NO_3)_2$, sedimented on a thin plastic foil. The target thickness corresponded to an energy average of 200 keV. Near the threshold energy at $E_d = 7.5$ MeV (indicated by arrows in Fig. 1) there are pronounced effects in $\sigma(\theta)$ at $\theta = 160°$ and 90° and in $A(\theta)$ at $\theta = 160°$, 140°, and 120°. The anomaly effects at $\theta = 20°$, 40°, and 60°—not shown in Fig. 1—are small. The observed structure is very similar to that measured with the ^{90}Zr target.[7]

The solid lines in Fig. 1 are the results of a DWBA calculation as modified by the resonance term. To exhibit more clearly the effect of the additional resonance, the dashed line is calculated without the resonance term. Then the difference of both curves may be considered as the "anomaly effect."

The optical potential for the proton-channel distorted waves has been obtained from a fit to the angular distributions of $A(\theta)$ and $\sigma(\theta)$ for the ^{88}Sr(p, p_0) and ^{90}Zr(p, p_0) elastic-scattering data at $E_p = 11$ MeV,[11] whereas for the deuteron channel the potential of Horton *et al.*[12] has been used. With these parameters the DWBA reproduces quite well the $\sigma(\theta)$ data of the reaction ^{88}Sr(d, p_0) measured at $E_d = 12$ MeV by Griffith, Karban, and Roman,[13] and fairly well their $A(\theta)$ data. That means that the shape of $A(\theta)$ is reproduced quite well, whereas the absolute values differ by up to a factor of 2. This supports the assumption that in the region $E_d = 6.5$ to 8.5 MeV the DWBA calculation represents the background transition amplitudes sufficiently well. The solid curve is calculated with the modified DWBA code DWUCK, where the radial integrals

$$R(E)_{L,J}{}^{\mathrm{DWBA}} = \int dr\, w_{p3/2}{}^{p}(r, k_p)\, u_{d5/2}{}^{n}(r)\, w_{L,J}{}^{d}(r, k_d) \tag{1}$$

are multiplied by a resonance factor:

$$R(E)_{L,J} = R(E)_{L,J}{}^{\mathrm{DWBA}}\left(1 - \frac{iA_L \exp(i\varphi_L)}{E_0 - E - [S(E) + iP(E) - b]\gamma^2 - i/2\Gamma}\right). \tag{2}$$

In the above formula the energy dependence is explicitly shown. The energy dependence of the resonance due to penetrability effects is contained in $R(E)_{L,J}{}^{\mathrm{DWBA}}$, whereas the energy dependence due to the isospin-coupled $3p_{3/2}$ neutron resonance near threshold is expressed in the denominator of the resonance term in exactly the same form as given by Lane.[1] We also used the same numerical values for $S(E)$, $P(E)$, b, γ^2, and Γ, the only change being a small shift of the "resonance energy" E_0 ($x_{3/2} = -0.5$ instead of $x_{3/2} = -1.5$, when using the symbols of Ref. 1). The energy-independent numerator of the resonance term is written as a complex number $A_L \exp(i\varphi_L)$. It can be chosen different for the $L = 1$ and $L = 3$ orbital angular momenta of the incident deuteron wave $w_{L,J}{}^{d}(r, k_d)$ that may populate the $2d_{5/2}$ single-particle neutron bound state $u_{d5/2}{}^{n}(r)$ in ^{89}Sr, if the outgoing proton wave $w_{p3/2}{}^{p}(r, k_p)$ has $l = 1$, $j = \frac{3}{2}$. Since deuteron spin forces are weak, we neglect a possible dependence of the resonance on the total angular momentum J of the deuteron channel.

A special feature of this parametrization (2) is that these resonance factors should be independent of the incident deuteron channel if the anomaly results from an isospin coupling interaction of the exit channel configurations $p + {}^{89}$Sr and $n + T^{-}({}^{89}$Sr) only. In fact, the solid curves in Fig. 1, which reproduce quite well the "anomaly effects" at all scattering angles, have been calculated by the use of only one complex number $A_L = 2.8$ and $\varphi_L = 20°$ for both $L = 1$ and $L = 3$.

We also checked, by calculation with these parameters, that the contribution of a resonant $p_{1/2}$ exit channel to the observables is negligibly small, as proposed by Tamura and Watson.[4] This demonstrates that the more phenomenological theory of Lane is able to describe the experimental observations sufficiently well. Hence for the investigation of these single-particle resonances near threshold it may be quite useful, first to use this framework to extract the parameters, and afterwards to perform the interpretation of these numbers by more refined calculations.

The authors are indebted to A. M. Lane for an illuminating correspondence and to P. von Brentano, J. Christiansen, E. Finckh, P. D. Kunz, C. F. Moore, R. Santo, and J. Zimanyi for stimulating or encouraging discussions.

*Work supported by Bundesministerium für Bildung und Wissenschaft.

†Sektion Physik der Universität München, München,

Germany.
‡A. v. Humboldt Fellow. Permanent address: Institute of Atomic Physics, Bucharest, Romania.
[1]A. M. Lane, Phys. Lett. 33B, 274 (1970).
[2]C. F. Moore, C. E. Watson, S. A. A. Zaidi, J. J. Kent, and J. G. Kulleck, Phys. Rev. Lett. 17, 926 (1966).
[3]S. A. A. Zaidi, W. R. Cocker, and D. G. Martin, Phys. Rev. C 2, 1384 (1970).
[4]T. Tamura and C. E. Watson, Phys. Lett. 25, 186 (1967).
[5]J. Zimanyi and B. Gyarmati, Phys. Lett. 41B, 571 (1972).
[6]R. Cocker and T. Tamura, Phys. Rev. 182, 1277 (1969).
[7]G. Clausnitzer, G. Graw, C. F. Moore, and K. Wienhard, Phys. Rev. Lett. 22, 793 (1969); K. Wienhard and G. Graw, in *Proceedings of the Third International Symposium on Polarization Phenomena in Nuclear Reactions, Madison, Wisconsin, 1970,* edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1970), p. 655.
[8]J. G. Cramer *et al.*, Phys. Rev. C 6, 366 (1972), and Ref. 14 therein.
[9]P. D. Kunz, the DWBA code DWUCK (private communication).
[10]G. Clausnitzer *et al.*, Nucl. Instrum. Methods 80, 247 (1970).
[11]W. Stach, Diplom-thesis, Universität Erlangen, 1973 (unpublished).
[12]J. L. Horton *et al.*, Nucl. Phys. A190, 362 (1972).
[13]J. A. R. Griffith, O.Karban, and S. Roman, Department of Physics, University of Birmingham, Report No. 711, 1971 (unpublished).

Cross-Section Measurements for the (p, n) Analog Transition in ^{181}Ta, ^{197}Au, and ^{209}Bi†

S. M. Grimes, J. D. Anderson, J. C. Davis, W. H. Dunlop, and C. Wong
Lawrence Livermore Laboratory, Livermore, California 94550
(Received 5 March 1973)

Cross sections for (p,n) transitions to analog states for targets of Ta, Au, and Bi have been measured. The cross section and decay width observed for Bi are inconsistent with those obtained from $(p,n\tilde{p})$ measurements. We propose an explanation for these discrepancies.

Because of the experimental difficulty of neutron measurements relative to charged-particle experiments, a number of investigations of the (p, n) reaction to analog states have utilized the subsequent proton decay of the analog state to determine cross sections for this transition. Low-lying analog states for medium and heavy nuclei are above the proton emission threshold and neutron decay can occur only through isospin mixing; thus, a significant fraction of the analog states would be expected to decay through proton emission. In general, this fraction is not known, but it would not depend on the proton bombarding energy. Measurement of the excitation function of the protons corresponding to decay of the analog state (denoted $\tilde{p}$) whould give the energy dependence of the analog (p, n) cross section itself and yield a lower limit for the absolute value of this cross section. In addition, since the $\tilde{p}$ decays lead to particle-stable states (of very small or zero width), the width of the $\tilde{p}$ peak should depend on the width of the analog state and kinematics. If the decay is to isolated final states, a determination of the analog state width from $\tilde{p}$ spectra is possible. Results have been published for both the energy dependence of the cross section and the width of the analog state based on $\tilde{p}$ measurements.

Unfortunately, both the width and cross-section measurements[1,2] have led to inconsistencies for lead. The analog-state widths deduced from $\tilde{p}$ measurements have been as much as a factor of 1.5 larger than those obtained from the (p, n) reaction or proton scattering. At the same time, the $\tilde{p}$ cross section, which should be a lower limit for the (p, n) cross section to the analog state, has been found to be larger than this value for ^{208}Pb. The present measurements were undertaken to extend the comparison to targets of Ta, Au, and Bi.

Cross sections for the (p, n) transition to analog states have been measured for targets of Ta, Au, and Bi at proton energies of 25 and 27 MeV with the time-of-flight spectrometer at the Lawrence Livermore Laboratory cyclograaff facility. Angular distributions for the three targets at 27 MeV are shown in Fig. 1. Integrated cross sections at both energies were obtained from five-