pounds, edited by M. Aven and J. S. Prener (North-Holland, Amsterdam, 1967), pp. 267–318.
[15]R. A. Stradling, Solid State Commun. 6, 665 (1968).
[16]R. E. Nahory and H. Y. Fan, Phys. Rev. Lett. 17, 251 (1966).
[17]D. L. Rode, Phys. Rev. B 2, 4036 (1970).
[18]L. Roth, B. Lax, and S. Zwerdling, Phys. Rev. 114, 90 (1959).
[19]M. Cardona, K. L. Shaklee, and F. H. Pollak, Phys. Rev. 154, 696 (1967).

Two-Step Mechanism in the Reaction ^{208}Pb(p,t)*

N. B. de Takacsy
Physics Department, McGill University, Montreal, Canada
(Received 8 May 1973)

It is shown that the differential cross section for the reaction ^{208}Pb(p,t) leading to the 3^+ (1.34-MeV) state of ^{206}Pb can be understood in terms of a two-step (p,d)-(d,t) mechanism.

The 3^+ (1.34-MeV) state in ^{206}Pb has recently been observed in high-resolution Pb(p,t) experiments performed[1] with the Michigan State University cyclotron at an incident energy of 35 MeV. The usual one-step distorted-wave Born-approximation description of (p,t) reactions[2,3] forbids transitions between a 0^+ initial state and an unnatural-parity final state. As expected, the observed cross section is quite weak (~10 μb/sr at the peak), but the shape of the angular distribution is not what one would expect from a compound-nucleus mechanism. It is the purpose of this note to show that the two-step (p,d)-(d,t) mechanism provides a very satisfactory description of this reaction. A similar approach has been used to study other (p,t) reactions,[4] as well as some charge-exchange and single-particle transfer reactions.[5]

The calculations are performed using a second-order, distorted-wave Born approximation in which the spin-orbit terms of the optical potential are neglected and a zero-range approximation is used at each single-nucleon transfer vertex. The detailed form of the transition amplitude has been given before.[5] However, because of some remarks by Robson,[6] it is worthwhile remarking that the radial Green's function which describes the propagation of the deuteron in the intermediate state is given by

$$g_l^{(+)}(r,r') = -(2mk/\hbar^2)\, u_l^{(+)}(r_>)\, u_l^{(R)}(r_<),$$

where both kinds of radial wave functions are calculated using an absorptive optical potential.

The parameters of two sets of optical potentials which were used in these calculations are shown in Table I. In both cases, the deuteron potential is obtained, following the Johnson-Soper prescription,[10] from the corresponding proton potential either by an approximate folding procecure[7] (set A) or by straight summation (set B).

TABLE I. Parameters for the optical potentials.

	Set A			Set B		
	p	d	t	p	d	t
V	47.9	107.8	166.2	53.41	103.94	167.0
r	1.25	1.25	1.25	1.17	1.17	1.16
a	0.65	0.682	0.65	0.75	0.75	0.752
W	0	0	0	5.0	1.20	10.3
$4W_D$	40.0	77.6	120.0	22.35	64.4	0
r_I	1.25	1.25	1.25	1.32	1.32	1.498
a_I	0.76	0.783	0.76	0.658	0.655	0.817
Ref.	7	7		8		9
		$D_0(p,d) = -(1.5\times10^4)^{1/2}$				
		$D_0(d,t) = -(3.3\times10^4)^{1/2}$				

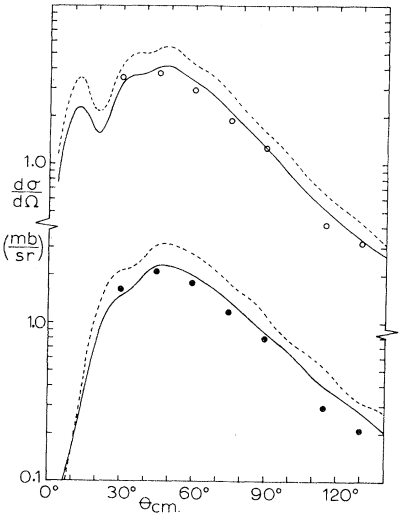

FIG. 1. One-step calculations for the reaction ^{208}Pb(d, t) at 17 MeV leading to the $\frac{3}{2}^-$ (0.9-MeV) state (open circles) and the $\frac{5}{2}^-$ (0.57-MeV) state (solid circles) of ^{207}Pb which were taken to be pure single-hole states. The solid curves and the dashed curves refer to optical-parameter sets A and B, respectively. The data are from Ref. 11 and the calculations were done with the distorted-wave Born-approximation code DWUCK (Ref. 12).

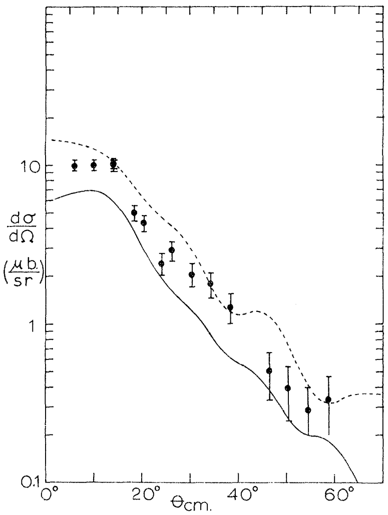

FIG. 2 Two-step calculations for the reaction ^{208}Pb(p, t) at 35 MeV leading to the 3^+ (1.34-MeV) state of ^{206}Pb. The solid curve refers to the calculation using optical-potential set A, while the dashed curve is obtained using set B.

The triton potential of set A is taken to be 3 times the proton potential (apart from the energy-dependent term), while the triton potential of set B fits the elastic triton scattering data at 20 MeV.[9] Both of these potential sets are known to fit the ^{208}Pb(p,d) data at 22 MeV,[7] and they also agree with the ^{208}Pb(d,t) data at 17 MeV[11] as shown in Fig. 1. Finally, the one-step calculations for the reactions Pb(p,t) leading to natural-parity states also agree well with experiment when these optical potentials are used.[1]

The two-step calculation for the reaction ^{208}Pb(p,t)^{206}Pb(3^+) uses the fact that the wave function of the 3^+ state is $|2p_{1/2}{}^{-1},\ 1f_{5/2}{}^{-1}\rangle$ with practically no configuration mixing.[13] The intermediate state consists of a (triplet) deuteron with the ^{207}Pb being in either the $\frac{1}{2}^-$ ground state or the $\frac{5}{2}^-$(0.57 MeV) excited state. All the one-nucleon-transfer form factors were calculated using DWUCK,[12] with $r_0 = 1.25$ fm and $a = 0.65$ fm and using the experimental neutron separation energies. The results are shown in Fig. 2. It can be seen that the shape of the experimental angular distribution is well reproduced, and that the magnitude of the cross section is also reasonable.

The dominant contribution to the cross section comes from the term with angular momentum transfer $L,S,J = 4,1,3$. The term with $L,S,J = 3,0,3$ is weaker, but significant, while all the other terms are negligible. The inclusion of "singlet" as well as "triplet" deuterons in the intermediate states, with the same optical potentials, cancels the contributions with spin transfer $S = 1$ and increases the contributions with $S = 0$; the resulting angular distribution does not agree as well with experiment.

We therefore conclude that the (p,t) reaction to the 3^+ (1.34 MeV) state in ^{206}Pb can be understood in terms of the two-step (p,d)-(d,t) mechanism.

I would like to thank P. D. Kunz for many informative communications and the use of the code DWUCK and W. A. Lanford for allowing me to use his data prior to publication and also for a number of useful discussions. Finally, I would like to thank S. Das Gupta and B. Margolis for their interest and encouragement.

*Work supported in part by the National Research Council of Canada.

[1]W. A. Lanford, private communication, and to be published, and in Cyclotron Laboratory, Michigan State University, Annual Report, 1972 (unpublished); W. A. Lanford and J. B. McGrory, Phys. Lett. 45B, 238 (1973).

[2]N. K. Glendenning, Phys. Rev. 156, 1344 (1967).

[3]N. Austern, *Direct Nuclear Reaction Theories* (Wiley, New York, 1970).

[4]P. D. Kunz, private communication; J. Bang and

S. Wollesen, Phys. Lett. 33B, 395 (1970).
[5]R. Schaeffer and G. Bertsch, Phys. Lett. 38B, 159 (1972); M. Toyama, Phys. Lett. 38B, 147 (1972); N. de Takacsy, Phys. Lett. 42B, 1 (1972); W. R. Coker, T. Udagawa, and H. H. Wolter, Phys. Lett. 41B, 237 (1972), and Phys. Rev. C 7, 1154 (1973); M. Igarashi, M. Kawai, and K. Yazaki, Phys. Lett. 42B, 323 (1972); P. D. Kunz, to be published.
[6]D. Robson, Phys. Rev. C 7, 1 (1973).
[7]G. R. Satchler, Phys. Rev. C 4, 1485 (1971).
[8]R. D. Becchetti and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).
[9]E. R. Flynn, D. D. Armstrong, J. G. Beery, and A. G. Blair, Phys. Rev. 182, 1113 (1969).
[10]R. C. Johnson and P. J. R. Soper, Phys. Rev. C 1, 976 (1970).
[11]R. A. Meyer, B. L. Cohen, and R. C. Diehl, Phys. Rev. C 2, 1898 (1970).
[12]The code DWUCK was written by P. D. Kunz, University of Colorado.
[13]W. W. True, Phys. Rev. 168, 1388 (1968); R. Tickle and J. Bardwick, Phys. Rev. 166, 1167 (1968).

Measurement of Neutron-Deuteron Polarization at 35 MeV*

J. Zamudio-Cristi,† B. E. Bonner,‡ F. P. Brady, J. A. Jungerman, and J. Wang
Crocker Nuclear Laboratory and Department of Physics, University of California, Davis, California 95616
(Received 19 June 1973)

The neutron polarization asymmetry in neutron–deuteron scattering has been measured from 44.5° to 160° (c.m.) neutron angle. The results display quantitatively the same structure as proton–deuteron polarization data, but discrepancies appear for angles corresponding to those near the minimum of the differential cross section. In this region the polarization is considerably more negative than in the proton–deuteron case, and both are more negative than current theoretical predictions.

A much better understanding of the theory of elastic scattering of nucleons on deuterium has been gained recently, particularly through calculations of polarization phenomena as well as differential cross sections.[1-8] Experimental data exist for proton polarization in a wide range of energies. For neutrons, sparse data exist up to 22.7 MeV. Although proton polarizations are measured in general with higher accuracy, neutron polarizations are more directly computable. The present work contributes polarization data for neutrons on deuterons at higher energy, 35 MeV. For angles near 120°, corresponding to those near the minimum of the differential cross section, we find that the *nd* values of polarization $P(\theta)$ are considerably more negative than those for *pd*. They are also more negative, as are the *pd* values, than current theoretical predictions.

It has been suggested[9,6] that the nucleon-deuteron polarization $P(\theta)$, rather than the cross section, may be a more sensitive testing ground for the structure of the scattering matrix. For example, the shape of $P(\theta)$ versus θ appears to change quite rapidly with energy.[6] However, the calculations with tensor forces are difficult and require a large number of coupled integral equations.

Phenomenological and semiphenomenological calculations[10-12] of $P(\theta)$ up to 40 MeV have been quite successful. Recently, several calculations of $P(\theta)$ starting from the coupled integral equations have been made. Krauss and Kowalski[6] used the unitary first-order–approximation procedure of Sloan[13] and assumed a simple separable Yamaguchi potential which included S-wave singlet and S- and D-wave triplet nucleon-nucleon partial-wave states, but not P waves. Pieper[3] then included S, P, and D waves in the two-potential formalism to calculate $P(\theta)$. Agreement with experiment is very good at low energies, $\lesssim 14$ MeV, and qualitatively good up to 40 MeV. At 14 MeV Doleschall[4] has also performed a calculation including P waves which is in good agreement with the experimental $P(\theta)$ distribution. It seems clear that eventually more exact dynamics and more realistic two-nucleon potentials will be used to produce reliable calculations at higher energy.

We have chosen 35 MeV for the *nd* neutron polarization measurements so as to be able to compare with the *pd* proton polarization measurements at 35 MeV.[14] A preliminary report[15] which contained early data has been given elsewhere.

Our experimental layout is shown schematically in Fig. 1 for the case where a scintillating target, neutron detectors, and a CAMAC data acquisition system were used. The 35-MeV neutron beam, of polarization $P_1 = 0.31 \pm 0.03$,[16] is