PHYSICAL REVIEW C VOLUME 9, NUMBER 5 MAY 1974

Neutron-deuteron differential cross sections at 35.0 and 46.3 MeV*

F. P. Brady, W. B. Broste,† J. C. Wang‡
Crocker Nuclear Laboratory and Department of Physics, University of California, Davis, California 95616

J. L. Romero
Facultad de Ciencias, Universitad de Chile, Department de Fisica, Casilla 5487, Santiago, Chile

P. Martens
Facultad de Ciencias Fisicas y Mathematics, Universitad de Chile, Department de Fisica, Casilla 5487, Santiago, Chile

(Received 2 July 1973; revised manuscript received 7 February 1974)

Differential cross sections have been measured for *nd* and *pd* scattering at 35.0 and 46.3 MeV. Only cross sections for c.m. angles $\gtrsim 90°$ have been measured in this work, which is in part a higher-precision remeasurement of earlier *nd* cross sections and whose main purpose has been to check possible *nd*-*pd* differences which appeared in the earlier measurements at 36.0 and 46.3 MeV. Absolute *nd* cross sections of $\simeq 5\%$ precision, obtained by normalization to precision *np* cross sections, are compared with absolute *pd* cross sections measured at the University of California at Los Angeles. The differences in this comparison and in the *nd*-*pd* relative cross sections measured here are smaller than indicated by the previous measurements. However, some systematic differences do appear to exist at angles near the cross-section minima and beyond.

NUCLEAR REACTIONS ^{2}H(n,d), $E=35.0$, 46.3 MeV; measured $\sigma(\theta n)$, $\theta n=90$–170° (c.m.). $\Delta\theta n=5°$; ^{2}H(p,d), $E=35.0$, 46.3 MeV; measured $\sigma(\theta p)$, $\theta p=90$–170° (c.m.), $\Delta\theta p=5°$.

I. INTRODUCTION

The neutron-deuteron interaction is one of the most fundamental three-body problems in nuclear and particle physics. Both on- and off-energy-shell aspects of the nucleon-nucleon interaction as well as possible three-body forces can be tested in *nd* scattering. In addition, three-nucleon experiments such as *nd* scattering may provide an easier access to information, such as that concerning the neutron-neutron interaction, which is not available in two-nucleon experiments.

A sound theoretical basis for the three-body formalism has been given.[1] The use of *S*-wave separable potentials[2,3] has permitted successful calculations[4-6] of low-energy properties of the three-nucleon system such as the *nd* differential cross section. Higher partial waves are necessary for the description of scattering at higher energies.

Sloan[7] has shown that multiple scattering series of the Faddeev type[1] do not converge rapidly for the lowest partial waves. Pieper[8] has recently calculated the *nd* scattering with *P* and *D* waves using a two-potential formalism,[9] and obtains good agreement with differential cross-section measurements, $\sigma(\Theta)$ near 14 MeV.

Kloet and Tjon[10] have applied the Padé technique to the Faddeev formalism and calculated *nd* scattering using local two-body *S*-wave potentials. Up to 22 MeV the agreement with experiment is good, becoming less good with increasing energy.

Dispersion calculations of the *N/D* type have been used to calculate nucleon-deuteron cross sections over a wide energy range.[11] The agreement with experiment at medium energies is quite good except that above 20 MeV the predicted minimum is sharper and deeper than experiment. The calculations of Sloan,[12] which use the separable-potential model of Ref. 4 with spin-dependent two-nucleon interactions and extend up to 40 MeV are in better agreement with the data at 31.0 MeV than the *N/D* predictions in that the calculated minimum is not much deeper than experiment.

Calculations[13] based on the approximation method of Sloan[14] give fairly good predictions for $\sigma(\Theta)$ up to 40 MeV, and earlier impulse-approximation methods at 32 and 40 MeV[15] and at 40, 95, and 150 MeV[16,17] give fair agreement when multiple-scattering effects are included, but only at the highest energies if multiple-scattering effects are neglected.

The nucleon-deuteron experimental situation with respect to $\sigma(\Theta)$ has been reviewed recently by Seagrave.[18] In the medium-energy range of interest here, *pd* data exist near 31.0,[19-21] 35.0,[22] 40.0,[23] 46.3,[22] and 49.4 MeV,[20] and in case of *nd* there exist the Los Alamos Scientific Laboratory measurements[24] extending up to 23.0 MeV and the 1970 University of California at Davis measurements at 36.0 and 46.3 MeV.[25]

In the present work both *pd* and *nd* relative differential cross sections have been measured for $\Theta_{c.m.} \gtrsim 90°$. In each case the same experimental equipment and setup, data-capture system, and cyclotron beam have been used, with the purpose of comparing the shapes of the *nd* and *pd* differential cross sections at backward angles where previously for $\Theta_{c.m.} \gtrsim 125°$ systematic differences appeared which averaged $\simeq 25\% \pm 15\%$ at 46.3 MeV and $\simeq 11\% \pm 15\%$ at 36 MeV.[25] Absolute *nd* cross sections are obtained by measuring *np* spectra at several angles and using *np* cross sections for normalization. The results are that the *nd*-*np* differences are smaller than noted previously,[25] but that some systematic differences do appear to exist at angles near cross-section minima and beyond.

II. EXPERIMENTAL

The general experimental facilities and techniques used are similar to those used in the earlier *nd* elastic scattering experiment.[25] Briefly, a proton beam from the Crocker Nuclear Laboratory 76-in. cyclotron of typically 8 μA is incident on a ^{7}Li target and produces a collimated neutron beam whose peak is $\simeq 2$ MeV full width at half maximum and contains $\simeq 10^6$ neutrons per sec over 2 cm^2 at 3 m from the ^{7}Li target.[26] The beam energies have been measured by a time-of-flight technique.[27]

For neutron production the proton beam is cleared by a magnet into a Farady cup and integrated. With the magnet turned off a proton current of less than 1 nA can pass down the neutron collimator and into the scattering chamber, all in vacuum. Proton energy losses in the full thickness of the Li target (3.2 mm) and in the polyethylene $(CH_2)_n$ (64.0 mg/cm^2) or deuterated polyethylene $(CD_2)_n$ (71.9 mg/cm^2) targets match on the average the energy loss in half the target plus the $^7Li(p,n)^7Be$ Q value of -1.66 MeV, so that mean proton and neutron beam energies at the target centers are the same to within $\simeq 250$ keV. The lack of beam-transport equipment in the latter part of the beam line made it difficult to measure *pd* scattering at the most forward angles.

The *DE*-*E* telescopes mounted in the scattering chamber consisted of a solid-state detector and a NaI scintillator coupled to an RCA 8575 phototube. One telescope was fixed at 15.5° on the right and two were movable, 20° apart, on the left-hand side of the beam. Zero-crossing timing signals, relative to a beam pick-off reference were used to select the beam peak. These signals were derived from the NaI-RCA 8575 detectors. Events in the beam-peak time window were characterized by *DE* and *E* parameters and data from the three telescopes and neutron beam monitor were stored in an 8000 data region of the PDP 15/40. Cuts in *DE* vs *E* space allowed proton and deuteron events to be selected, single-parameter histograms produced, and the elastic peaks fitted and integrated. The measurement of recoil deuterons corresponds to measuring cross sections for c.m. angles $\gtrsim 90°$. Cross sections for c.m. angles $<90°$ were not measured here as they had been measured ealier.[25] The point of the effort here was to check discrepancies near and beyond the cross-section minimum.

The neutron beam was monitored by a scintillation-counter proton-recoil telescope described earlier[28] which was placed in the beam behind the scattering chamber. Following the ^{7}Li production target the proton beam was magnetically deflected into a Faraday cup. Integration of this beam provided a secondary monitor of fairly high precision (2%). The proton beam which passed down the neutron collimator and through the scattering chamber was not measured quantitatively or integrated. Thus an absolute measure of the *pd* cross section was not obtained.

III. DATA ANALYSIS AND RESULTS

The recoil proton and deuteron spectra obtained by cuts in *DE*-*E* space were reasonably clean and unambiguous. Events due to carbon in the $(CD_2)_n$ and $(CH_2)_n$ targets were subtracted using spectra taken with matching carbon targets. In the case of *nd* spectra the neutron beam monitor allowed background normalization. For *pd* data proton scattering from carbon was used.

The largest corrections were those applied to account for nuclear interactions of protons and deuterons in the Si(Li) and NaI detectors and for finite solid angles of about ±2° lab. The former correction was assumed to be the same as in silicon[29] and was judged to be accurate to 10% in the correction. For the data points at or near the cross-section minima an extrapolation from adjacent points was used to correct for the effects of finite solid angle. This correction of $\simeq 8\%$ was judged to produce a probable uncertainty of 4% in the cross sections which had been folded in to produce the quoted errors. The angular uncertainty is estimated to be less than ±0.2° c.m. The fixed telescope provided normalization for calculating relative *nd* and *pd* differential cross sections. Absolute *nd* cross sections were obtained by using the *np* differential cross sections recently measured at 25.8 and 50 MeV[30] and interpolating between them with an adjusted fit of the Bryan-Gersten model.[31] The lack of a Faraday cup behind the neutron scattering chamber permitted only relative *pd* cross sections.

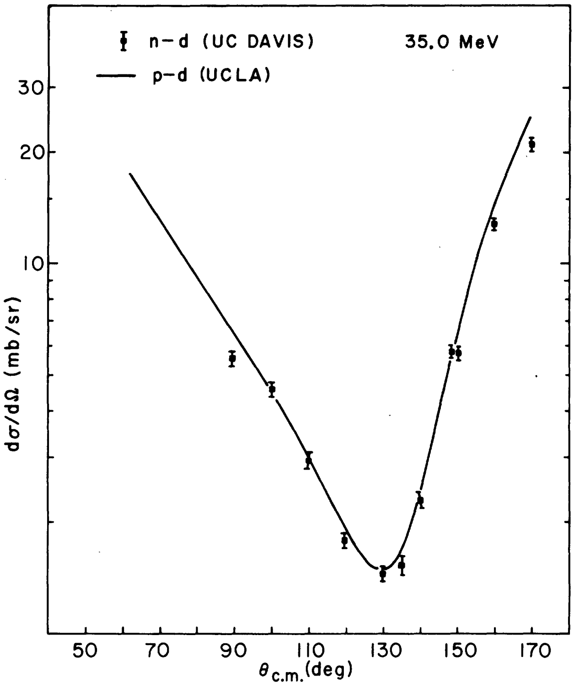

FIG. 1. The *nd* cross sections measured here are the plotted points and the line is drawn through the UCLA *pd* measurements, both at 35.0 MeV lab. See the text for uncertainties in the *pd* data.

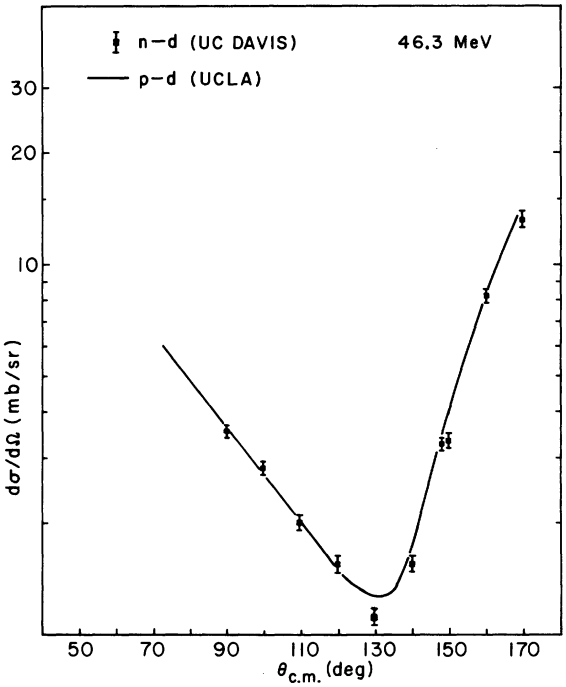

FIG. 2. As in Fig. 1, both at 46.3 MeV.

TABLE I. Differential cross sections for *nd* and relative *pd* elastic scattering.

c.m. angle (deg)	$\sigma(nd)$ c.m. (mb/sr)	Rel. errors (%)	$\sigma(pd)$ c.m. (rel.) (mb/sr)	Rel. errors (%)
		35.0 MeV		
169.3	21.00	2.67		
159.8	12.69	3.00	13.45	5.2
149.7	5.67	3.99	5.91	5.4
148.9	5.73	3.00		
139.6	2.27	3.55	2.38	4.9
134.6	1.54	7.10		
129.5	1.43	6.90	1.53	5.0
119.4	1.76	3.89	1.93	5.9
109.4	2.90	4.57	3.00	5.9
99.4	4.52	3.29	4.50	4.9
89.2	5.23	4.14	6.17	4.7
		46.3 MeV		
169.9	13.33	4.66		
159.9	8.18	4.23	8.21	4.4
149.8	3.34	4.96	3.95	5.2
148.8	3.25	3.08		
139.8	1.55	4.45	1.66	5.1
129.8	1.13	6.72	1.28	4.9
119.7	1.50	5.44	1.60	4.8
109.7	1.95	4.81	1.97	5.4
99.7	2.62	4.20	2.74	5.0
89.7	3.55	4.06	3.69	4.8
79.7			5.25	4.9

The measured *nd* differential cross sections are plotted in Figs. 1 and 2 along with the *pd* cross sections from the University of California at Los Angeles (UCLA).[22] The line is through the UCLA data points which were taken approximately every 5° c.m. and have relative uncertainties of 1–2% for $\Theta < 123°$. For the back angles $\Theta \geq 124°$ the relative errors are in the ranges 4–7% at 35.0 MeV and 2–4% at 46.3 MeV. The absolute error in each case is ≃2%. There is a systematic tendency for the *nd* values to be smaller than the *pd* at large c.m. angles. The average difference at $\Theta_{\text{c.m.}} \geq 130°$ is ≃ 10% at 35 MeV and ≃9% at 46.3 MeV.

Table I gives the numerical results for *nd* and relative *pd* differential cross sections measured here. The *pd* are normalized to those from UCLA at 100–110° c.m. The relative errors given are due mainly to statistics in foreground and background spectra which ranged from 2 to 4% and uncertainties in peak fitting and integration. The scale error due to uncertainties in normalizing to the *np* differential cross sections is ≃ 2.5% and that due to target compositions is ≃1% resulting in a net probable scale error or nearly 3%.

In Fig. 3 are shown our *pd* cross sections and those from UCLA at 35.0 MeV. The latter are given by the line and the former are normalized to the UCLA values in the range 100–110° c.m. It can be seen that the UCLA back-angle *pd* cross sections are slightly higher, by an average of 3.5% than the *pd* measured here. However, the corresponding normalization uncertainty is ≃ 3%. The lack of a Faraday cup and other technical limitations of the neutron line such as the lack of certain beam-transport facilities limited the range of angles and the precision of our *pd* results. Within over-all uncertainties, they agree with the shape of the higher-precision UCLA data which include more angles and extend to larger c.m. angles.

Figure 4 shows a comparison of *nd* and *pd* cross sections measured here at 46.3 MeV. The *pd* have been normalized to *nd* at 100 and 110° c.m., since over this angular range no discrepancies were seen previously between *nd* and *pd*.[25] The line merely gives the trend of the *pd* values. For angles at the minimum and beyond, systematic differences are seen as in the comparison with the UCLA *pd* values. Comparison with a recent calculation of Kloet and Tjon[10] at 46.3 MeV is shown in Fig. 5. The local two-body potential

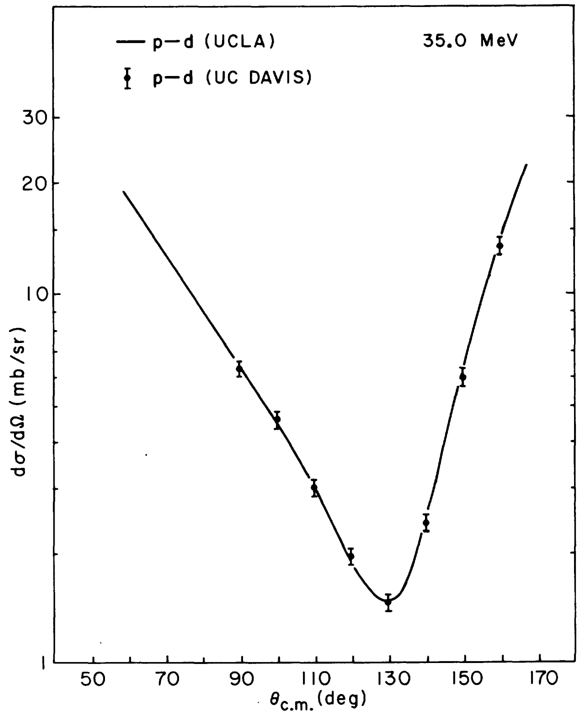

FIG. 3. The *pd* data of this work are the plotted points normalized to the UCLA data over the range 100–110° c.m.; the UCLA *pd* data are indicated by the line (see the text), both at 35.0 MeV.

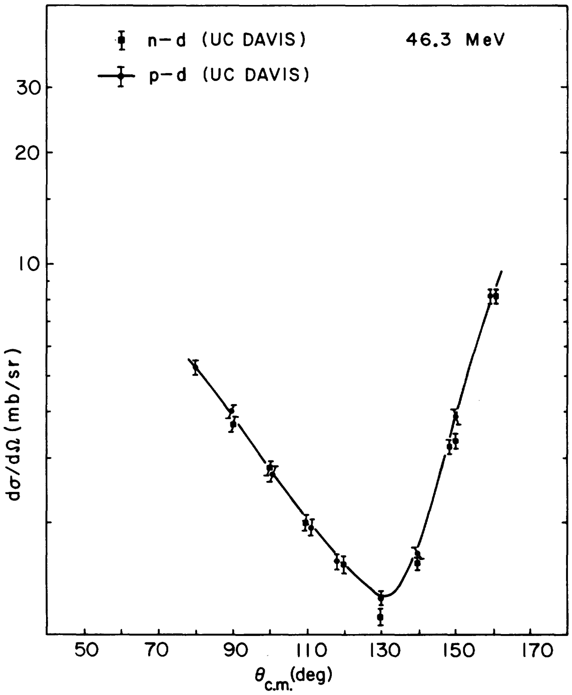

FIG. 4. The *nd* and *pd* cross section from this work at 46.3 MeV with the *pd* normalized to the *nd* at 100 and 110° c.m. The line through the *pd* has no significance. Several points for *nd* and *pd* at the same angle are displaced horizontally to avoid overlapping.

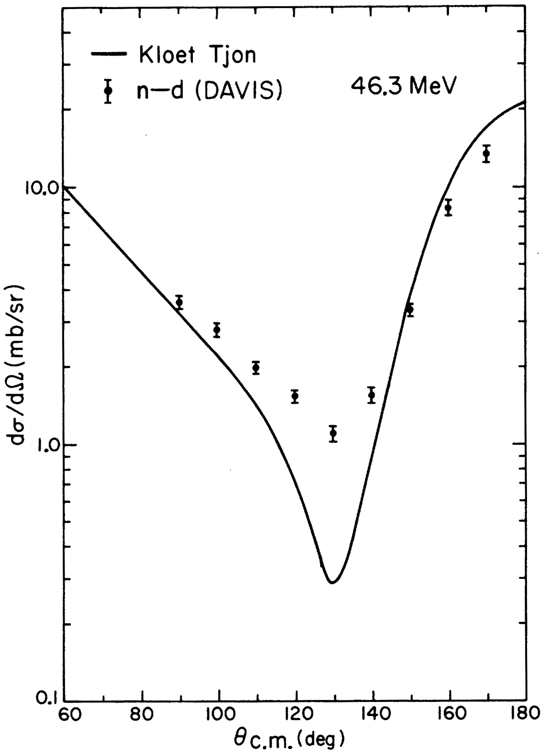

FIG. 5. A comparison of the calculation of Kloet and Tjon (Ref. 10) and the cross sections measured here, both at 46.3 MeV.

TABLE II. *nd* nonelastic total cross section, σ_{ne}.

Energy (MeV)	σ_{total} (Ref. 32) (mb)	$\sigma_{\text{el}} = \int \sigma(\theta)\, d\Omega$ (mb)	$\sigma_{\text{ne}} = \sigma_t - \sigma_{\text{el}}$ (mb)	σ_{ne} (mb)
35.0	342 ± 4	203 ± 13 [a]	139 ± 13	117 [b]
36.0	331 ± 3	203 ± 13 [c]	128 ± 13	
46.3	251 ± 3	147 ± 8 [a]	104 ± 8	93 [d]
46.3	251 ± 3	145 ± 6 [c]	106 ± 7	

[a] Present data and forward hemisphere data from Ref. 25. No correction has been made for the 1-MeV difference in the beam energy for the 35- and 36-MeV data.

[b] Reference 12.

[c] From Ref. 25. Table VIII (and henceforth Table IX) of that reference should be corrected because of small numerical errors in the value of the a_0's in the Legendre polynomial fitting. For the case of nine parameters, the new values are $a_0 = 16.1 \pm 1$ (old value = 16.0) and $a_0 = 11.6 \pm 0.5$ (old value = 11.3) for 36 and 46.3 MeV, respectively. From these one obtains $\sigma_{\text{el}} = 4\pi a_0$.

[d] Reference 10.

used is *S* wave with a repulsive soft core in both the spin-singlet and -triplet states.

The effect of the Coulomb interaction has been examined by Harms.[32] He finds that the addition of Coulomb effects produces destructive interference at forward angles, ≃ 7% at 90° c.m., and constructive interference averaging ≃ 4% at $\theta_{\text{c.m.}} \gtrsim 125°$. A single intersection occurs at $\theta_{\text{c.m.}} \gtrsim 123°$. The particular numbers are model-dependent but the general behavior is as described.

Based on comparisons of our absolute *nd* cross sections with the absolute *pd* values of UCLA and on the comparison of *nd* and relative *pd* cross sections measured here we conclude that systematic *nd*-*pd* differences exist at c.m. angles near the minimum and beyond. However, these differences which average ≃ 9% are less than those reported earlier.[25] Part of the discrepancy between the latter and the present results can be traced to the normalization procedure. For the present results we normalize to new *np* measurements[28,30] while the older data[25] were normalized, it appears, to too small a total cross section.[33] The scale error assigned to the older *nd* data is ≃ 10% so that the two sets of data do have at most angles overlapping absolute errors.

As discussed in Sec. I the theoretical situation is that recent calculations produce fairly good but not quantitative agreement with differential cross sections at these energies.[10-12] The Coulomb force is not usually included in the calculations. Harms[32] is considering Coulomb effects as well as those due to charge-symmetry violations in the nuclear interaction.[32]

The total elastic cross sections can be obtained from integrals of the differential cross sections. Subtracting these from the *nd* total cross sections measured recently[34] one obtains the total nonelastic cross sections. Sloan[12] has calculated the nonelastic cross section up to 40 MeV and the prediction at 35.0 MeV is 117 mb (given in Table II) and a straight-line extrapolation produces a prediction of 92 mb at 46.3 MeV. In Ref. 10 the total elastic and total nonelastic cross sections are predicted to be 201 and 93 mb, respectively, for an energy of 46.3 MeV. A summary is given in Table II.

We are grateful to Dr. W. M. Kloet and Dr. J. A. Tjon for sending us their calculated differential cross sections at 46.3 MeV. We thank Walter Kemmler and Bill Cline for technical assistance and Gene Russell and crew for stable proton beams. One of us (JCW) thanks Associated Western Universities for support. Two of us (JLR and PM) thank the Ford Foundation, University of California–University of Chile Convenio for support.

*Work supported in part by the National Science Foundation.

†Present address: E G and G Company, Los Alamos, New Mexico.

‡Associated Western Universities Fellow.

[1] L. D. Faddeev, Zh. Eksp. Teor. Fiz. 39, 1459 (1960) [transl.: Sov. Phys.—JETP 12, 1014 (1961)].

[2] A. M. Mitra, Nucl. Phys. 32, 529 (1962).

[3] R. D. Amado, Phys. Rev. 132, 485 (1963).

[4] R. Aaron, R. D. Amado, and Y. Y. Yam, Phys. Rev. 136, B650, (1964).

[5] A. C. Phillips, Phys. Rev. 142, 984 (1966).

[6] L. M. Delves and A. C. Phillips, Rev. Mod. Phys. 41, 437, (1969).

[7] I. H. Sloan, Phys. Rev. 185, 1361 (1969).

[8] S. C. Pieper, Phys. Rev. Lett. 27, 1738 (1971); 28, 1154(E) (1971).

[9] E. O. Alt, P. Grassberger, and W. Sanhas, Nucl. Phys. B2, 167 (1967).

[10] W. M. Kloet and J. A. Tjon, Phys. Lett. 37B, 460 (1971); Ann. Phys. (to be published).

[11] W. Ebenhoh, A. S. Rinat-Reiner, and Y. Avishai, Phys. Lett. 29B, 638 (1969); Y. Avishai, W. Ebenhoh, and A. S. Rinat-Reiner, Ann. Phys. 55, 341 (1969).

[12] I. H. Slaon, Nucl. Phys. A168, 211 (1971).

[13] J. Krauss and K. L. Kowalski, Phys. Rev. C 2, 1319 (1970).

[14] I. H. Sloan, Phys. Rev. 165, 1587 (1968); Phys. Lett. 25B, 84 (1967).

[15] N. M. Queen, Nucl. Phys. 55, 177 (1964).

[16] K. L. Kowalski and D. Feldman, Phys. Rev. 130, 276 (1963).

[17] H. Kottler and K. L. Kowalski, Phys. Rev. 138, B619 (1965).

[18] J. D. Seagrave, *The Three-Body Problem in Nuclear and Particle Physics*, edited by J. S. C. McKee and P. M. Rolph (North-Holland, Amsterdam, 1970), p. 41.

[19] C. C. Kim, S. M. Bunch, D. W. Devins, and H. H. Forster, Nucl. Phys. 58, 32 (1964).

[20] V. J. Ashby, UCRL Report No. UCRL-2091, 1953 (unpublished).

[21] A. R. Johnston, W. R. Gibson, E. A. McClatchie, J. H. P. Megaw, and G. T. A. Squier, RHEL R/136, 1966 (unpublished).

[22] S. N. Bunker, J. M. Cameron, R. F. Carlson, J. R. Richardson, P. Tomas, W. T. H. van Oers, and J. W. Verba, Nucl. Phys. A113, 461 (1968).

[23] J. H. Williams and M. K. Brussel, Phys. Rev. 110, 136 (1958).

[24] J. D. Seagrave, J. C. Hopkins, R. K. Walter, A. Nüler, P. W. Keaton, Jr., E. C. Kerr, and R. H. Sherman, LASL Report No. LA-DC 12954, 1971 (unpublished).

[25] J. L. Romero, J. A. Jungerman, F. P. Brady, W. J. Knox, and Y. Ishizaki, Phys Rev. C 2, 2134 (1970).

[26] J. A. Jungerman and F. P. Brady, Nucl. Instrum. Methods 89, 167 (1970).

[27] F. P. Brady, W. J. Knox, and S. W. Johnsen, Nucl. Instrum. Methods 89, 309 (1970).

[28] F. P. Brady, W. J. Knox, J. A. Jungerman, M. R. McGie, and R. L. Walraven, Phys. Rev. Lett. 25, 1628 (1970).

[29] T. A. Cahill, F. P. Brady, S. Corbett, W. Hammontree, K. Isaacs, and E. Young, Nucl. Instrum. Methods 87, 151 (1970).

[30] T. M. Montgomery, F. P. Brady, B. E. Bonner, W. E. Broste, and M. W. McNaughton, Phys. Rev. Lett. 25, 1628 (1970); and private communications.

[31] R. A. Bryan and A. Gersten, Phys. Rev. D 6, 341 (1972).

[32] E. Harms, private communications.

[33] Scanlon *et al.*, Nucl. Phys. 41, 40 (1963).

[34] F. P. Brady, W. J. Knox, R. L. Walraven, and J. L. Romero, Phys. Rev. C 6, 1150 (1972).