Elastic Scattering of Deuterons by Lithium-7*

J. L. C. FORD, JR.†
California Institute of Technology, Pasadena, California
(Received 6 January 1964; revised manuscript received 3 August 1964)

The elastic scattering of deuterons by lithium-7 nuclei has been investigated in the energy region from $E_d=0.40$ to 1.80 MeV. The scattering cross sections tend to be lower than the Rutherford value below about 0.85 MeV, and then rise to values several times the Rutherford value for higher energies. A conspicuous anomaly in the scattering cross section occurs near 1 MeV, where the reaction cross sections also show resonances, while there is no prominent scattering anomaly corresponding to the reaction resonances near 0.80 MeV. The apparent presence of broad overlapping energy levels in the compound nucleus, together with the incomplete nature of the data on the various reaction cross sections, has prevented a detailed theoretical analysis of the elastic scattering over the energy region investigated. An *s*-wave analysis, however, does provide an adequate fitting of the scattering angular distributions up to about 1 MeV, and the relatively sharp scattering anomaly near 1 MeV appears to be due to *p*-wave deuterons. When elastic-scattering data over a wider energy region and more accurate reaction cross sections become available, it may be possible to extract more quantitative information from the present data.

I. INTRODUCTION

ALTHOUGH the elastic scattering of neutrons, protons, and alpha particles by nuclei has provided a great deal of information concerning the properties of individual nuclear energy levels, the elastic scattering of deuterons has mainly been studied at sufficiently high energies, or in sufficiently heavy nuclei, that resonant structure of the scattering cross sections has not been observed. In these cases it has been customary to parameterize the elastic scattering in terms of a complex optical potential. There are, however, a few cases where resonant structure has been observed in deuteron elastic scattering such as ^{4}He(d,d),[1–3] ^{9}Be(d,d),[4] and ^{12}C(d,d).[5–7]

Although the capture of low-energy deuterons by ^{7}Li produces the high excitation energy of about 17 MeV in the ^{9}Be compound nucleus, there are indications of resonant structure in the reaction cross sections.[8–15] At these high excitation energies many channels are energetically open for the decay of the compound nucleus. If a large cross section is observed for a particular reaction, it is usually assumed to be a direct reaction, and in the case of the ^{7}Li$(d,p)^8$Li reaction, at least, the angular distributions can be fitted very well by stripping theory.[11] The present work was therefore undertaken to see first of all whether resonant structure would appear in the elastic-scattering cross sections, and if so, whether one could obtain further information about the spins, parities, and partial widths of those levels of the compound nucleus which have appreciable values of Γ_d/Γ.

In addition, deuteron elastic scattering might be expected to exhibit some novel features due to the rather large size of the deuteron, and to the polarization resulting from the noncoincidence of the center of mass and center of charge.[16–18] Detailed numerical calculations, however, showed that such effects would be expected to be far too small to be observed under the conditions of the present work. These small predicted deviations from Rutherford scattering might be measurable in the case of a high-Z target nucleus.

In the present experiment, the elastic scattering of deuterons from ^{7}Li was studied between 0.40 and 1.80 MeV to investigate the excited states of ^{9}Be from 17.00 to 18.09 MeV. In this energy region, the elastic scatter-

* Assisted in part by the Joint Program of the Office of Naval Research and the U. S. Atomic Energy Commission.
† Present address: Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[1] T. Lauritsen, T. Huus, and S. G. Nilsson, Phys. Rev. **92**, 1501 (1953).
[2] A. Galonsky, R. A. Douglas, W. Haeberli, M. T. McEllistrem, and H. T. Richards, Phys. Rev. **98**, 586 (1955).
[3] L. S. Senhouse (to be published).
[4] M. K. Jurić and S. D. Ĉirilov, Bull. Inst. Nucl. Sci. "Boris Kidrich" (Belgrade) **6**, 45 (1956). The structure found by these authors has not been confirmed in a more recent investigation by J. H. Renken, Ph.D. thesis, California Institute of Technology, 1963 (unpublished), and Phys. Rev. **132**, 2627 (1963).
[5] M. T. McEllistrem, K. W. Jones, Ren Chiba, R. A. Douglas, D. F. Herring, and E. A. Silverstein, Phys. Rev. **104**, 1008 (1956).
[6] E. Kashy, R. R. Perry, and J. R. Risser, Phys. Rev. **117**, 1289 (1960).
[7] J. M. F. Jeronymo, G. S. Mani, F. Picard, and A. Sadeghi, Nucl. Phys. **43**, 417 (1963).
[8] L. M. Baggett and S. J. Bame, Jr., Phys. Rev. **85**, 434 (1952).
[9] S. Bashkin, Phys. Rev. **95**, 1012 (1954).
[10] R. W. Kavanagh, Nucl. Phys. **15**, 411 (1960).
[11] J. P. F. Sellschop, Phys. Rev. **119**, 251 (1960).
[12] D. H. Wilkinson, *Proceedings of the International Conference on Nuclear Structure, Kingston, 1960* (North-Holland Publishing Company, Amsterdam, and The University of Toronto Press, Toronto, 1960).
[13] J. B. Woods and D. H. Wilkinson (to be published).
[14] W. L. Imhof, L. F. Chase, and D. B. Fossan, Bull. Am. Phys. Soc. **9**, 391 (1964).
[15] J. C. Slattery, R. A. Chapman, and T. W. Bonner, Phys. Rev. **108**, 809 (1957).
[16] J. B. French and M. L. Goldberger, Phys. Rev. **87**, 899 (1952).
[17] N. F. Ramsey, B. J. Malenka, and V. E. Kruse, Phys. Rev. **91**, 1162, 1165 (1953).
[18] C. F. Clement, Phys. Rev. **128**, 2724, 2728 (1962).

ing competes with the following reactions:

$$
\begin{aligned}
{}^7\text{Li}+d &\rightarrow {}^8\text{Li}+p\\
&\rightarrow {}^4\text{He}+{}^5\text{He},\ {}^5\text{He}\rightarrow n+{}^4\text{He}\\
&\rightarrow {}^8\text{Be}+n,\ {}^8\text{Be}\rightarrow 2{}^4\text{He}\\
&\rightarrow 2{}^4\text{He}+n\\
&\rightarrow {}^6\text{Li}+t\\
&\rightarrow {}^9\text{Be}+\gamma.
\end{aligned}
$$

The integrated (d,p) cross section indicates resonances near 0.36, 0.8, 1.0, and 2.0 MeV.[8–14] The very distinct resonance at 1.4 MeV observed by Sellschop[11] is only slightly discernible in the data of Baggett and Bame,[8] while no level is apparent at this energy in the measurements of Bashkin[9] or Kavanagh.[10] Neither the values of the integrated cross section nor the resonance energies quoted by the various observers are in satisfactory mutual agreement. The very sharp resonance at 0.36 MeV is also a resonance for the γ-ray reaction.[13,14]

Angular distributions have been measured for the (d,p) reaction by Sellschop.[11] These angular distributions show unexpectedly good stripping patterns at all energies, including the regions of the 1.0- and 1.4-MeV resonances.

The angular distribution of the alpha particles from the ${}^7\text{Li}(d,\alpha){}^5\text{He}$ reaction has been measured by Riviere and Treacy at 0.90 MeV, and found to be isotropic to within 2%, suggesting formation of the compound nucleus by s-wave deuterons.[19] The angular correlation, at the same energy, of the ground-state alpha particles with the alpha particles from the ^{5}He breakup indicates $J=\frac{5}{2}^-$ for the compound nucleus in this energy region.[20] At a bombarding energy of 0.160 MeV, an angular correlation measurement between the ground-state alpha particles and the neutrons from the ^{5}He breakup indicates that $J=\frac{3}{2}^-$ for the compound nucleus concerned.[21] At 0.90 MeV the reactions other than the ${}^7\text{Li}(d,\alpha){}^5\text{He}$ reaction are responsible for less than 10% of the neutrons produced.[20]

The measured (d,n) excitation functions include the neutron yields from the three reactions which produce neutrons. This composite (d,n) cross section has been measured at 90° by Baggett and Bame,[8] and in the forward direction by Slattery *et al.*[15] Resonances were observed near 0.7, 1.0, and 1.8 MeV.

Angular distributions of the neutron groups corresponding to the various excited levels in ^{8}Be have also been measured.[22,23] But as the reaction ${}^7\text{Li}(d,n){}^8\text{Be}$ appears to contribute only a small portion of the neutrons observed, the contribution of the neutron-producing reactions to the total reaction cross section cannot be very well determined from the published data.

Summarizing the reaction data briefly, there are indications of resonances at incident deuteron energies of about 0.36, 0.8, 1.0, and 1.8 MeV; the positions and widths of these levels are not well determined. There is less positive evidence of a resonance at 1.4-MeV incident deuteron energy. The quantum numbers of these levels are unknown, except for an indication that the 0.8-MeV state may be formed by s-wave deuterons.

II. EXPERIMENTAL APPARATUS AND TECHNIQUES

The Kellogg Radiation Laboratory 1.8-MV electrostatic generator was used to accelerate the charged particles used in the present experiment. After the various mass components of the ion beam are magnetically separated by deflection through an angle of about 3°, the desired mass beam enters, and is deflected by an 80° electrostatic analyzer. A horizontal slit system at the exit of the analyzer regulates the electrostatic generator voltage, and in conjunction with the entrance slits of the analyzer defines the beam energy to within about 0.2%. The electrostatic analyzer was calibrated by measuring the yield of gamma rays from the ${}^{27}\text{Al}(p,\gamma){}^{28}\text{Si}$ and ${}^{19}\text{F}(p,\alpha\gamma){}^{16}\text{O}$ reactions which have resonances at proton energies of 992.0 ± 0.5 keV and 872.5 ± 0.4 keV,[24] respectively.

The particles scattered from thick natural Li targets were analyzed by a high-resolution double-focusing magnetic spectrometer, which can be rotated from 0 to 160°. The energy calibration and solid angle of the magnetic spectrometer were determined by observing the elastic scattering of protons and deuterons from thick copper targets. Such measurements were made at the beginning of each experimental run, so that a continual check on the magnet energy calibration and solid angle were available.

Detection apparatus with good energy resolution was necessary in order to perform the present experiment. The bombardment of lithium by deuterons produces a large number of different reaction products. At most incident deuteron energies protons, tritons, ^{3}He particles, and alpha particles will be produced, by reactions with the lithium isotopes at some depth in a thick natural lithium target, with the required energy to pass through the magnet at a given magnet setting, and these particles must be separated by the detector from the elastic deuteron group. In addition, the very large neutron background produced in the deuteron bombardment of lithium requires a detector which is insensitive to neutrons and to neutron-capture gamma radiation. The above problems are made rather critical by the low energy of the deuterons elastically scattered through large angles due to the large center-of-mass motion resulting from lithium plus deuteron reactions.

[19] A. C. Riviere and P. B. Treacy, Australian J. Phys. **10**, 209 (1957).
[20] A. C. Riviere, Nucl. Phys. **2**, 81 (1956/57).
[21] F. J. M. Farley and R. E. White, Nucl. Phys. **3**, 561 (1957).
[22] J. Catala, R. Fant, F. Senent, and J. A. y M. de la Cuadra, Nuovo Cimento Suppl. 2, **9**, 377 (1958).
[23] C. H. Johnson and C. C. Trail, Phys. Rev. **133**, B1183 (1964).
[24] J. B. Marion, Rev. Mod. Phys. **33**, 139 (1961).

A silicon *n-p* junction counter[25] at the focal plane of the spectrometer provided a satisfactory solution to these requirements, and gave a pulse-height resolution of about 20% for 170-keV deuterons. The pulses from the solid-state counter were amplified by a charge-integrating preamplifier in which the noise level was significantly reduced by supplying the filament voltages from a well-filtered, dc power supply. A conventional amplifier followed the preamplifier, and the deuteron pulses were then separated from the other particle groups by means of a differential discriminator and recorded on a scaler. An RIDL 100-channel pulse-height analyzer was used to record many of the spectra, particularly at low energies, to determine the position and number of deuterons relative to the other particle groups, and also as a check on the bias settings of the differential discriminator.

When a beam of particles is incident on a thick target, reaction products are formed with energies extending down to zero from those energies corresponding to reactions at the surface of the target. The high resolution of the double-focusing magnetic spectrometer allows the selection of the reaction products produced in a thin lamina, of thickness determined by the resolution of the magnet and the kinematics of the reaction under study, and located at any desired depth in the target. In the present experiment, the depth of suitable laminae within the target was severely limited, on one hand, by the surface contaminants in the target surface layers, and on the other, by the deuterons elastically scattered from the natural ^{6}Li content of the target.

The preparation of sufficiently uncontaminated targets to obtain accurate cross-section measurements was a major source of difficulty in the present experiment. The problem of contaminants is a more serious one when deuterons are used as the incident particles than when protons are used, primarily because of the larger center-of-mass motion which produces a more rapid variation of the energy of the scattered particles with angle. For this reason, nuclei distributed over a greater range of depths within the target, possibly including those regions near the surface where the contaminants are more likely to be located, can scatter particles with energies lying within the resolution of the magnetic spectrometer.

The targets used consisted of very smooth, thick layers of metallic lithium, evaporated inside the scattering chamber onto a backing which was previously prepared by evaporating a thick layer of copper onto a glass microscope slide. The lithium was cut under kerosene so that the bright metal was exposed, placed in the scattering chamber, and the system was then pumped overnight before the lithium was evaporated. The evaporation furnace consisted of a hollow cylinder of carbon heated by a coil of molybdenum wire wound directly onto the cylinder. A cold trap, located close to the target, was kept filled with liquid nitrogen not only while the evaporation was made, but also whenever the target was bombarded by the beam. The subsequent slow oxidation of the target surface while in the scattering chamber made the target useless after about one day. The very rapid buildup of carbon and oxygen in the surface layers of the target during bombardment necessitated the frequent changing of target spots to regions which had not been previously bombarded.

Excitation functions were measured at the zeros of the Legendre polynomials, P_1, P_2, and P_3, i.e., at center-of-mass angles 90°, 125° 16′, and 140° 46′, respectively. Data were taken at intervals of 20 keV from below 0.40 to 1.80 MeV, except at 90° where the fact that the magnetic spectrometer available for the present work could only bend deuterons with energies less than 0.90 MeV required an incident deuteron energy below 1.40 MeV. These excitation functions, plotted as a function of the deuteron laboratory energy, are shown in Fig. 1. There is an obvious scattering anomaly near 1 MeV, but nothing conspicuous appears at either 0.80 or 1.40 MeV where resonances have been reported in the reaction data. The behavior of the cross section near 0.80 MeV, however, is consistent with a broad level in this region. The scattering cross sections tend to be lower than the Rutherford value below about 0.85 MeV, and then rise to values several times the Rutherford value in the energy region of the anomaly near 1 MeV. Above 1.10 MeV the ratio of the scattering cross section to the Rutherford cross section continues to rise smoothly throughout the energy interval investigated.

Angular distributions were taken at 20 different energies emphasizing the regions of suspected resonances. The scattering yields were generally determined at 10 to 13 angles taken at intervals of 0.1 in $\cos\theta_{\text{c.m.}}$ between +0.4 and −0.9. In Fig. 2 are plotted some of the angular distributions passing over the region of 0.80 MeV where the first resonance is observed in the reaction data. Tabulated values of the observed cross sections, as well as a more detailed account of the attempts to analyze the data than that given in this paper, may be found in Ref. 26.

At low energies the measured scattering cross sections were considerably lower than the Rutherford cross section. At a bombarding energy of 0.400 MeV, where elastic proton-scattering experiments typically yield cross sections close to the Rutherford value, the ratio of the scattering cross section to the Rutherford cross section varies from 0.92 to 0.69 as the scattering angle is changed from $\theta_{\text{c.m.}}=66°\,25'$ to $\theta_{\text{c.m.}}=134°\,26'$. Various possible instrumental reasons for the low cross sections have been examined.

[25] Obtained from the Hughes Aircraft Corporation through the courtesy of Dr. J. W. Mayer.

[26] J. L. C. Ford, Jr., Ph.D. thesis, California Institute of Technology, 1962 (unpublished).

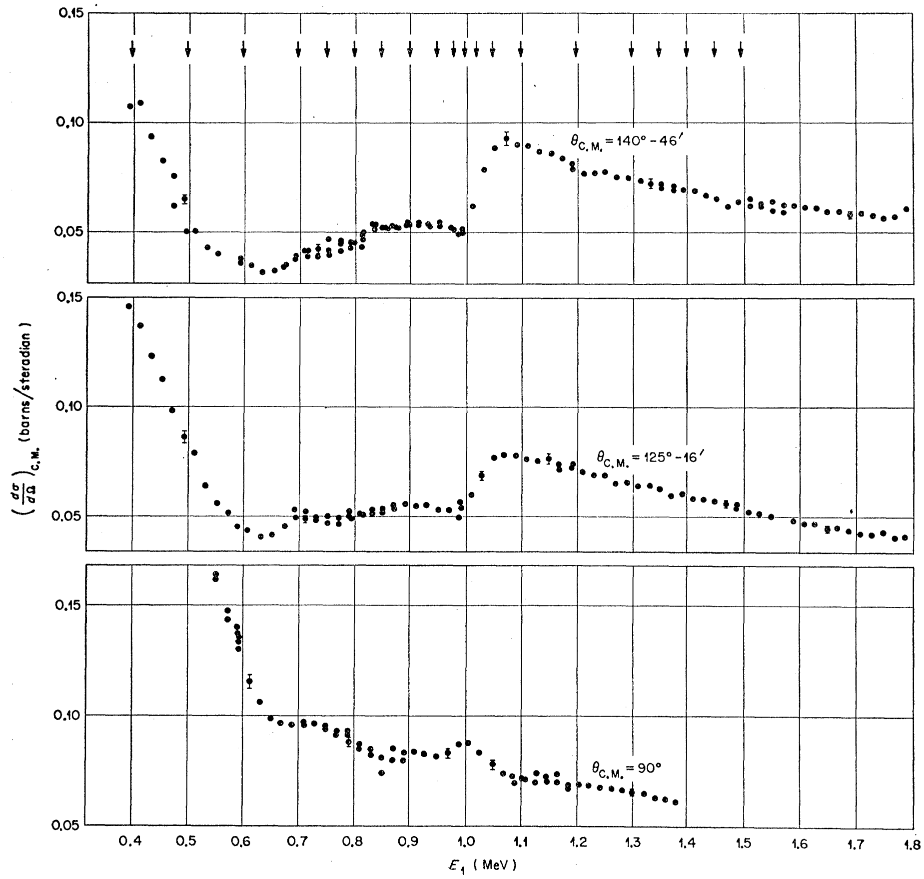

FIG. 1. The elastic scattering of deuterons from ^{7}Li nuclei. The differential cross section in the center-of-mass system is shown as a function of the deuteron energy in the laboratory system at the center-of-mass angles corresponding to the zeros of the second, third, and fourth Legendre polynomials. The relative error shown is of the order of 3%. The arrows indicate the energies at which the angular distributions were taken. Note the suppressed zeros.

The number of particles which traverse the magnetic spectrometer must be corrected for those lost due to charge exchange in the target, and residual gas of the vacuum system. During the present experiment, the correction for charge exchange in the target was often a significant one, and was made by using the charge equilibrium ratios given by Phillips[27] for old surfaces, or "dirt." To check the magnitude of the charge-exchange correction, deuterons were scattered from copper down to an incident energy of 150 keV. To within the relative experimental error of about 3%, the values of the charge-exchange correction derived from Ref. 27 seem to be sufficiently accurate. These measurements also verify the constancy of the spectrometer solid angle down to $E_d = 150$ keV.

The proton momentum distribution, taken at the beginning of each experimental run as a check on the lithium target surface condition and on the amount of contaminants present, gives a further check on the data-taking procedure by allowing these measured cross sections to be compared with those of previous experiments. Proton-scattering data taken in the present experiment agree well at all energies with those taken by Warters *et al.*[28] after lowering their data by 8.7%[29] as required by more recent determinations of the stopping cross sections involved.

The possibility that the low values obtained for the cross sections in the energy range below 0.8 MeV are due in some way to the observed contamination of the surface layers of the target must be examined. For reasons of brevity, only a summary of the straightforward but rather complicated procedure used to estimate the effects of target contaminants is presented here. For a more detailed discussion of these computations, the reader may consult Ref. 26.

The necessary relations to obtain cross sections from thick-target yields have been discussed in a number of articles.[30–32] For a nonuniform target, the usual uniform target equations for the thick-target yield, the depth at which the reaction occurs, and the reaction energy at

[27] J. A. Phillips, Phys. Rev. **97**, 404 (1955).

[28] W. D. Warters, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **91**, 917 (1953).

[29] N. Jarmie and J. D. Seagrave, Los Alamos Scientific Laboratory Report, LA-2014, 1957 (unpublished), and W. A. Fowler (private communication).

[30] A. B. Brown, C. W. Snyder, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **82**, 159 (1951).

[31] R. K. Bardin, Ph.D. thesis, California Institute of Technology, 1961 (unpublished).

[32] D. Powers and W. Whaling, Phys. Rev. **126**, 61 (1962).

that depth can be suitably modified by replacing the stopping cross sections in the uniform target equations by the quantity

$$\beta = \epsilon_T + (n_I/n_T)\epsilon_I. \qquad (1)$$

The subscripts on ϵ, the stopping cross section, and on n the number of atoms per unit volume, denote the target and impurity elements, respectively. The distribution of contaminants in a lithium target is both expected and observed to be a rapidly decreasing function of depth within the target. Therefore, since the magnetic spectrometer accepts particles from a range of depths within the target, the yield must be integrated over the solid angle subtended by the magnet at the target, and over the energy acceptance window of the magnet.

The oxygen peaks observed in the ^{7}Li(p,p) momentum profiles taken with the magnetic spectrometer were used to estimate the distribution of oxygen within the target, and its effect on the yield of scattered deuterons. Momentum profiles measured with typical targets used in the present experiment can be seen in Figs. 3(a) and (b). The ratio of the number of oxygen atoms to the number of lithium atoms was determined at points on the low-energy side of the oxygen peak by treating the oxygen as the target nucleus, and the ratio obtained was extrapolated to a value of $\frac{1}{2}$, corresponding to Li_2O, at the target surface. The calculated oxygen distribution was then used, in turn, to recompute the oxygen peak by integrating over the spectrometer energy and angle windows numerically. The computed oxygen peak was usually within 10% of the one observed experimentally, which was taken as reasonable agreement considering the approximations made necessary by the fact that the effective spectrometer resolution was comparable to the width of the oxygen peak.

The calculated oxygen distribution can then be used to determine the energy at which the deuterons are elastically scattered from the lithium for a given magnetic field setting, and the reduction in counting rate due to dilution of the lithium by the oxygen contamination. Although the oxygen distribution could be determined only approximately, the effect of the oxygen contamination could be estimated well enough to show that a reduction in the 90° ^{7}Li(d,d) yield of only a few percent was possible at 0.4 MeV, whereas the reduction at $E_d = 0.3$ MeV might become as large as 20%. It is therefore believed that the target contamination, which is largely in the surface layers of the target, does not significantly affect the cross-section measurements above 0.5 MeV.

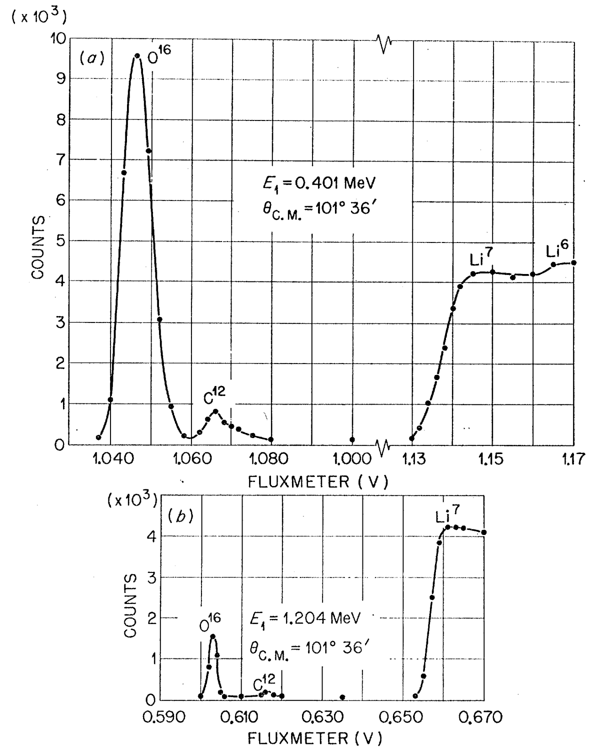

FIG. 3. (a) A typical momentum distribution of protons elastically scattered from a thick target of natural lithium at an incident energy of 0.401 MeV to determine the target condition. As the abscissa represents the magnet fluxmeter setting, the energy of the scattered particles increases to the left. The position of the particle groups scattered from the ^{6}Li and ^{7}Li, as well as from the ^{16}O and ^{12}C nuclei within the target can be seen. (b) A momentum profile obtained at a higher incident proton energy from which the strong energy dependence of the heights of the ^{16}O and ^{12}C peaks may be seen. The ^{6}Li step occurs at a higher fluxmeter setting than plotted in the figure.

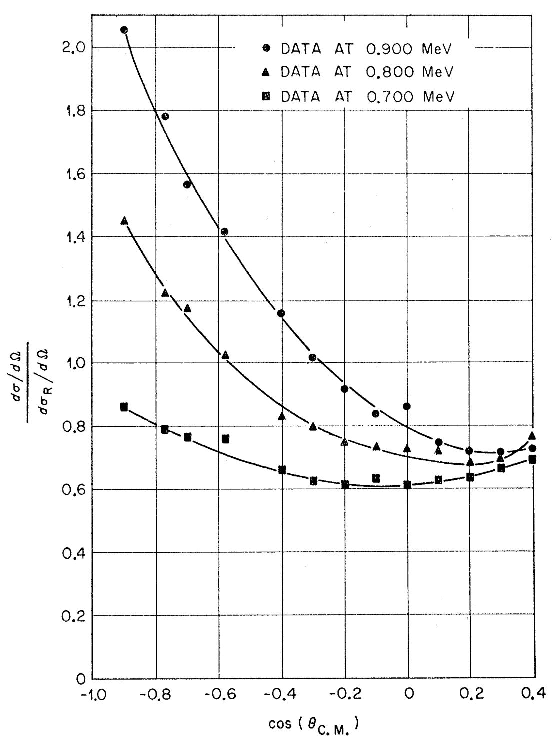

FIG. 2. The ^{7}Li(d,d) angular distributions measured over the energy region where the first resonance is observed in the reaction cross sections. The curves are merely guides to the data points.

The probable error of the relative cross sections is estimated to be about 3% over the range of energies and angles used in the experiment above 0.5 MeV, and about 7% between 0.4 and 0.5 MeV. Except at the lower energies where contaminants become more significant, the probable error in the absolute cross sections is of the order of 6%, with the main contribution arising from the 3% uncertainties in the lithium and copper stopping cross sections. Between 0.4 and 0.5 MeV, the probable error in the absolute cross sections may be as high as 10% due chiefly to the uncertainty in the effects of the target contaminants.

III. ANALYSIS AND CONCLUSIONS

The scattering data of the present experiment, as well as the reaction data obtained by previous investigators, show clearly that contributions from many compound nuclear levels may be present in the energy region under study. As the properties of these levels are essentially unknown, a complete analysis of the data was found to be impractical, due to the complexities of the scattering of a spin-1 particle, the restricted energy range of the scattering data, and the inadequate information concerning the reaction cross sections.

As a first step in the analysis, and also because of the indications from the reaction data that the compound nucleus is formed by s-wave deuterons at low energies, an attempt was made to see how well the scattering data could be fitted on the assumption of s-wave nuclear scattering interfering with Rutherford scattering. For this analysis, the graphical method suggested by Christy[33] was employed. The equation for pure s-wave scattering can be written as:

$$\frac{d\sigma/d\Omega}{R}-1=\left[\frac{\sin\xi}{k\sqrt{R}}-\frac{1}{2k^2R}\right](X-1)-\frac{\cos\xi}{k\sqrt{R}}Y-\frac{U}{4k^2R}, \quad (2)$$

where R is the Rutherford cross section, k the wave number of the incident particle, and $\xi=-(Z_1Z_2e^2/\hbar v)\times\ln\sin^2(\frac{1}{2}\theta)$ is the phase of the Rutherford amplitude. The angle-independent parameters X, Y, and U are related to the unknown nuclear scattering amplitude, and are limited by the restrictions

$$-1\leq X\leq 1,\quad -1\leq Y\leq 1,\quad X^2+Y^2\leq 1-U. \quad (3)$$

In addition, the quantity U is equal to k^2/π times the integrated s-wave reaction cross section. If the s-wave reaction cross section is known, then at each angle the s-wave scattering differential cross section involves the two unknowns X and Y, and may be plotted in the (X,Y) plane as a straight line. The common intersection of the lines corresponding to the various angles of the angular distribution furnishes the required solution for X and Y. If the uncertainty in the common intersection exceeds that deemed permissible by the experimental error, or if the conditions of Eqs. (3) are not obeyed, then the data require that additional angular-momentum waves be included in the analysis.

Since the reaction cross sections are large, and vary rapidly with energy, it was necessary to estimate the s-wave reaction cross section as well as possible.[34] In addition to the difficulty in separating out the s-wave portion of the reaction cross section, and the large uncertainties in the reaction cross sections leading only to charged particles, the differential cross section for the reactions producing neutrons has been measured only at 0 and 90°. On the assumption that the interaction is principally due to s waves, the total cross section for the neutron-producing reactions was estimated by taking 4π times the 90° differential cross section. The procedure adopted to estimate the s-wave contribution to the total reaction cross section was to remove the penetration factors from the cross-section measurements of Baggett and Bame,[8] symmetrize the resultant peak near 0.750 MeV to which was added a constant background to account for the distant s-wave levels, and then reintroduce the penetration factors to obtain the desired cross section. The total s-wave reaction cross section computed in this manner is shown in Fig. 4. It was found that an acceptable s-wave fit to the scattering data could be obtained up to about 1 MeV, which also satisfied the unitarity conditions of Eqs. (3) on the collision matrix, only if the total reaction cross section was arbitrarily reduced to $\frac{3}{4}$ or less of the (admittedly crude) estimate obtained in the manner described above. Examples of the graphical analyses are shown in Fig. 5, for 0.400 MeV the lowest energy at which an angular distribution was measured, and in Fig. 6, at 0.750 MeV corresponding to an energy approximately that of the first resonance observed in the reaction data. The fit to the data at 0.400 MeV may be somewhat fortuitous considering the possible effects of target

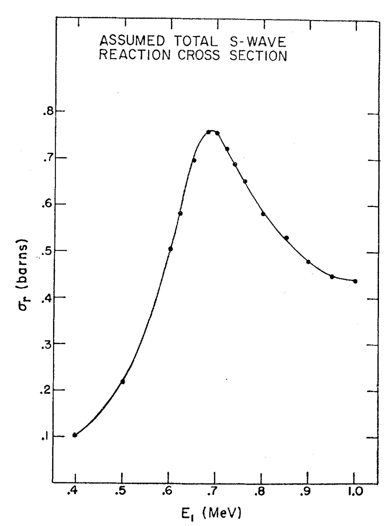

FIG. 4. The estimated total s-wave reaction cross section for deuterons incident on lithium-7. It was necessary to reduce this cross section to obtain a satisfactory s-wave analysis as explained in the text. The points shown indicate the energies at which the plots of the different reaction cross sections were evaluated.

[33] R. F. Christy, Physica 22, 1009 (1956).

[34] F. B. Morinigo, Nucl. Phys. 36, 529 (1962).

contaminants, and indeed there is a larger uncertainty as to the true intersection at this energy than in the plots corresponding to higher energies. Although in the region of 0.8 MeV, the motion of the point of intersection in the (X,Y) plane has the general energy variation expected for a reaonance, the arbitrary procedure employed in estimating the s-wave reaction cross section reduces the significance that can be attached to the data fits.

In the region near 1 MeV, the s-wave fits, as judged from the intersections obtained in the X-Y plots, became poorer, and failed completely above 1 MeV, presumably as a result of contributions from the state situated near 1 MeV, and possibly also from higher states. Although the s-wave fits imply odd parity for

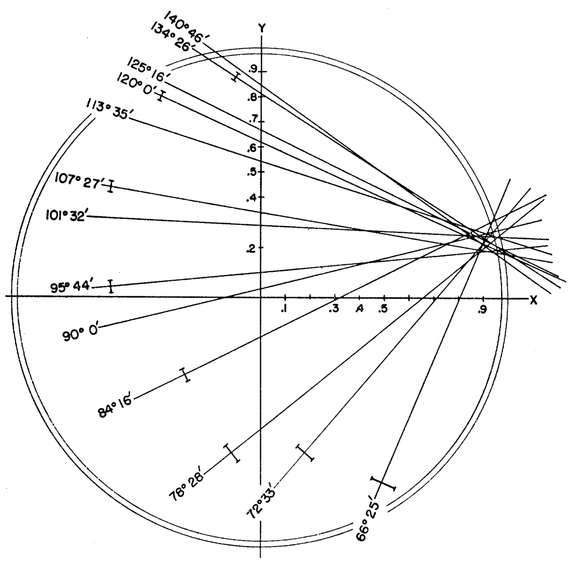

FIG. 5. The (X,Y) plot of the scattering data at an incident deuteron energy of 0.400 MeV. The value of U used in the s-wave analyses of the ^{7}Li(d,d) scattering data, seen in Figs. 5 and 6, was obtained by multiplying the cross section of Fig. 4 by $\frac{5}{8}$. The common intersection of the lines corresponding to the various angles in the center-of-mass system was taken as $X=0.91$, $Y=0.24$. This intersection must lie within the inner circle determined by $[1-U]^{1/2}$. The error bars are due to the experimental relative error.

the state (or states) below 1 MeV, the spins, and even the number, of these levels could not be determined since this additional information, in general, requires interference with states of some other known angular momentum.

The prominent scattering anomaly near 1 MeV appears to be symmetrical, as a function of energy, at 90° in the center-of-mass system. This suggests that the corresponding state of ^{9}Be is formed by deuterons with odd orbital angular momentum. In addition, the presence of a strong asymmetric anomaly at 140° 46′, a zero for P_3, suggests that the resonance is probably formed by p waves. The observed width of the level near 1 MeV would also violate the Wigner limit for orbital angular momenta of three or higher. If the

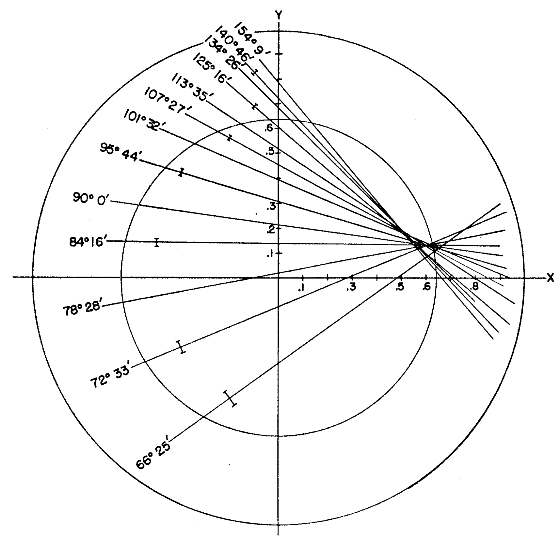

FIG. 6. The (X,Y) plot of the scattering data at an incident deuteron energy of 0.750 MeV. This is the approximate energy of the first resonance observed in the reaction data. The common intersection was taken as $X=0.57$, $Y=0.14$.

1-MeV resonance is formed by p waves, and if the deuteron partial width equals the observed total width, Γ_d is less than 10% of the Wigner limit. By dividing the differential cross section into "resonance" and "background" contributions in a plausible way, and assuming that the state is formed by p-wave deuterons, it was possible to get a successful p-wave fit to this resonance using a "narrow-level" analysis.[33] Unfortunately, the unknown angular momenta in the background contribution make the actual phase shifts determined for this level of doubtful reliability.

A further attempt was made to fit the scattering data with a computer program, developed by Overley,[35] on the basis of an assumed s-wave state at about 0.80 MeV and a p-wave state at about 1.02 MeV. Although many choices were tried for the widths and spins of these assumed levels, no satisfactory fit was obtained. There are several possible reasons for the failure to obtain a fit, such as contributions from the higher levels which are clearly indicated by the scattering data, and the neglect of the "direct" reactions. A complete analysis of the deuteron elastic scattering in this energy region might become feasible, possibly including the effect of distant levels with an optical potential, when scattering data over a wider energy range and more accurate differential cross sections for the reactions become available.

The absence of a scattering anomaly at 1.4 MeV might be due to such a level having a small value of Γ_d/Γ, but the conflicting evidence of the reaction data raises the possibility that the 1.4-MeV level is due to some contaminant in those experiments where it was observed. It seems excluded that the resonance at

[35] J. C. Overley (private communication).

360 keV could have any significant effect on the differential cross sections above 400 keV, even if Γ_d/Γ should be large for this resonance, because of the quoted width, $\Gamma<2$ keV.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Professor C. A. Barnes for his assistance and guidance during the course of this experiment. The advice and support of Professor R. F. Christy, Professor W. A. Fowler, Professor R. W. Kavanagh, Professor T. Lauritsen, Professor H. A. Weidenmüller, and Professor W. Whaling have been appreciated. The aid of Mrs. B. A. Zimmerman in the programming and operation of the electronic computer used for many of the calculations is gratefully acknowledged.

PHYSICAL REVIEW VOLUME 136, NUMBER 4B 23 NOVEMBER 1964

Elastic Scattering of Deuterons by Ca^{40}†

R. H. Bassel, R. M. Drisko, and G. R. Satchler
Oak Ridge National Laboratory, Oak Ridge, Tennessee

and

L. L. Lee, Jr., J. P. Schiffer, and B. Zeidman
Argonne National Laboratory, Argonne, Illinois

(Received 6 July 1964)

The elastic scattering from Ca^{40} of deuterons with energies of 7, 8, 9, 10, 11, and 12 MeV has been measured and subjected to optical-model analysis, as a preliminary to a distorted-wave study of the $Ca^{40}(d,p)$ reaction. Considerable ambiguities in the optical-model parameters are found, and the results are discussed in detail. Inclusion of a polarization potential and of spin-orbit coupling is found to have little effect. An attempt is made to find a set of parameters that gives a good over-all fit at all the energies.

I. INTRODUCTION

THE usefulness of reactions such as deuteron stripping as sources of information about nuclear structure has been enhanced in recent years by the introduction of analysis by the distorted-wave Born approximation. A prerequisite for the application of this theory is a knowledge of the *elastic* scattering of the particles involved. In practice, this scattering is analyzed in terms of an optical-model potential, which is used to generate the distorted waves in the reaction calculation.

The present measurement and analysis of the scattering of deuterons by Ca^{40} at energies from 7 to 12 MeV was undertaken as a preliminary to a detailed study of the validity of the distorted-wave theory for the deuteron-stripping reaction $Ca^{40}(d,p)Ca^{41}$. For this reason, considerable attention was paid in the analysis to questions such as the existence of ambiguities in the choice of optical-model potential, and to the possibility of finding a potential whose parameters show at most a slow variation over this energy range. At the same time, of course, an attempt to understand the observed scattering is of interest in itself.

Many deuteron-scattering experiments have been analyzed recently, and optical-model potentials have been found whose parameters show systematic trends through the periodic table.[1,2] Although data have been taken at a number of energies, there have been very few systematic measurements of the scattering as a function of energy.

II. EXPERIMENTAL METHOD AND RESULTS

Thin natural Ca targets (96.97% Ca^{40}) were bombarded with 7.0-, 8.0-, 9.0-, 10.0-, 11.0-, and 12.0-MeV deuterons from the Argonne tandem Van de Graaff. The targets were thin rolled foils of Ca metal about 1 mg/cm^2 thick, mounted in the center of a scattering chamber 18 in. in diameter, which was developed by Braid and Heinrich. Elastically scattered deuterons were detected in a commercial surface-barrier Si detector mounted on an arm whose angular position could be remotely controlled with a precision better than 0.2°. Measurements were made at 5° intervals over an angular range from 10 to 165°. The incident beam was defined by two circular apertures $\frac{1}{16}$in. in diameter and fixed 11 in. apart, followed by a slightly larger antiscattering aperture. The collimating system was electrically insulated, and the beam was always focused so that less than 25% was intercepted by any of the slits.

To avoid possible inaccuracies due to microscopic nonuniformities in the targets, all angular distributions were measured relative to a monitor counter fixed at

---

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] E. C. Halbert, Nucl. Phys. 50, 353 (1964).
[2] C. Perey and F. Perey, Phys. Rev. 132, 755 (1963).