Deuteron-Helium Differential Scattering Cross Sections*

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(Received December 27, 1954)

Deuteron-helium elastic scattering cross sections have been measured from $E_d=0.28$ to 4.62 Mev. A resonance at $E_d=1.070$ Mev and $\Gamma\sim 35$ kev was observed at 9 angles from 90° to 173.6° c.m. This resonance corresponds to the previously observed 2.187-Mev state of Li^6. No scattering anomaly was observed at the deuteron energy corresponding to the known 3.58-Mev level of Li^6. This negative result is consistent with an assignment of $J=0^+$, $T=1$ to this state. A very broad scattering anomaly is observed from about 3 Mev to 4.62 Mev. Most of the cross section measurements are good to 3 percent or better in absolute magnitude.

I. INTRODUCTION

LITHIUM-6 is the simplest nucleus in which the coupling of two p-nucleons may be investigated. Previous experiments have indicated excited levels at 2.187 Mev[1,2] ($J=3^+$, $T=0$)[2] and 3.58 Mev ($J=0^+$, $T=1$).[3] In order to obtain further information on the Li^6 levels, $He^4(d,d)He^4$ differential cross sections have been measured from $E_d=0.28$ to 4.62 Mev. This range of deuteron bombarding energies corresponds to a range of excitation in Li^6 of 1.66 to 4.55 Mev.

II. EXPERIMENTAL ARRANGEMENTS

An electrostatic generator was used to provide a beam of deuterons. The beam energy was both monochromatized and measured to ±0.05 percent by a 90° cylindrical electrostatic analyzer. After passing through this analyzer the beam was collimated to a half-angle of 12 min by two 1.5-mm circular apertures. It then entered a differentially pumped helium chamber in which the scattered deuterons were detected at variable angles by two proportional counters. The target thickness was always less than 3 kev. Except for minor changes, the scattering chamber and associated equipment have been described elsewhere in more detail.[4,5]

Since the energy of back-scattered deuterons is only 1/9 of the incident deuteron energy, observation of the back-scattered deuterons is difficult at low bombarding energies. The large scattering angles are, however, most important for detecting and interpreting nuclear scattering anomalies. After considerable effort the problem of quantitatively detecting the low-energy back-scattered deuterons was solved by using 1000-A nickel foils[6] to separate the chamber gas from the counter gas. The thin nickel foil was mounted on a cylindrical surface of a 0.4-cm radius of curvature and the pressure differential between counter and chamber always kept positive. Under these circumstances foils would sometimes stand 2 cm Hg differential over an opening 1.5×0.35 cm^2.

Below $E_d=1.2$ Mev, data were taken with two counters simultaneously. One counter—used for the back angles—had a very thin (1000-A nickel) foil so as to pass the low energy, back scattered deuterons. The other counter—used for laboratory angles less than 90°—had a thicker (5000-A nickel) foil to stop the recoil α particles. Above 1.2 Mev the counter gas was changed from propane to a 2 percent mixture of CO_2 in argon in order to decrease the sensitivity of the counters to neutrons. Satisfactory pulse height distributions with A-CO_2 gas fillings were not achieved for the counter with the thick foil although the other counter behaved satisfactorily. Hence all of the data above 1.2 Mev were taken with one counter. Since there was not time to change foils frequently, and it was the back angle data that were chiefly desired, the counter foil was kept thin and the appearance of the recoil α particle group at laboratory angles less than 90° was unavoidable.

Proper choice of observational angles can be of considerable help in the analysis and interpretation of the data. Thus when $\sin^2\theta_{c.m.}\ll 1$, the contribution to the cross section of deuterons that have undergone a spin reorientation in the scattering process is negligible. Also, since all Legendre polynomials have maximum amplitude at 180°, observation at the back angle is advantageous for detecting resonances. The largest angle permitted by the geometry of the scattering chamber corresponded to 173.6° in the c.m. system and therefore $\sin^2\theta_{c.m.}=0.0123$. The other angles of observations were chosen to give c.m. angles near the zeros of various low-order Legendre polynomials.

III. EXPERIMENTAL RESULTS

The measured deuteron-helium differential cross sections in the center-of-mass system are plotted in Figs. 1, 2, and 3 against the deuteron bombarding energy. For the closely spaced points in Fig. 1 the energy difference between neighboring points is 3 kev. Except for the large peak at 1.07 Mev in Fig. 1 where, for the sake of clarity, the experimental points have been

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* Work supported by the U. S. Atomic Energy Commission and the Wisconsin Alumni Research Foundation.

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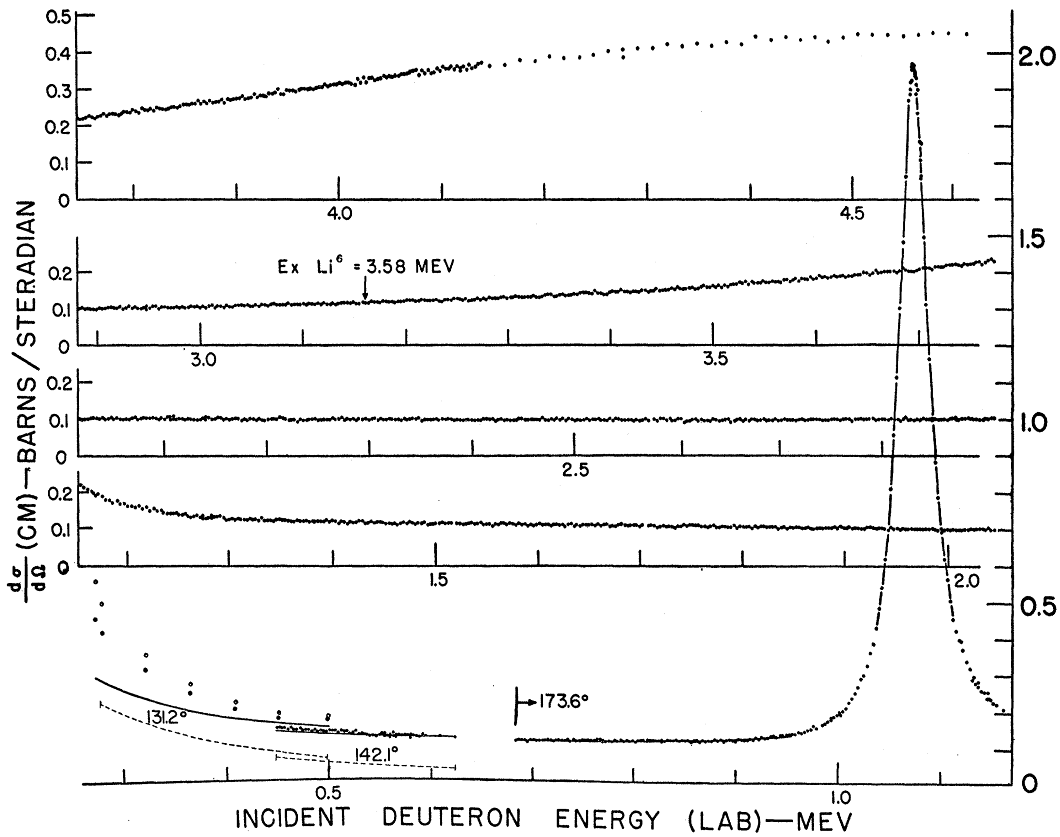

FIG. 1. The center-of-mass differential cross section for elastic scattering of deuterons by helium. All data for laboratory deuteron energies above 0.68 Mev are at 173.6°. The c.m. angles for the lower energy points are indicated. Dashed curves are Rutherford cross sections; solid curves below $E_d=1$ Mev are Rutherford plus $l=0$ wave; solid lines connecting points of 1.07-Mev resonance are only for visual aid. Solid points at 131.2° include a charge loss correction; the open circles are the raw data.

connected by solid lines, all curves—solid, dotted, dashed, and dot-dashed—in Figs. 1, 2, and 3 are curves corresponding to a phase-shift analysis which is discussed in an accompanying paper.[7]

The cross sections were computed from the observed number of scattered deuterons, Y; the number of deuterons incident on the target, N; the number of target helium nuclei/cm^3, n; a geometry factor of the counter slit system, G[8]; and the laboratory and center-of-mass scattering angles, θ_{lab} and $\theta_{\text{c.m.}}$ by means of the following relation:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}}=\frac{Y}{NnG}(\sin\theta_{\text{lab}})\left[\frac{\sin^2\theta_{\text{lab}}}{\sin^2\theta_{\text{c.m.}}}\cos(\theta_{\text{lab}}-\theta_{\text{c.m.}})\right].$$

The first angular factor expresses the variation of target thickness with angle and the second, the variation with angle of the ratio of laboratory to center-of-mass solid-angle elements. To a first approximation G is independent of angle.[9] However, the finite dimensions of the rectangular slits introduce a one percent variation in G over the angular range investigated.

The deuteron bombarding energy corresponding to the previously reported 3.58-Mev excited state[3] in Li^6 is 3.15 Mev. Figure 1 shows no sign of a resonance at this energy. Conservation of angular momentum and conservation of isobaric spin would each forbid a state of $J=0^+$, $T=1$ from appearing in the deuteron-helium scattering.

IV. ACCURACY OF THE CROSS SECTIONS

The accuracy of the cross sections is limited in most cases by the uncertainty in Y. The statistical uncertainty in Y was generally about 2 percent, although individual values varied from 0.2 percent at the resonance peaks to as much as 5 percent at resonance minima where the counting rate was low.

Three discriminator-scalers were used for each pro-

[7] A. Galonsky and M. T. McEllistrem, following paper, Phys. Rev. **98**, 590 (1955).

[8] Worthington, McGruer, and Findley, Phys. Rev. **90**, 899 (1953).

[9] Breit, Thaxton, and Eisenbud, Phys. Rev. **55**, 1036 (1939); H. R. Worthington, Ph.D. thesis, University of Wisconsin, 1952 (unpublished) has specialized for rectangular slits the expression given by Breit, *et al.*

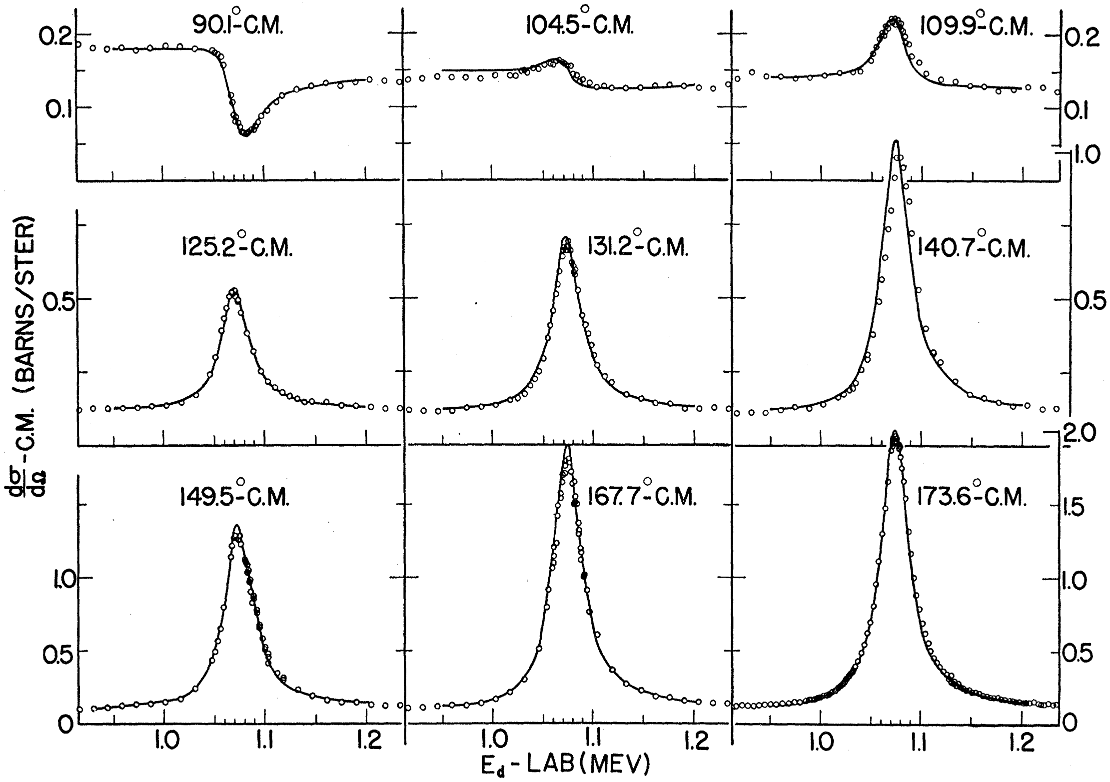

FIG. 2. The $E_d = 1.07$-Mev resonance for various center-of-mass angles. The solid curves are from the phase shift analysis of the accompanying paper by Galonsky and McEllistrem and indicate that the level of Li^6 involved has even parity and $J=3$.

portional counter. In this manner information on the pulse height spread of the counter pulses was obtained continuously. The spread in pulse height generally caused less than 2 percent difference in the counting rates of two scalers triggered at 1/3 and 2/3 the average height of the group. Most of this difference usually disappeared after subtraction of background. The straggling of the α particle group (see Sec. II) is the major source of error in the data in Fig. 3 at the center-of-mass angles 90.1° and 109.9°.

TABLE I. Summary of cross section uncertainties (total rms uncertainty in percent).

(a)

C.m. angle	Energy (Mev) 0.9	1.0	1.07	1.15	1.2–3.1	3.1–3.8	3.8–4.62
90°		1.8	2.2	2.2			
104.5°		4.1	2.2	2.2			
109.9°		4.0	2.2	2.2			
131.2°	3.1						
142.1°	3.0						
173.6°	3.8	3.3	1.8	3.0	2.4	1.9	1.6

(b)

C.m. angle	Energy (Mev) 2.30	2.59	2.88	3.17	3.31	3.46	3.75	4.03	4.32
90°			3.7	4.3	4.6	5.5	5.9	6.0	8.3
109.9°	2.2	2.9	5.3	10	10	10			
125.2°	2.0	2.0	2.8	3.3	2.5	2.4	4.5	3.9	6.4
140.7°	2.2	2.2	3.7	2.6	2.8	2.5	2.7	2.7	4.5
149.5°	2.3	2.3	3.1	2.7	2.6	2.4	3.0	2.6	9.3
167.7°	2.8	2.4	3.2	2.9	2.2	3.4	2.4	2.2	2.6

Background corrections were generally 1 percent and were always less than 4 percent except for the 4.32-Mev point at 90° where the background was 10 percent. A sufficient number of background counts was taken that the uncertainty in final cross sections from this cause was less than 1 percent, in most cases about 0.2 percent.

The target gas was U. S. Bureau of Mines Grade A Helium. Before entering the scattering chamber the helium was passed through a liquid-air trap. Gas samples from the chamber were analyzed on a Consolidated-Nier model 21-201 mass spectrometer and found to contain less than 0.2 percent air. With the helium flow shut off direct pressure measurements with the oil manometer gave a residual pressure of 0.002 cm oil. Since the usual helium pressure was 10 cm oil, this corresponds to an air leakage contamination of 0.02 percent. An identical result was obtained from a comparison of the scattering yields of protons at 90° lab when the chamber was filled with air and then with hydrogen. As the deuteron-air cross sections are not known, no correction could be made for the small air impurity. An uncertainty in Y of 0.3 percent is assigned from this source.

The uncertainties in n and G are quite small: 0.1 percent and 0.2 percent respectively.

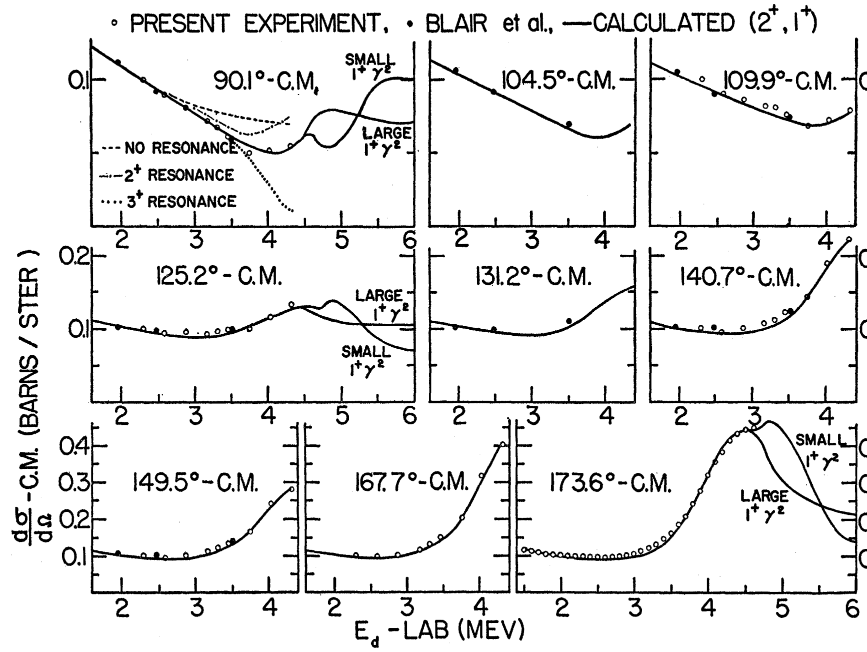

FIG. 3. The high-energy deuteron-helium scattering data for various center-of-mass angles. The solid curves are again from the phase shift analysis of Galonsky and McEllistrem in which overlapping 2^+ and 1^+ resonances have been assumed. The extrapolations to higher energy correspond to extreme assumptions about the width and location of the 1^+ resonance. Because of the condensed energy scale, only every 33rd datum point of Fig. 1 is shown here.

The scattering angles, θ_{lab}, were measured to an accuracy of $\pm 0.05°$. An error of $0.05°$ in θ_{lab} introduces a 0.4 percent error into $d\sigma/d\Omega$ at the back angle, 173.6° c.m., and smaller errors at the other angles.

The uncertainty in N due to the measurement of the deuteron charge collected is 1 percent. (The current integrator used for this measurement was not operated at its maximum accuracy, which is about 0.01 percent.) For energies below ~0.6 Mev there is additional uncertainty in N because of rather large corrections made for scattering and charge neutralization of the incident beam in the collector cup foil.

Deuterons scattered in the foil by more than 17.5° miss the collector cup. The percentage of deuterons lost by single scattering in the foil (2500-A nickel) is $0.12/(E_iE_f)$ percent, where E_i and E_f are the deuteron energies before entering and after leaving the foil. The percentage of deuterons lost through multiple scattering is less than 0.1 percent.[10]

The data of Hall[11] were used to find the percentage of neutral deuterons in the collected beam. At low energies charge neutralization is a very strong function of the energy. Since the equilibrium ratio of neutral to charged deuterons is determined by E_f, the accuracy of the correction made depends upon the uncertainty in the foil thickness. The manufacturer's value, 2500-A, was used in the calculations, although some carbon buildup on the collector cup foil undoubtedly occurred.

Corrections for scattering and charge neutralization have been applied to the 131.2° and 142.1° data in Fig. 1. Both the uncorrected (open circles) and corrected (solid circles) data for the lowest energies (131.2° data) have been plotted.

As an over-all check on the accuracy of the deuteron-helium cross sections the proton-proton scattering cross section was measured at 54.94° lab, for a proton bombarding energy of 2.433 Mev. For this measurement the current integrator was operated at 0.2 percent accuracy. The cross section obtained is 0.7 percent less than the value obtained by Worthington, McGruer, and Findley.[8] The estimated rms uncertainty in our value is 0.5 percent; in that of Worthington *et al.*, 0.2 percent.

Representative values of the rms percentage uncertainties in the cross sections are summarized in Tables I(a) and I(b). The five blank positions in Table I(b) correspond to energies and angles where the recoil alpha particles had sufficient energy to penetrate the counter foil but were still so low in energy that their straggling made it impossible to count the deuteron pulses. The cross sections plotted for these five points in Fig. 3 were obtained by interpolation with higher angles where the recoil alphas could not enter the counter and lower angles where they entered as a clean group.

TABLE II. Energies for peak cross sections on 1.07-Mev resonance.

θ	E (peak), Mev	
90.1°	1.084±0.001	(dip)
104.5°	1.066±0.002	
109.9°	1.071±0.002	
125.2°	1.070±0.002	
131.2°	1.074±0.002	
140.7°	1.076±0.003	
149.5°	1.074±0.002	
167.7°	1.073±0.001	
173.6°	1.073±0.001	

[10] Calculated by graphical method of W. C. Dickinson and D. C. Dodder, Rev. Sci. Instr. **24**, 428 (1953).

[11] Theodore Hall, Phys. Rev. **79**, 504 (1950).

The uncertainties in the cross sections over the 1.07 Mev resonance at 125.2°, 131.2°, 140.7°, 149.5°, and 167.7° have not been included in Table I(a) because of a possible systematic error in these data. These data were taken with a 1000-A counter foil whose copper backing had not been completely and uniformly removed. No other data were taken with this foil. Comparison data at 109.9° taken with a completely copper-stripped foil indicated that 9 percent of the foil area was opaque to the scattered deuterons. This correction has been applied to the data at the five angles and the energies mentioned above. It is possible that these corrections should be more than 9 percent because the scattered deuteron energies are lower at these angles than at 109.9° and less copper is required to stop the deuterons. The deuteron energies at which the resonance peaks occur are not affected by this error.

The cylindrical analyzer was calibrated in terms of the $Li^7(p,n)Be^7$ threshold (assumed equal to 1.8816 Mev±0.05 percent[12]). Corrections were applied for the loss of energy in the helium between the cylindrical analyzer and the center of the scattering chamber, for beam-induced current on the analyzer plates, and for the relativistic mass increase. On the 1.07-Mev resonance the total correction varied from 3 to 6 kev.

[12] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952), bottom of p. 334.

Because of interference effects, the deuteron energy for the peak yield should be different at different angles. In fact the variation is a sensitive test for the phase shift analysis of the accompanying paper.[7] Table II lists for the 1.07-Mev resonance the energies for the peak cross sections at various angles. (At 90° where no peak occurs the energy of the dip is given.)

V. COMPARISON WITH OTHER CROSS-SECTION MEASUREMENTS

In a recent experiment performed by Lauritsen, Huus, and Nilsson[2] the deuteron-helium differential cross sections were measured to 10–20 percent accuracy at 90°, 120°, and 156° c.m. from $E_d=1.0$ to 1.2 Mev. Their 90° data agree with ours to within their experimental errors. Plots of the cross sections as functions of angle show a similar agreement for their 120° and 156° data.

The solid points in Fig. 3 are interpolated from the data of Blair *et al.*[13] They are in agreement with the open points, which were obtained in the present experiment. The uncertainties in Blair's data are about 3 percent.

An interpretation of these cross sections in terms of parameters of the energy states of Li^6 is given in an accompanying paper.[7]

[13] Blair, Freier, Lampi, and Sleator, Phys. Rev. **75**, 1678 (1949).

PHYSICAL REVIEW VOLUME 98, NUMBER 3 MAY 1, 1955

Energy Levels of Li^6 from the Deuteron-Helium Differential Cross Sections*

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The deuteron-helium differential cross sections presented in the preceding paper have been analyzed in terms of a dispersion formalism to classify energy levels of Li^6. A level at $E_x=2.185$ Mev is confirmed to be a single particle, 3^+, $T=0$ level. The broad anomaly extending from 3 Mev to the limit of observation, 4.62 Mev, cannot be analyzed in terms of a single level. Instead, it has been fitted with two single-particle levels, a 2^+ level at $E_x=4.53$ Mev in Li^6 and a 1^+ level at 5.4 ± 0.5 Mev. The 1^+ level cannot be located more accurately because only the tail is visible at the bombarding energies available. All of the other two-level combinations have been ruled out. The assignments, (3^+, 2^+, 1^+), and locations of the levels agree with an intermediate coupling model which is close to the $L-S$ extreme. In the neighborhood of and above the 3^+ resonance the usual hard-sphere phase shifts, which are always negative, cannot be used for the P-wave. This result may indicate odd-parity states above the presently investigated energy region. For the other partial waves, hard-sphere phase shifts corresponding to radii anywhere from 3 to 5×10^{-13} cm were satisfactory, provided the reduced width of the ground state of Li^6 was simultaneously varied from the Wigner limit to very small values.

I. INTRODUCTION

THE differential cross sections presented in the preceding paper are empirical facts of the deuteron-helium system for which a nuclear theory must account. It is, however, possible to meet the theory part-way by fitting the cross sections with a small number of parameters. These parameters should then be significant numbers to be derived by any specific nuclear theory. Reaction cross sections can always be described in terms of parameters of quasi-stationary states of the compound nucleus, such as angular momenta, parities, resonance energies, and level widths.[1,2]

* Work supported by the U. S. Atomic Energy Commission and the Wisconsin Alumni Research Foundation.
† Now at Oak Ridge National Laboratory, Oak Ridge, Tennessee.

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[2] T. Teichmann and E. P. Wigner, Phys. Rev. **87**, 123 (1952)