negative. But Eq. (3.19) and $\beta_0^2-U(r)>0$ require that the right-hand side of Eq. (A7) be positive. In other words, for Eq. (A6) to be satisfied Eq. (4.2) must hold. Furthermore, by an argument similar to the one just used it may be shown that Eq. (4.2) cannot hold if $\phi_{03}(-\xi^2,r)$ has the behavior given in Eq. (4.3).

By a rather lengthy but straightforward application of the definitions of the functions involved, the other condition implied by Eq. (A2) may be reduced to

$$\Delta_0(1,3;0',-\xi^2;c)\Delta_0(1,1;-\beta_0^2,0;c) -\Delta_0(1,3;-\beta_0^2,-\xi^2;c)\Delta_0(1,1;0',0;c)=0, \quad \text{(A8)}$$

where

$$\Delta_0(1,j;0',\lambda^2;c)=\Delta_0(1,j;0,\lambda^2,c)$$

but with the replacements

$$\phi_{01}(0,c)\rightarrow\frac{d}{d\lambda^2}\phi_{01}(\lambda^2,c)\Big|_{\lambda^2=0},$$

$$\phi_{01}'(0,c)\rightarrow\frac{d}{d\lambda^2}\phi_{01}'(\lambda^2,c)\Big|_{\lambda^2=0}.$$

The left-hand side of Eq. (A9), however, is identically equal to

$$\Delta_0(1,3;0,-\xi^2,c)\Delta_0(1,1;0',-\beta_0^2;c), \quad \text{(A9)}$$

an expression which is necessarily zero by virtue of Eq. (4.2). Therefore, no condition on the parameters other than Eq. (4.2) is needed.

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Protons from the Deuteron Bombardment of Helium-4

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Proton spectra from the bombardment of He^4 with deuterons of energies between 7.7 and 11 MeV have been obtained. A binding energy of -0.93 ± 0.07 MeV and a width of 0.57 ± 0.02 MeV are obtained for the He^5 ground state. A $He^4(d,p)He^5$ excitation function over the Li^6 excitation-energy range from 6.5 to 8.7 MeV failed to confirm the existence of the proposed 7.4-MeV, $T=0$ level. An extrapolation and integration of the present measurements yields an estimate for the total reaction cross section of 460 ± 80 mb at 10 MeV and 460 ± 50 mb at 11 MeV.

I. INTRODUCTION

THIS paper reports on a study of proton spectra from the bombardment of He^4 with deuterons of energies between 7.7 and 11 MeV. Protons may arise through any of the following three reactions or sequences of reactions:

$$\begin{aligned} &d+He^4\rightarrow He^5+p+Q_1,\\ &He^5\rightarrow He^4+n+Q_2, \end{aligned} \quad (1)$$

$$\begin{aligned} &d+He^4\rightarrow Li^5+n+Q_1',\\ &Li^5\rightarrow He^4+p+Q_2', \end{aligned} \quad (2)$$

$$d+He^4\rightarrow He^4+n+p-2.226\text{ MeV}, \quad (3)$$

where He^5 (or Li^5) may be left in its ground state or in an excited state, and where $Q_1+Q_2=Q_1'+Q_2'=-2.226$ MeV.

A study of these reactions is of interest from several points of view. Firstly, from reaction (1), one may obtain information about the width and binding energy of the ground state of He^5; one may also look for evidence for excited states of He^5, although the contributions from reactions (2) and (3) are likely to obscure such effects in a noncoincidence experiment such as the present one.[1] Secondly, the present range of bombarding energies covers the range of Li^6 excitation from 6.5 to 8.7 MeV. If reaction (1) proceeds at least partly via a compound-nucleus mechanism, an excitation function might be expected to yield information about the proposed $T=0$ state in Li^6 near 7.4 MeV.[2] In particular, Sokolov *et al.*[3] reported that this state decays preferentially to He^4+n+p rather than to He^4+d, so the present reaction (1) might be expected to be particularly sensitive to the effects of such a state. Finally, values of the total reaction cross section for deuterons on He^4 may be obtained by extrapolation and integration of the proton spectra obtained in the present measurements; these quantities are useful for a phase-shift or optical-model analysis of the d-He^4 interaction.

Protons from these reactions have been studied previously by several authors. Burge *et al.*[4] observed

[1] For a summary of experiments which bear on the first excited state of He^5 see P. Fessenden and D. R. Maxson, Phys. Rev. **133**, B71 (1964).

[2] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

[3] I. L. Sokolov, M. M. Sulkovskaia, E. I. Karpushkina, and E. A. Albitskaia, Zh. Eksperim. i Teor. Fiz. **30**, 1007 (1956) [English transl.: Soviet Phys.—JETP **3**, 740 (1956)].

[4] E. J. Burge, H. B. Burrows, W. M. Gibson, and J. Rotblat, Proc. Roy. Soc. (London) **A210**, 534 (1951).

reaction (1) by a nuclear emulsion technique at 8 MeV. Allred *et al.*,[5] also using an emulsion technique, determined the total reaction cross section at a deuteron energy of 10.3 MeV. Warburton and McGruer[6] have observed the reaction (1) together with a portion of the lower energy proton region using a magnetic spectrometer. Artemov and Vlasov[7] have observed proton spectra using 20-MeV deuterons, and Erramuspe and Slobodrian[8] have recently obtained data in the 21- to 28-MeV energy range.

Neutrons from these reactions have been studied by Henkel *et al.*[9] (4–7 MeV), Lefevre *et al.*[10] (8–10 MeV), Bogdanov *et al.*[11] (13 MeV) and Rybakov *et al.*[12] (18 MeV).

II. GENERAL

A He^4 gas target was bombarded by a deuteron beam from the Australian National University tandem electrostatic accelerator. The experimental apparatus has been described in detail elsewhere[13] with only minor modifications having been made for the present experiment.

The He^4 particles resulting from the various reactions were rejected by means of an aluminum foil placed directly in front of the solid-state detector. The thickness of this foil was such as to stop all alpha particles, including those arising from d-α elastic scattering; this thickness ranged from zero to 14 mg/cm^2 in addition to the unavoidable thickness (equivalent to about 1.6 mg/cm^2 of aluminum) of the target exit window and gas.

Data were accumulated on 100 or 400 channels of a pulse-height analyzer. The stability of the amplifier-analyzer system was monitored with a mercury pulser, and gain shift corrections (never exceeding 1%) were applied to each spectrum. After a target-empty background was subtracted, each spectrum was corrected point by point for energy loss in the target gas and stopping foils and converted into absolute units. The energy and foil thickness calibration was accomplished with p-He^4 elastic scattering under identical conditions of foil placement, detector bias, etc., and is believed to be accurate to within ± 30 keV. The energy of the bombarding particles at the center of the target was known to within 10 keV in every case.

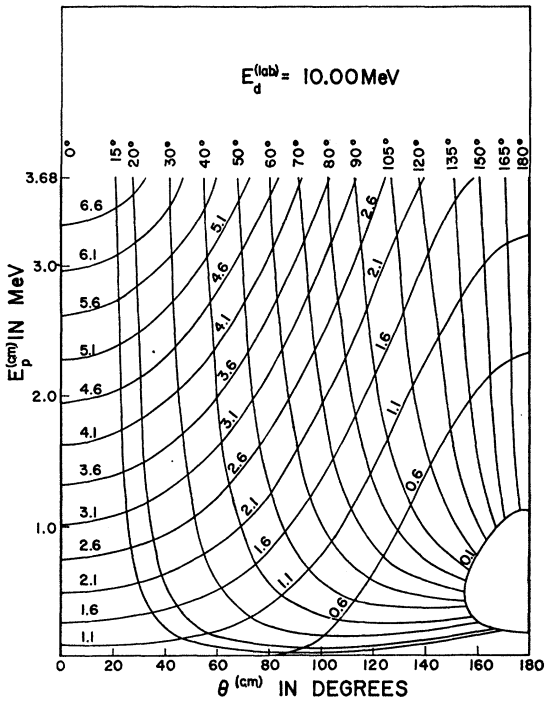

FIG. 1. Diagram showing the variation of $E_p^{(c.m.)}$ and $\theta^{(c.m.)}$ with $E_p^{(lab)}$ and $\theta^{(lab)}$ for a deuteron bombarding energy 10.00 MeV. The two families of curves represent fixed laboratory angles and fixed laboratory energies as indicated.

In general, the over-all uncertainty in the differential cross sections obtained is of the order of 5%. The largest (3%) uncertainty results from the correction of the spectra for dead-time losses. Measurements of the detector slit geometry, target gas pressure, and integrated beam current contribute a combined uncertainty less than 2%. A target pressure of about $\frac{1}{4}$ atm was used, and the gas was changed frequently to avoid buildup of contaminants. A minimum of 5000 counts per channel was obtained for channels near the peak.

For most of the spectra, an angular resolution of 2° was used together with an analyzer channel width of about 100 keV. For those spectra from which the position and width of the He^5 ground state were estimated, an angular resolution of 0.7° was used together with a channel width of about 25 keV. The energy resolution of the system, not including kinematic spread, was approximately 50 keV. The stopping foils increased the energy spread by about 35 keV for the thickest foils employed.

The formulas which relate the observed laboratory energy and angle to those in the zero-momentum system are as follows:

$$E^{(c.m.)}=E^{(lab)}-2a(E^{(lab)})^{1/2}\cos\theta^{(lab)}+a^2,$$

$$\cos\theta^{(c.m.)}=\frac{(E^{(lab)})^{1/2}\cos\theta^{(lab)}-a}{[E^{(lab)}-2a(E^{(lab)})^{1/2}\cos\theta^{(lab)}+a^2]^{1/2}},$$

[5] J. C. Allred, D. K. Froman, A. M. Hudson, and L. Rosen, Phys. Rev. **82**, 786 (1951).
[6] E. K. Warburton and J. N. McGruer, Phys. Rev. **105**, 639 (1957).
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[8] H. J. Erramuspe and R. J. Slobodrian, Nucl. Phys. **49**, 65 (1963).
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[10] H. W. Lefevre, R. R. Borchers, and C. H. Poppe, Phys. Rev. **128**, 1328 (1962).
[11] G. F. Bogdanov, N. A. Vlasov, S. P. Kalinin, B. V. Rybakov, and V. A. Sidorov, Zh. Eksperim. i Teor. Fiz. **30**, 981 (1956) [English transl.: Soviet Phys.—JETP **3**, 793 (1956)].
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[13] G. G. Ohlsen and P. G. Young, Nucl. Phys. **52**, 134 (1964).

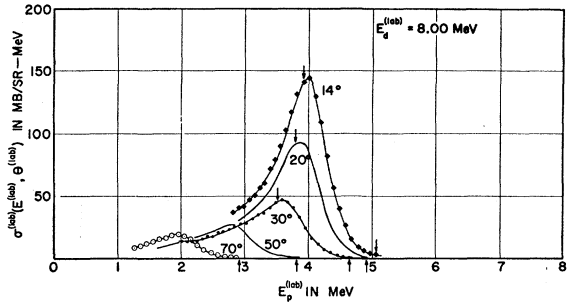

FIG. 2. The proton spectra obtained at several angles with a deuteron energy 8.00 MeV. The arrows refer to the maximum possible proton energy and to the position of the peak calculated from a $He^4(d,p)He^5$ Q value of -3.18 MeV.

where

$$a^2=m_d m E_d^{(\mathrm{lab})}/(m_d+m_\alpha)^2.$$

The quantities m_d, m_α, and $E_d^{(\mathrm{lab})}$ are the deuteron mass, alpha-particle mass, and laboratory deuteron bombarding energy, respectively. The quantity m is the mass of whichever of the final particles is being observed. The Jacobian of the transformation is given by

$$\frac{\partial(E^{(\mathrm{lab})},\cos\theta^{(\mathrm{lab})})}{\partial(E^{(\mathrm{c.m.})},\cos\theta^{(\mathrm{c.m.})})}=\left(\frac{E^{(\mathrm{c.m.})}}{E^{(\mathrm{lab})}}\right)^{1/2}$$

and the inverse transformation is obtained by changing

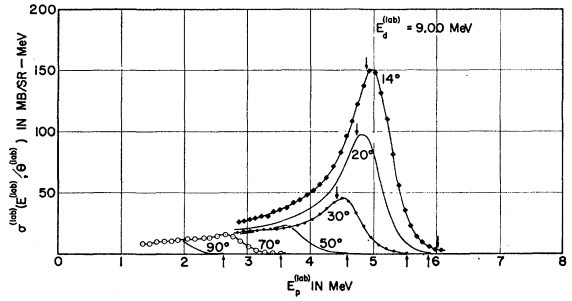

FIG. 3. The proton spectra obtained at several angles with a deuteron energy 9.00 MeV. The arrows refer to the maximum possible proton energy and to the position of the peak calculated from a $He^4(d,p)He^5$ Q value of -3.18 MeV.

a to $-a$. A diagram showing the variation of $E_p^{(\mathrm{c.m.})}$ and $\theta^{(\mathrm{c.m.})}$ with $E_p^{(\mathrm{lab})}$ and $\theta^{(\mathrm{lab})}$ for $E_d^{(\mathrm{lab})}=10$ MeV is presented in Fig. 1.

The relation between the proton energy $E_p^{(\mathrm{c.m.})}$ measured in the zero-momentum system and the relative energy E_p in the p-$n\alpha$ system is

$$E_p=\left(\frac{m_\alpha+m_n+m_p}{m_\alpha+m_n}\right)E_p^{(\mathrm{c.m.})},$$

where m_p and m_n are the proton and neutron masses, respectively. The kinetic energy E_n in the n-α system is

$$E_n=\left(\frac{m_\alpha}{m_d+m_\alpha}\right)E_d^{(\mathrm{lab})}-2.226-E_p$$
$$=E_d^{(\mathrm{c.m.})}-2.226-E_p.$$

III. RESULTS

Angular distributions of the proton spectra were obtained at 8.00, 9.00, 10.00, and 11.00 MeV. The smallest laboratory angle at which data were taken was 14° in each case, and the largest angle ranged from 80° at 8 MeV to 135° at 11 MeV. Some sample spectra are shown in Figs. 2–5. The curves shown in the figures

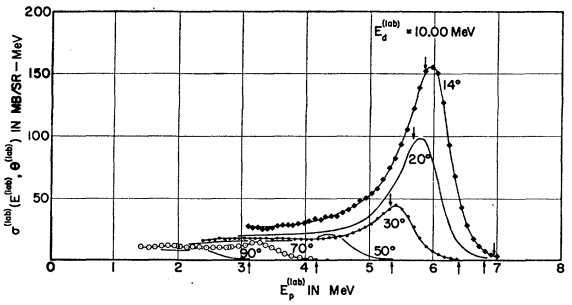

FIG. 4. The proton spectra obtained at several angles with a deuteron energy 10.00 MeV. The arrows refer to the maximum possible proton energy and to the position of the peak calculated from a $He^4(d,p)He^5$ Q value of -3.18 MeV.

represent smooth fits by eye to the data points. For clarity, some of the data points have been omitted.

Background corrections were made by subtracting from each proton spectrum a target-empty spectrum taken under the same conditions. The use of foils to eliminate alpha particles, together with the increasing background in lower analyzer channels, placed a lower limit on the observable proton energy. Data were rejected if the background exceeded 30% of the observed yield in a given channel. Thus, assuming the background correction to have an uncertainty of about 30%, the error on the points in Figs. 2–5 increases to 15% for the points at the lowest energy on each curve.

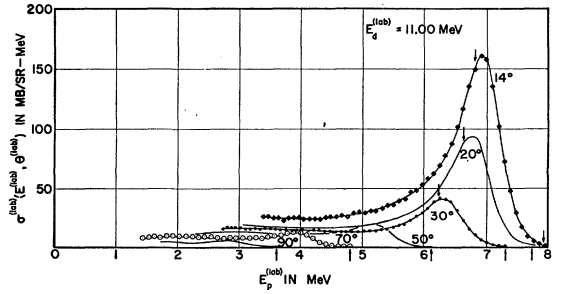

FIG. 5. The proton spectra obtained at several angles with a deuteron energy 11.00 MeV. The arrows refer to the maximum possible proton energy and to the position of the peak calculated from a $He^4(d,p)He^5$ Q value of -3.18 MeV.

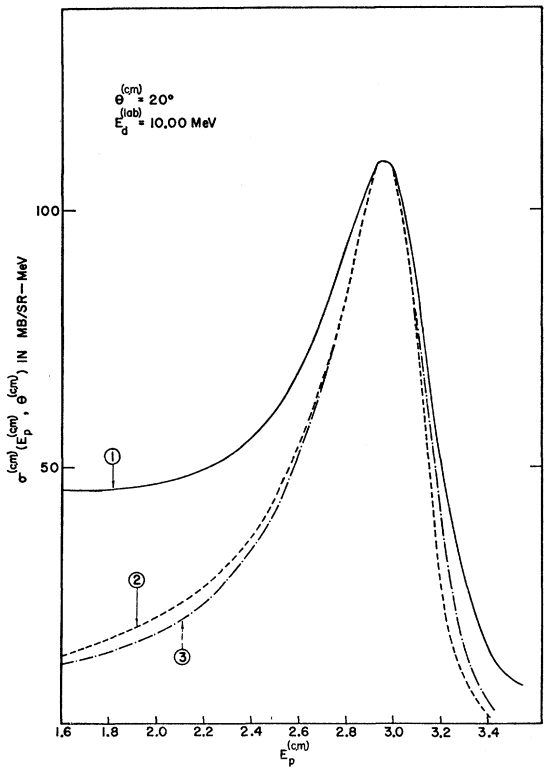

FIG. 6. The center-of-mass cross section at 10.00 MeV laboratory deuteron energy and 20° c.m. angle. Curve (1) represents the experimental data and is the result of interpolation between spectra at several laboratory angles. Curve (2) is obtained from Eq. (8) using $E_0=-4.3$ MeV, $\gamma^2=6.9$ MeV, and $a=2.9$ F. Curve (3) is the result of Eq. (8) with the same parameters but without the deuteron factor. Both curves are normalized to the data.

This error decreases rapidly with increasing proton energy and becomes negligible 0.5 to 1 MeV higher.

An excitation function was obtained using 100-keV increments at $\theta^{(\mathrm{lab})}=14°$ over the energy range 7.7 to 11 MeV. The proton yield from the $He^4(d,p)He^5$ (ground-state) reaction increased smoothly over the energy range, and no evidence for structure was seen. The energy range covered corresponds to the Li^6 excitation energy range from 6.5 to 8.7 MeV. Thus, the present measurements do not confirm the existence of the proposed 7.40-MeV $T=0$ level. However, it should be emphasized that the angular distributions obtained in the present measurements indicate that the reaction proceeds largely via a direct reaction mechanism. It is possible, therefore, that the compound-nucleus contribution is too small to observe under the present conditions, and accordingly the existence of the 7.40-MeV level cannot be excluded.

A theoretical line shape for the reaction $He^4(d,p)He^5$ (ground state) may be calculated from the known n-He^4 phase shifts as follows. The center-of-mass differential cross section for observing protons in the solid angle $d\Omega_p$ and energy increment $dE_p^{(\mathrm{c.m.})}$ and neutrons in the solid angle $d\Omega_n$ may be written in the form[14]

$$\frac{d^3\sigma}{d\Omega_n d\Omega_p dE_p^{(\mathrm{c.m.})}}=\frac{2\pi}{\hbar^2}\frac{\mu_d}{k_d^{(\mathrm{c.m.})}}|M|^2\rho(E_p^{(\mathrm{c.m.})}), \quad (4)$$

where $E_p^{(\mathrm{c.m.})}$ is the energy of the observed protons in the zero-momentum system. The density of final states is given by

$$\rho(E_p^{(\mathrm{c.m.})})=\frac{2(m_p m_n m_\alpha)^{3/2}(m_p+m_n+m_\alpha)^{1/2}}{h^6(m_n+m_\alpha)^2}\times[E_p^{(\mathrm{c.m.})}(E_{\max}-E_p^{(\mathrm{c.m.})})]^{1/2},$$

where

$$E_{\max}=\frac{m_n+m_\alpha}{m_p+m_n+m_\alpha}(E_d^{(\mathrm{c.m.})}+Q). \quad (5)$$

The deuteron energy $E_d^{(\mathrm{c.m.})}$ and momentum $k_d^{(\mathrm{c.m.})}$ are measured in the center-of-mass system, and μ_d is the deuteron-alpha reduced mass. Q is the energy required for the breakup of the deuteron (−2.226 MeV).

Assuming the reaction to proceed via a stripping mechanism, Werntz[14] showed that the energy dependence of the matrix element M may be approximated by a deuteron factor times the value of the final-state

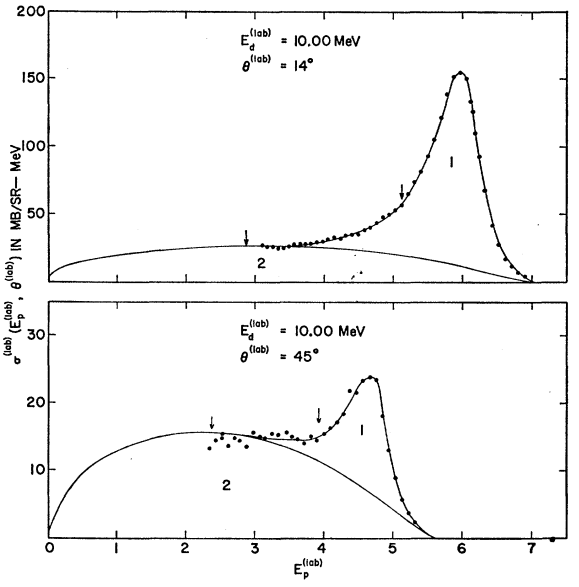

FIG. 7. Data obtained at 10.00 MeV at angles 14° and 45°. The curves show the method of extrapolation to zero energy and the separation of the spectra into two parts as discussed in the text. The arrow at the higher energy indicates the maximum possible proton energy from the $He^4(d,n)Li^5(p)He^4$ reaction, assuming the Li^5 ground state to be sharp with a binding energy of −1.79 MeV. The other arrow indicates the most probable proton energy from this reaction sequence, corresponding to protons from Li^5 nuclei recoiling at 180° in the d-He^4 c.m. system.

[14] C. Werntz, Phys. Rev. **128**, 1336 (1962). Several authors have used similar formulas arrived at from various approaches; see, for example, G. Weber, Phys. Rev. **110**, 529 (1958); F. C. Barker and P. B. Treacy, Nucl. Phys. **38**, 33 (1962); and E. W. Hamburger and J. R. Cameron, Phys. Rev. **117**, 781 (1960).

scattering wave function evaluated at a suitable channel radius a. For the present case, where the n-α interaction is in a $p_{3/2}$ state, the approximation may be written

$$M \propto \phi_d(\tfrac{1}{2}\hbar\mathbf{k}_d-\hbar\mathbf{k}_p)(e^{i\delta_1{}^+}\sin\delta_1{}^+/k_na) \times[G_1(k_na)+\cot\delta_1{}^+F_1(k_na)]\cos\chi, \quad (6)$$

where $\delta_1{}^+$ is the n-α $p_{3/2}$ phase shift, χ is the angle between the vectors $\mathbf{k}_n$ and $(-\mathbf{k}_d+\frac{4}{5}\mathbf{k}_p)$, and where $\phi_d(\mathbf{p})$ is the deuteron wave function in momentum space. F_1 and G_1 are[15] the neutron wave functions for $l=1$. The magnitudes of the wave vectors $\mathbf{k}_p$ and $\mathbf{k}_n$ are the relative wave numbers in the p-$n\alpha$ and in the n-α center-of-mass systems, respectively, and are given by

$$k_p=(2\mu_pE_p)^{1/2}, \quad \mu_p=\frac{(m_n+m_\alpha)m_p}{m_n+m_p+m_\alpha};$$

$$k_n=(2\mu_nE_n)^{1/2}, \quad \mu_n=m_nm_\alpha/(m_n+m_\alpha).$$

The $\cos\chi$ factor is present because of the angular dependence of the p-wave scattering wave function.

Using single-level theory to express the phase shift $\delta_1{}^+$ in terms of resonance parameters, the approximate matrix element may be written

$$M \propto \phi_d(\tfrac{1}{2}\hbar k_d-\hbar k_p)(e^{i\delta_1{}^+}\sin\xi_1{}^+/k_na) \times[F_1{}^2(k_na)+G_1{}^2(k_na)]^{1/2}\cos\chi, \quad (7)$$

where

$$\delta_1{}^+=\phi_1+\xi_1{}^+,$$

$$\phi_1=-\tan^{-1}[F_1(k_na)/G_1(k_na)],$$

$$\xi_1{}^+=\tan^{-1}[\tfrac{1}{2}\Gamma/(E_0+\Delta_1-E_n)],$$

with

$$\Gamma=2P_1\gamma^2, \quad P_1=k_na/(F_1{}^2+G_1{}^2)$$

and

$$\Delta_1/\gamma^2=k_na(F_1F_1'+G_1G_1')/(F_1{}^2+G_1{}^2).$$

The differential cross section becomes (after integration over the unobserved angle $d\Omega_n$)

$$\frac{d^2\sigma}{d\Omega_pdE_p}\propto\frac{1}{k_d}|\phi_d(\tfrac{1}{2}\hbar\mathbf{k}_d-\hbar\mathbf{k}_p)|^2\frac{\sin^2\xi_1{}^+}{(k_na)^2} \times(F_1{}^2+G_1{}^2)[E_p{}^{(\mathrm{c.m.})}(E_{\max}-E_p{}^{(\mathrm{c.m.})})]^{1/2}, \quad (8)$$

where all energy- and angle-independent factors have been omitted. The entire angular dependence of this expression is in the deuteron factor.

In Fig. 6 the observed center-of-mass proton spectrum at 20° is shown together with the line shape calculated from the above formulas. The experimental curve was obtained by interpolation from laboratory spectra at several angles. The dashed curves are calculated from the parameters $E_0=-4.3$ MeV, $\gamma^2=6.9$ MeV, and $a=2.9\times10^{-13}$ cm with and without the deuteron factor, as indicated. The theoretical curves have been normalized to the experimental data. The parameters used are those given by Dodder and Gammel.[16]

Although it appears to be possible to obtain a reasonable fit to the data by varying the parameters, the approximations involved in obtaining the theoretical expressions would seem too crude to allow resonance parameters to be confidently extracted. In addition, there are two competing reactions which may affect the observed line shape:

(1) A contribution from the direct three-body reaction $d+\mathrm{He}^4\rightarrow\mathrm{He}^4+n+p$.

(2) A contribution from the sequence of reactions $d+\mathrm{He}^4\rightarrow\mathrm{Li}^5+n+Q_1'$; $\mathrm{Li}^5\rightarrow\mathrm{He}^4+p+Q_2'$. For a given value of Q_1' the maximum possible proton energy at a given angle may be calculated. As can be seen for the particular case illustrated in Fig. 7, the upper limit calculated from the nominal Li^5 binding energy of -1.97 MeV falls well below the peak. However, the Li^5 ground state is very broad and accordingly it is possible to get a contribution from this reaction well above the energy calculated from the nominal binding energy. At lower bombarding energies the calculated limit moves to still higher energies with respect to the peak position.

In addition, no account has been taken of the possible effect of the first excited state of He^5 or of the s-wave interaction which is found necessary to explain the n-He^4 scattering and total cross section data.[17]

The binding energy of the He^5 ground state was calculated from the 10.00-MeV laboratory spectra at various angles between 14° and 50°. Using the energy at which the yield is a maximum to define the energy of the state, a binding energy of -0.85 ± 0.05 is obtained. The 50-keV error is composed of a 30-keV energy calibration uncertainty and an estimated 20-keV error in determining the energy at which the yield is maximum. Good (±15 keV) consistency was obtained at the various angles.

A summary of previously given values of the binding energy, as determined from various reactions in which He^5 is a final state, is presented in Table I.[4,6,18–31] All of

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[16] D. C. Dodder and J. L. Gammel, Phys. Rev. **88**, 520 (1952).

[17] See, for example, R. K. Adair, Phys. Rev. **86**, 155 (1952); P. E. Hodgson, Phil. Mag. Suppl. **7**, 1 (1958); and Ref. 16.

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[20] Li Ga Youn, G. M. Osetinskii, N. Sodnom, A. M. Govorov, I. V. Sizov, and V. I. Salatskii, Zh. Eksperim. i Teor. Fiz. **39**, 225 (1960) [English transl.: Soviet Phys.—JETP **12**, 163 (1961)].

[21] D. B. Smith, N. Jarmie, and A. M. Lockett, Phys. Rev. **129**, 785 (1963); D. B. Smith (private communication). The value for the He^5 ground-state width is quoted in the laboratory system. This has been corrected in Table I.

[22] R. G. Freemantle, T. Grotdal, W. M. Gibson, R. McKeague, D. J. Prowse, and J. Rotblat, Phil. Mag. **45**, 1090 (1954).

[23] D. S. Craig, W. G. Cross, and R. G. Jarvis, Phys. Rev. **103**, 1427 (1956).

[24] G. M. Frye, Phys. Rev. **93**, 1086 (1954). The value given for

TABLE I. Summary of He^5 ground-state parameter measurements.

Reaction	He^5 binding energy (MeV)	Width (MeV)	Method of obtaining width	Energy measurement method	Reference
$He^3(t,p)He^5$ or $T(He^3,p)He^5$	-0.90 ± 0.07	···	···	range in emulsion	18
	-0.95 ± 0.07	···	···	pulse height in NaI crystal	19
	$-0.8\ \pm0.1$	···	···	pulse height in CsI crystal	20
	-0.79 ± 0.03	0.56 ± 0.03	full width at half-maximum of experimental curve	magnetic spectrometer	21
$He^4(d,p)He^5$	~-0.9	≥0.32	f.w.h.m. of experimental curve	range in emulsion	4
	-0.87 ± 0.05	···	···	range in emulsion	22
	···	0.55 ± 0.03	f.w.h.m. of Gaussian fit	magnetic spectrometer	6
$Li^6(t,\alpha)He^5$	-0.97 ± 0.04	0.7 ± 0.2	f.w.h.m. of experimental curve	pulse height in proportional counter	23
$Li^6(n,d)He^5$	-1.09 ± 0.1	1.1	f.w.h.m. of experimental curve	range in emulsion	24
$Li^6(d,He^3)He^5$	-0.88 ± 0.09	0.69 ± 0.2	f.w.h.m. of Gaussian fit	magnetic spectrometer	25
$Li^7(d,\alpha)He^5$	-0.8	0.25	f.w.h.m. of experimental curve (poor resolution)	range in air	26
	-1.7	···	···	pulse height in proportional counter	27
	$-0.9\ \pm0.1$	···	···	pulse height in proportional counter	28
	$-0.9\ \pm0.1$	$0.3\ \pm0.1$	f.w.h.m. of experimental curve	range in emulsion	29
	-0.86 ± 0.09	0.66 ± 0.2	f.w.h.m. of Gaussian fit	magnetic spectrometer	25
	-1.38 ± 0.02	···	···	magnetic spectrometer	30
	$-1.0\ \pm0.05$	···	···	magnetic spectrometer	31

the values quoted in Table I are based on the peak yield point, as used above. However, the He^5 binding energy is more reasonably defined as the energy at which the resonant phase shift ξ_1^+ is 90°. For the present reaction, this energy yields a binding energy about 80 keV more negative. The exact value of this shift, which results almost entirely from the factor $(F_1^2+G_1^2)/(k_na)^2$, depends on the parameters used; the value of 80 keV is based on the parameters[16] $\gamma^2=6.9$ MeV, $E_0=-4.3$ MeV and $a=2.9\times10^{-13}$ cm. The shift does not vary more than ±20 keV around this value for any reasonable set of parameters. We would accordingly give as our best value for the binding energy -0.93 ± 0.07 MeV, where all sources of error have been combined linearly.

The peak in the He^4 neutron total cross section at

the He^5 ground-state width is in the n-Li^6 zero-momentum system. This has been corrected in Table I.

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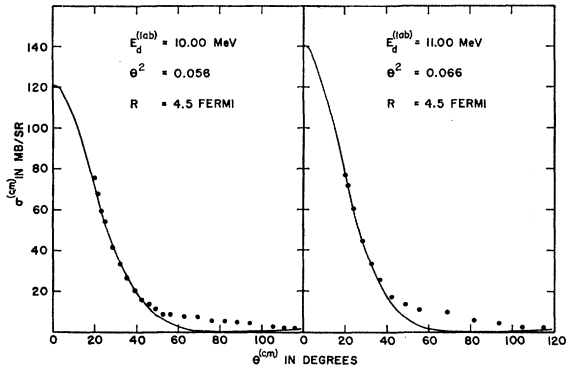

FIG. 8. Stripping fits obtained at $E_d^{(\mathrm{lab})}=10.00$ MeV and $E_d^{(\mathrm{lab})}=11.00$ MeV.

1.15 ± 0.05 MeV[32,33] corresponds to a He^5 binding energy -0.92 ± 0.04 MeV. For s and p waves only the total cross section σ_T is related to the phase shifts by

$$\sigma_T=(4\pi/k^2)(\sin^2\delta_0+2\sin^2\delta_1{}^+ +\sin^2\delta_1{}^-).$$

Thus the peak in the yield should correspond closely to the energy at which $\delta_1{}^+$ is 90°. For the parameters used above, the resonant phase shift $\xi_1{}^+$ passes through 90° at an energy about 20 keV lower. The best estimate for the binding energy from the total cross-section measurements would therefore be -0.90 ± 0.04 MeV. This value is in good agreement with the result of the present experiment.

The full width at half-maximum of the observed peaks (converted to the n-He^4 c.m. system) is about 0.85 ± 0.05 MeV, although this observed width almost certainly includes a contribution from other processes as discussed above. For the resonance parameters used above, the full width at half-maximum (f.w.h.m.) of the resonance curve (ignoring the deuteron factor, which would increase the predicted f.w.h.m. by ~80 keV) is about 0.60 MeV. The full width at half-maximum of a Gaussian-type fit is about 0.57 ± 0.02 MeV, which is consistent with previous measurements which have used this method for width estimation (see Table I).

IV. TOTAL REACTION CROSS SECTION

One of the aims of the present measurements was to obtain an estimate of the total reaction cross section. The extraction of total cross sections from the data requires that each spectrum be integrated over the continuous energy range of the protons, and this in turn requires that each spectrum be extrapolated to zero proton energy. In addition, the differential cross sections which were determined covered only a portion of the angular range, so a further extrapolation to 0° and 180° must be made before the integration over solid angle can be performed. Unfortunately, only for the data at 10 and at 11 MeV were the extrapolated contributions sufficiently small to make this procedure feasible.

To minimize errors in the extrapolations, each spectrum was somewhat arbitrarily separated into contributions which were assigned to (1) the proton group resulting from the $He^4(d,p)$ stripping reaction to the ground state of He^5 [reaction (1)], and (2) a smoothly varying contribution of protons from reactions (2) and (3). The separation aided primarily in the extrapolation to small angles since it was possible to fit stripping curves to the cross sections resulting from reaction (1). The angular dependence of the cross sections corresponding to reactions (2) and (3) was much less severe, and a reasonable angular extrapolation could be obtained by merely drawing a smooth curve.

Examples of the separation into the contributions (1) and (2) are shown in Fig. 7. The curves used are of the form of a density of states function $\rho(E_p{}^{(\mathrm{c.m.})})$ multiplied by a p-wave penetrability function $P_1(E_n)$. In many cases, the observed region of the spectrum extended below the most probable energy for protons from Li^5 decay and no evidence for a significant peak was seen. Thus, it was felt that the smooth extrapolation to zero energy was not unreasonable.

The 10- and 11-MeV differential cross sections of the $He^4(d,p)He^5$ ground-state reaction, as estimated by the

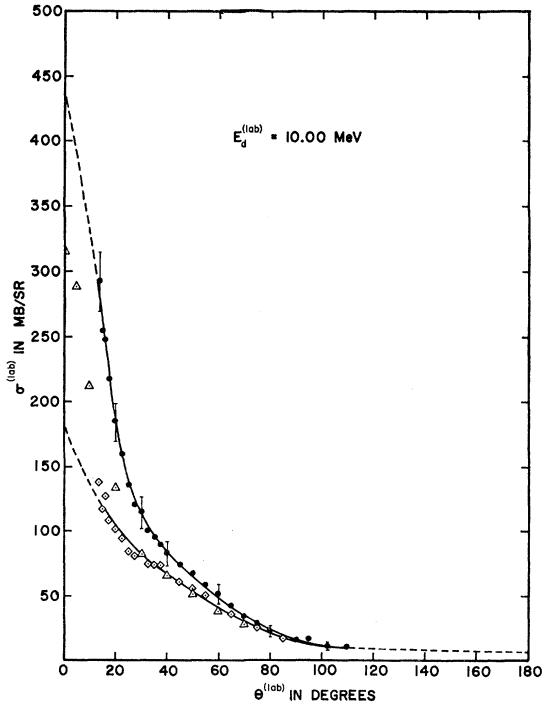

FIG. 9. Integrated cross sections obtained at 10.00 MeV. The upper curve corresponds to the sum of the areas indicated by 1 and 2 of Fig. 7 while the lower curve corresponds to the area indicated by 2. The triangles are from the data of Ref. 10.

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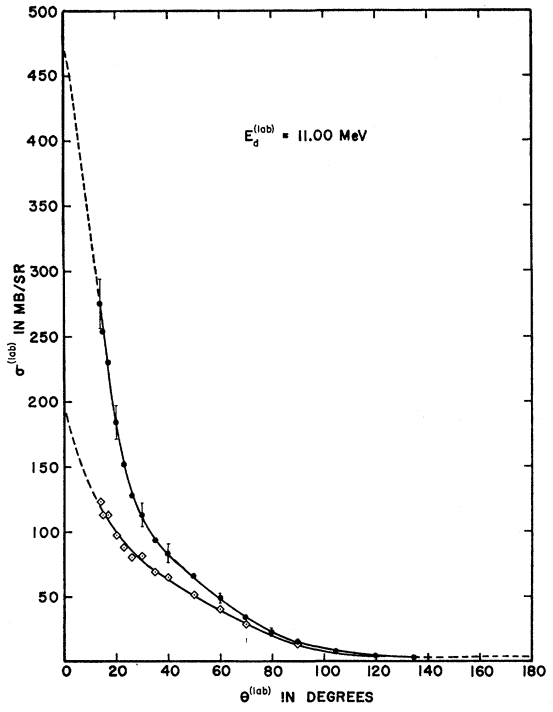

FIG. 10. Integrated cross sections obtained at 11.00 MeV. The upper curve corresponds to the sum of the areas indicated by 1 and 2 of Fig. 7 while the lower curve corresponds to the area indicated by 2.

above procedure, are shown in Fig. 8. The experimental points are indicated along with curves computed using plane wave Born approximation theory.[34,35] The stripping curves were fit to the small-angle points, and the parameters which were used are indicated with each curve.

From the point of view of extracting plane-wave theory stripping widths from the data, it would have been more desirable to fit each observed peak with a theoretical line shape of the type discussed in Sec. III, and to use the area under these curves as an estimate of the differential cross section. In all cases, the method used gives a lower value for the cross section than the more elaborate method; the difference ranges from about 15% at small angles to perhaps 100% or more at large angles. Since the stripping widths are determined mainly by the small-angle points, it is clear that the widths obtained are about 15 to 20% lower than would be obtained by the more elaborate method.

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TABLE II. Total reaction cross sections.

Energy (MeV)	Contribution from reaction (1) (mb)	Contribution from reactions (2) and (3) (mb)	Total reaction cross section (mb)
10.00	100±10	360±70	460±80
11.00	100±10	360±40	460±50

The results of the extrapolations and integrations are indicated in Figs. 9 and 10. The error bars correspond to an assumed 30% error in the extrapolated contribution. The solid points represent the total extrapolated yield and the open rectangles represent the extrapolated contribution from reactions (2) and (3) above. The triangles in Fig. 9 represent an approximate integration of the 10-MeV neutron yield data of Lefevre *et al.*[10]

In Figs. 9 and 10, the extrapolation to large angles is arbitrary. However, in the laboratory system even a pure "phase-space" cross section is peaked forward because of the motion of the center of mass; for example, at 10 MeV the ratio between the yield at 0° and the yield at 180° would be about 20 to 1. Also the importance of the small- and large-angle regions is somewhat reduced by the $\sin\theta$ factor in the integration over solid angle.

The results of the integration of the 10- and 11-MeV data are given in Table II. Within the present level of accuracy the cross section is the same for these two energies. At 8 and 9 MeV the cross section appears to be nearly as large. The quoted errors represent a 30% uncertainty in both the angular and energy extrapolations.

Allred *et al.*[5] obtained an estimate of the total reaction cross section at 10.3 MeV of 300±100 mb. An approximate integration of the 10-MeV data of Lefevre *et al.*[10] yields a value of about 350±100 mb. In view of the rather large errors on the measurements, the present results may be regarded as in reasonable agreement with the earlier work.

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