

## Reaction ${}^3\text{He}(d,t)2p$ at 23.5 MeV center of mass\*

R. W. Rutkowski<sup>†</sup> and E. E. Gross

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 24 April 1975)

We have measured the absolute spectra for the yield of high-energy tritons for the process  ${}^3\text{He}(d,t)2p$  at 24 MeV c.m. Elastic scattering of deuterons from  ${}^3\text{He}$  has also been measured at the same c.m. energy. The reaction data are characterized by forward and backward peaking and by a deep minimum near  $90^\circ$  c.m. The forward-angle triton spectrum is consistent with a simple pickup process. A comparison of the forward-angle triton yield to the cross section for elastic scattering at back angles provides strong evidence both for the dominance of the pickup process at small angles in the reaction and for the importance of this process to back-angle elastic scattering.

[NUCLEAR REACTIONS  ${}^3\text{He}(d,t)$  and  ${}^3\text{He}(d,d)$ ,  $E=23.5$  MeV c.m., measured]  
 $d\sigma(E_t, 10^\circ\text{--}180^\circ$  c.m.).

### I. INTRODUCTION

The reaction  ${}^3\text{He}(d,t)2p$  is of importance from several points of view. First, the reaction can be used to study the final-state interaction of the two protons through their influence on the energy spectrum of the tritons.<sup>1</sup> An understanding of this effect can then lead to information on the dineutron system through a study<sup>2</sup> of the charge symmetric system  ${}^3\text{H}(d,{}^3\text{He})2n$ . Secondly, since only two first-order reaction mechanisms are involved (i.e., pickup and charge exchange) one can hope to determine their relative importance by a detailed study of this reaction.<sup>3</sup> Finally, this is one of several reactions involving light nuclei which can be related to elastic scattering of the same projectile and target.<sup>4</sup>

Early attempts<sup>5</sup> to account for the final-state interaction effect gave the following result for the triton energy spectrum:

$$\frac{d^2\sigma}{d\Omega dE} = \frac{2\pi\rho(E)}{k_0} |\phi_{2p}(E)|^2, \quad (1)$$

where  $k_0$  is the relative momentum in the incident channel,  $\rho(E)$  is the density of states available to the observed triton, and  $\phi_{2p}(E)$  is the  ${}^1S_0$  wave function for the unobserved diproton system.

Equation (1) is obtained by assuming a complete separation of the final-state interaction from the primary reaction mechanism. However, the Born approximation (BA) gives the following result<sup>4</sup> for the triton energy spectrum:

$$\frac{d^2\sigma}{d\Omega dE} = \frac{2\pi\rho(E)}{k_0} \left| \int \Psi(\vec{r}) \phi_{2p}(\vec{r}, E) d\vec{r} \right|^2. \quad (2)$$

Here, the influence of the reaction mechanism is contained in the overlap of the diproton wave function with the function  $\Psi(\vec{r})$ . In the case of a pickup

process,  $\Psi(\vec{r})$  describes the radial extent of two protons in  ${}^3\text{He}$ , whereas in the case of a charge-exchange process  $\Psi(\vec{r})$  is the deuteron radial wave function. Neglect of a momentum transfer term in Eq. (2) limits the applicability of the expression to angles near  $0^\circ$  or  $180^\circ$  and to small relative energy in the diproton system. The BA result, Eq. (2), reduces to the Watson-Migdal result, Eq. (1), if  $\Psi(\vec{r})$  can be regarded as a spatial  $\delta$  function compared to the diproton wave function.

In the case of a charge-exchange process, the deuteron wave function cannot be considered as a  $\delta$  function compared with the radial extent of the diproton wave function, and Eq. (1) is thus expected to be a poor approximation to Eq. (2). This was first pointed out by Phillips<sup>6</sup> for the charge-exchange process in the reaction  $d(n,p)2n$ . He showed that Eq. (2) leads to a much sharper final-state peak than Eq. (1). Experimental verification of this effect was provided by the work of Morton *et al.*,<sup>7</sup> who compared triton spectra near  $0^\circ$  and  $180^\circ$  from the reaction  ${}^3\text{He}(d,t)2p$  at 21 MeV c.m. They found<sup>8</sup> the forward-angle spectrum well represented by the Watson-Migdal theory, while the back-angle spectrum was better represented by the Phillips treatment. Even for a pickup process the Watson-Migdal expression is marginal,<sup>9</sup> and the full overlap expression, Eq. (2), is required to account adequately for the data.<sup>10</sup> It would thus appear that the detailed shape of the final-state spectrum is useful in elucidating reaction mechanisms.

Most investigations of the reaction  ${}^3\text{He}(d,t)2p$  have been limited to observations at a few very forward or backward angles.<sup>1,2,7,11</sup> A notable exception is the work of Jakobson, Manley, and Stokes.<sup>3</sup> They measured the complete doubly differential cross section at 8.4 MeV c.m. The data

of Jakobson *et al.*<sup>3</sup> have been analyzed in terms of partial-wave Born approximation (PWBA) and distorted-wave Born approximation (DWBA) by Henley, Richards, and Yu.<sup>4</sup> These authors found that pickup dominated at forward angles and that charge exchange was an important process at back angles. They obtained qualitative agreement with the differential cross section, but their calculated energy spectra were in poor agreement with the data. The assumptions used in their analysis, however, should be better fulfilled at higher energies. Another complication in the data of Jakobson *et al.*<sup>3</sup> is the contribution of tritons from the sequential decay of the resonant state of the  $\alpha$  particle at 20.3 MeV. This process undoubtedly distorted the final-state peak at very large angles.<sup>12</sup>

Larson *et al.*<sup>13</sup> have measured triton spectra from the reaction  ${}^3\text{He}(d, t)2p$  at 6.6 MeV c.m. over the limited angular range between  $6^\circ$  and  $20^\circ$  lab. Application of the Watson-Migdal theory produced a qualitative fit to only those spectra at very forward angles. Since the theory did not give a systematic description of the data, they suggested that agreement at forward angles might be fortuitous. They also analyzed their data (and those of others) by using the plane-wave Born approximation with a realistic nucleon-nucleon potential and a completely antisymmetrized final-state wave function for the five-particle system. One drawback, of course, is that the PWBA neglects distortion effects. Energy spectra calculated in this way agreed much better with experiment, but the agreement with the differential cross section was poor. It is also possible that, at the low c.m. energies involved in the experiments of Larson *et al.*<sup>13</sup> and Jakobson *et al.*,<sup>3</sup> second-order effects and compound-nucleus processes are important.

In an attempt to shed further light on these questions we investigated the reaction  ${}^3\text{He}(d, t)2p$  by measuring absolute energy spectra over the entire angular range and at a higher energy than previous work.<sup>3,13</sup> We chose the center-of-mass energy to be 24 MeV, which is near the maximum energy attainable with the deuteron beam at the Oak Ridge isochronous cyclotron (ORIC). At this energy some of the theoretical assumptions made in the Born approximation should more nearly be valid, and separation of the reaction mechanisms involved should be easier. In addition, at this c.m. energy, tritons from the sequential decay of the 20.3-MeV state in  ${}^4\text{He}$  appear more than 10 MeV lower in energy than the tritons of interest in this experiment. After setting forth in Sec. II the theoretical framework used to analyze our data, we describe the experimental arrangements in Sec. III and the results in Sec. IV. Section V

contains the analysis and discussion, and our conclusions appear in Sec. VI.

## II. THEORY

Pickup and charge exchange are the only two first-order reaction mechanisms involved in the  ${}^3\text{He}(d, t)2p$  reaction. Higher-order effects should be unimportant at the energies used in this experiment, particularly for the region of phase space of interest to us, namely, that corresponding to low relative proton energies. For these reasons the diproton can be described by effective-range theory, and the analysis of reaction modes can be carried out by using the theory set forth by Henley *et al.*<sup>4</sup> They point out that, because the same two processes—pickup and charge exchange—contribute to both  ${}^3\text{He}(d, t)2p$  and  ${}^3\text{He}(d, d)3\text{He}$  at small relative proton energy, these two interactions can be compared in a way which is only slightly model dependent. In addition to normal shape elastic scattering, there is a contribution to elastic scattering from proton pickup by the deuteron. These two processes cannot be distinguished experimentally, so the pickup must be included explicitly in the theory. The latter process will dominate when  ${}^3\text{He}$  is observed close to the direction of the incident deuteron; that is to say, for  ${}^3\text{He}(d, d)3\text{He}$ , the cross section at the forward angles will be dominated by shape elastic scattering, while at large angles the proton pickup process will be important. If only nuclear effects are considered, then the reaction can be compared to the experimentally measured elastic scattering. To avoid interference effects, the comparison is carried out only for very small and very large angles. We list the results that Henley *et al.*<sup>4</sup> found for the ratio of reaction to elastic scattering cross sections. In the region where charge exchange dominates, presumably near  $180^\circ$  in our experiment, the ratio of the reaction cross section near  $180^\circ$  to the elastic scattering cross section near  $0^\circ$  is given by<sup>4</sup>

$$\frac{d^2\sigma_{\text{CE}}/d\Omega_t d\epsilon}{d\sigma_{\text{Pot, El}}/d\Omega_{\text{He}}} = \frac{1}{2\pi^2} N\sqrt{N\epsilon} \frac{k}{K} \left( \frac{A^2}{144 - 72A + 11A^2} \right) \left| \frac{I_{\text{CE}}}{J_{\text{CE}}} \right|^2, \quad (3)$$

where

$$I_{\text{CE}} = \int \chi_\epsilon^{-*}(\vec{r}) e^{-(i/2)(\vec{K} + \vec{k}) \cdot \vec{r}} u_d(r) d^3r, \quad (4)$$

$$J_{\text{CE}} = 3 \int e^{-(i/2)(\vec{K} + \vec{k}) \cdot \vec{r}} u_d^2(\vec{r}) d^3r, \quad (5)$$

$u_d(\vec{r})$  is the radial wave function for the deuteron,  $\chi_\epsilon(\vec{r})$  is the wave function for the diproton system with relative energy  $\epsilon$ ,  $A$  determines the strength

of exchange forces in the nucleon-nucleon potential and has the value 1 for a Serber force, and  $\bar{\mathbf{k}}$  and  $\bar{\mathbf{k}}'$  are the relative momenta in the incident and exit channels, respectively. In the region where the pickup process is expected to dominate, near  $0^\circ$  in our experiment, the ratio of the reaction cross section near  $0^\circ$  to the elastic scattering cross section near  $180^\circ$  is given by<sup>4</sup>

$$\frac{d^2\sigma_{\text{PU}}/d\Omega_t d\epsilon}{d\sigma_{\text{PU,El}}/d\Omega_{\text{He}}} = \frac{1}{6\pi^2} N\sqrt{N\epsilon} \frac{k}{K} \left| \frac{I_{\text{PU}}}{J_{\text{PU}}} \right|^2, \quad (6)$$

where

$$I_{\text{PU}} = \int \chi_\epsilon^{-*}(\bar{\mathbf{x}}) v(\bar{\mathbf{x}}) d^3x, \quad (7)$$

$$J_{\text{PU}} = 2 \int v(\bar{\mathbf{x}}) u_d(\bar{\mathbf{x}}) d^3x, \quad (8)$$

and  $v(\bar{\mathbf{x}})$  is the wave function describing the spatial extent of two protons in  $^3\text{He}$ .

Note that in the pickup region the ratio depends on neither the momentum transfer nor the nature of the interaction, while in the charge-exchange region it depends on both. In addition, there are in reality some differences between the reaction and elastic scattering: examples are the phase space, various spin-isospin factors, and the di-nucleon binding energy. The binding energy of the deuteron,  $\epsilon_d$ , is negative, while  $\epsilon$  is positive. If  $E_i$  is the incident center-of-mass energy, there can be errors of the order of  $(|\epsilon_d| + \epsilon)/E_i$ . The higher the incident energy, the better the comparison should be.

### III. EXPERIMENTAL DETAILS

The 24-MeV c.m. condition was obtained by bombarding  $^3\text{He}$  with 40-MeV deuterons and deuterium gas with 60-MeV  $^3\text{He}$ . Beam energies were determined by magnetic analysis, and are known to  $\pm 150$  keV. The program OPTIK<sup>14</sup> was used to calculate linear displacements and angular divergences for the beam as it passed through several active elements on its way to the target. The angular divergence at the target position was calculated to be  $\pm 0.3^\circ$  full width. The energy spread in the beam as it leaves the beam analyzing magnet is determined by the sizes of the entrance and exit slits. Slits were chosen so that the maximum amount of beam could be transmitted without an undue contribution to the over-all energy resolution.

Several targets were used during this experiment. At forward angles, where there would be no interference from tritons from the ( $^3\text{He}, t$ ) reaction on  $^{12}\text{C}$ , deuterated polyethylene foils were used; beam currents were restricted to less than 60 nA to avoid damaging the foil. At other angles

a gas target ( $^3\text{He}$  or  $^2\text{H}$ ) cooled to 77°K was used; windows of 2.4  $\mu\text{m}$  Havar of 13  $\mu\text{m}$  beryllium were held in place with epoxy. Beam currents with the gas target were unrestricted, reaching 850 nA of  $^3\text{He}^{++}$  and 500 nA of deuterons.

The major contributions to the over-all energy resolution of the experiment came from the kinematics of bombarding a mass-3 target with a mass-2 projectile, and vice versa. The energy of the outgoing particle changes rapidly as a function of angle, reaching 1.5 MeV/deg in the worst case. Uncertainties in the angle due to various causes were  $\pm 0.12^\circ$  (slit system),  $\pm 0.3^\circ$  (incoming beam divergence), and variable amounts of multiple scattering in target and foils (reaching  $\pm 1.0^\circ$  in the worst case). Beryllium was used where possible in an effort to decrease the contribution due to multiple scattering. Over-all values of resolution calculated for the two-body reactions  $^3\text{He}(d, p)^4\text{He}$  and  $^{12}\text{C}(^3\text{He}, t)^{12}\text{N}$  agreed fairly well with experimental results.

Data at forward angles were taken by using Kodak NTB nuclear emulsions in the focal plane of a broad-range magnetic spectrograph.<sup>15</sup> At angles near  $90^\circ$  (c.m.) and for elastic scattering measurements, a  $dE/dx - E$  counter telescope was used consisting of a Si transmission detector and a NaI stopping counter. Data from the tele-

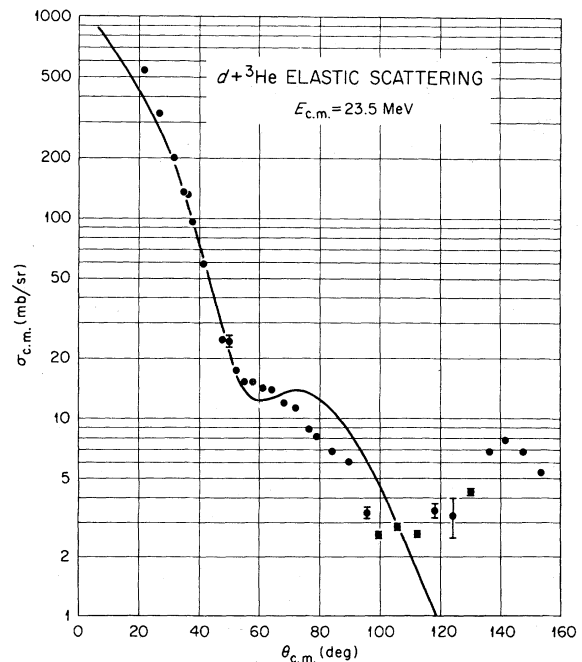


FIG. 1. The points show the experimentally measured  $d + ^3\text{He}$  elastic differential cross section. The smooth curve is an optical model representation chosen to fit the forward angle data.

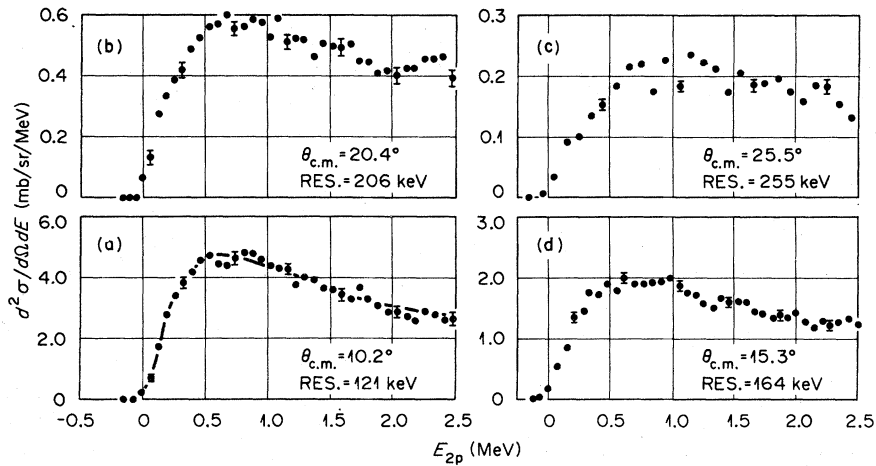


FIG. 2. Absolute triton energy spectra for the reaction  ${}^3\text{He}(d, t)2p$  at 23.5 MeV c.m. Error bars indicate the magnitude of relative errors. The solid curve on the  $10.2^\circ$  data is the Born-approximation prediction (Eq. 2) for a pickup process normalized to the integrated cross section over the interval  $0 \leq E_{2p} \leq 1.5$  MeV.

scope were stored in a Victoreen 20 000-channel analyzer in the  $100 \times 200$  coincidence mode. The beam current was monitored with a Faraday cup, where possible; in other instances, a NaI counter or a  $dE/dx - E$  telescope consisting of two pieces of Pilot B plastic scintillator was used as a monitor counter. Cross sections were calculated for data taken with the gas target by using the formalism of Silverstein.<sup>16</sup> Care was taken to make measurements using the  $dE/dx - E$  telescope and the spectrograph at overlapping angles.

#### IV. EXPERIMENTAL RESULTS

To obtain optical potentials for DWBA analysis of the data, an elastic scattering angular distri-

bution was measured by bombarding  ${}^3\text{He}$  with 39.1-MeV deuterons. Both deuterons and  ${}^3\text{He}$  particles were detected by using a  $\Delta E - E$  counter telescope and a 20 000-channel multiparameter analyzer. The results are shown in Fig. 1; the curve is the result of an optical-model fit described below. Error bars are shown where the relative error is larger than the size of the plotted point; the absolute error is estimated to be 10%.

The reaction data consist of absolute triton spectra at 24 angles and are shown in Figs. 2–6. These show the typical final-state enhancement features at angles near  $0^\circ$  and  $180^\circ$ . The angular distribution is shown in Fig. 7 for the case where

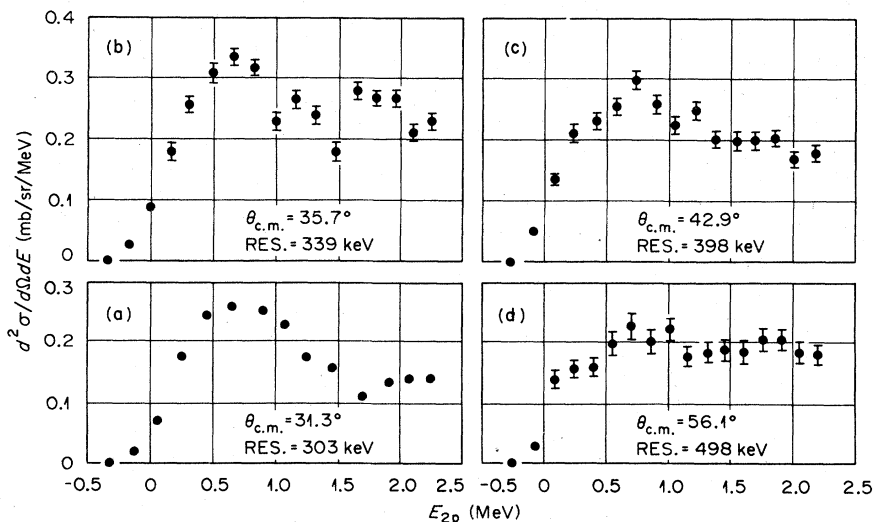


FIG. 3. Absolute triton energy spectra for the reaction  ${}^3\text{He}(d, t)2p$  at 23.5 MeV c.m. for the indicated center-of-mass angles. Occasional relative errors are shown.

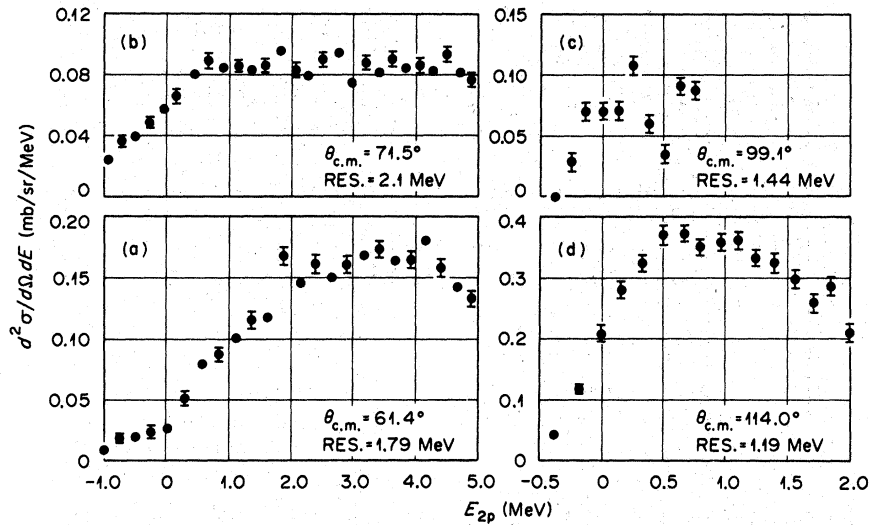


FIG. 4. Absolute triton energy spectra for the reaction  ${}^3\text{He}(d,t)2p$  at 23.5 MeV c.m. for the indicated center-of-mass angles. Occasional relative errors are shown.

the final-state protons have 1 MeV in their c.m. systems. As can be seen from Figs. 2–6, this energy is near the maximum cross section of the final-state enhancement peak. The forward and backward peaking of the cross section is characteristic of peripheral direct processes such as pickup and charge exchange. Another outstanding feature of these data is the deep destructive minimum near  $90^\circ$  c.m.—a feature that was not evident in the lower-energy data of Jakobson *et al.*<sup>3</sup> Finally, we draw attention to the bump in the reaction data near  $40^\circ$  c.m., which we believe is related to the bump in the elastic cross section (Fig. 1) near  $140^\circ$  c.m.

## V. ANALYSIS AND DISCUSSION

### Angular distribution

The solid curve on the  $\theta_{\text{c.m.}} = 10.2^\circ$  spectrum of Fig. 2(a) is calculated from Eq. (2) by taking a  ${}^1S_0$  effective range wave function for  $\phi_{2p}$  and a Gaussian wave function for the spatial distribution of two protons in  ${}^3\text{He}$ . The effective range parameters used for the diproton wave function were the generally accepted values<sup>17</sup> of  $-7.7$  fm for the scattering length and 2.84 fm for the effective range parameter. The Gaussian range parameter used for the two protons in  ${}^3\text{He}$  had the value 0.36 fm, which agrees with the value obtained from an

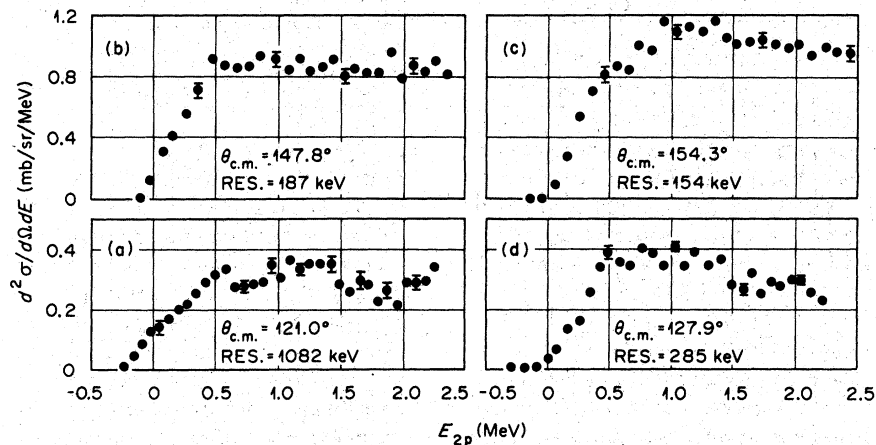


FIG. 5. Absolute triton energy spectra for the reaction  ${}^3\text{He}(d,t)2p$  at 23.5 MeV c.m. for the indicated center-of-mass angles. Occasional relative errors are shown.

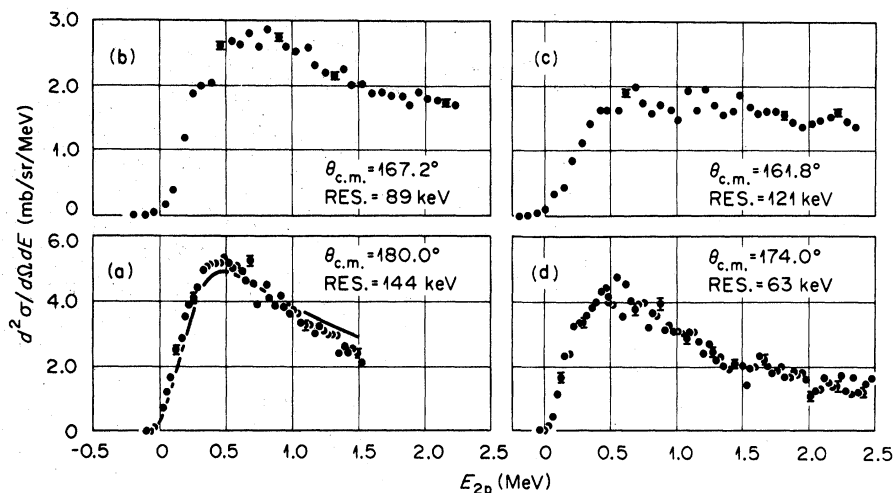


FIG. 6. Absolute triton energy spectra for the reaction  ${}^3\text{He}(d,t)2p$  at 23.5 MeV c.m. for the indicated center-of-mass angles. Error bars are relative errors only. The solid curve on the  $180^\circ$  data is the Born-approximation prediction (Eq. 2) for a charge-exchange process normalized to the integrated cross section over the interval  $0 \leq E_{2p} \leq 1.5$  MeV.

analysis<sup>18</sup> of electron scattering data. The value 0.36 fm was obtained from a least squares fit of Eq. (2) to the  $10.2^\circ$  spectrum for the interval  $0 \leq E_{2p} \leq 2.0$  MeV with the assumption that the Gaussian range parameter was the only unknown variable.<sup>10</sup> This success suggests that a single process, the pickup process, does indeed dominate at small angles. At extreme back angles, one would expect the charge-exchange process to play a significant role.<sup>8</sup> The appropriate wave function for  $\psi(\vec{r})$  in Eq. (2) for this case is the deuteron wave function. The solid curve on the  $180^\circ$  spectrum of Fig. 6(a) is the prediction of Eq. (2) using a deuteron wave function<sup>19</sup> for  $\psi(\vec{r})$  and the above-described diproton wave function. Although the charge-exchange prediction fails, it is in better agreement with the measured  $180^\circ$  triton spectrum than the prediction for a pickup process. A destructive interference between the two mechanisms could account for the  $180^\circ$  spectrum.

#### Triton spectra

The DWBA method was used to analyze the angular distribution. The optical potential was determined in the conventional way by fitting the differential cross section for  $d+{}^3\text{He}$  elastic scattering with an automatic search code.<sup>20</sup> Initial calculations indicated that surface absorption gave better fits than volume absorption, and we used only the former in subsequent investigations. As will be argued below, we believe that the maximum in the elastic scattering cross section at back angles is related to the pickup process and not to shape elastic scattering. In fitting the elastic scattering data, therefore, we have con-

centrated on the forward angles ( $\theta_{c.m.} < 90^\circ$ ) and have omitted a spin-orbit term from the potential. Under these conditions ambiguities abound, but these can largely be resolved by using the reaction data. It was found that only a narrow range of

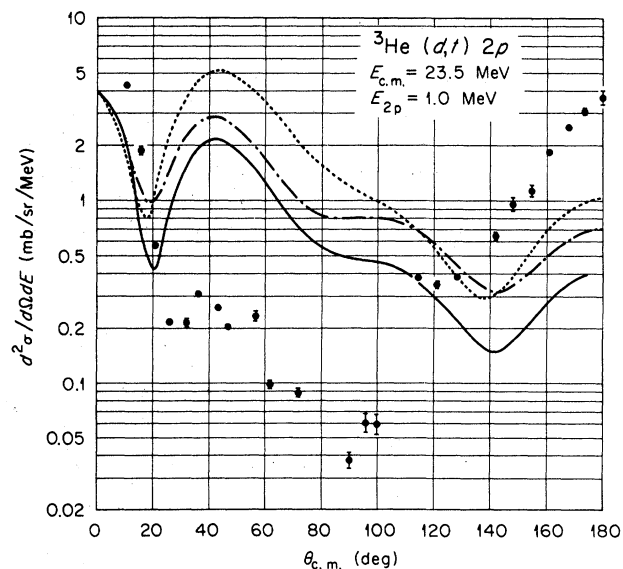


FIG. 7. Triton differential cross section for the reaction  ${}^3\text{He}(d,t)2p$  at 23.5 MeV c.m. The cross sections are for the condition that the diproton center-of-mass energy is 1.0 MeV. The errors are relative. The curves are various DWBA pickup calculations. The dashed curve is a zero-range calculation while the dot-dashed curve is zero range with a lower radial cutoff of 0.9 fm. The solid curve is a finite range calculation using a 1.0 fm range parameter. The calculations are arbitrarily normalized.

optical parameters would account for the minimum near  $30^\circ$  c.m. in the reaction data when these parameters were employed in a simple pickup process calculation.<sup>21</sup> In this manner the best potential found was  $V_0 = 67.06$  MeV,  $r_R = 1.25$  fm,  $a_R = 0.550$  fm,  $W_D = 7.40$  MeV,  $r_I = 1.70$  fm, and  $a_I = 0.476$  fm, with  $r_c = 1.3$  fm. We used the same parameters to generate the distorted waves in the exit channel. The bound-state wave function for  ${}^3\text{He}$  was obtained by solving the Schrödinger equation for a proton bound in a Woods-Saxon well with the well depth adjusted to give the proper binding energy. The angular distribution for a simple pickup process calculated with the above parameters using the program JULIE<sup>21</sup> is shown as the dotted curve in Fig. 7. The location of the first minimum is seen to be poorly predicted by this zero-range calculation. Some of the effects of finite range can be simulated by introducing a lower radial cutoff in the JULIE calculation. The dot-dash curve in Fig. 7 is the result of such a procedure for a 0.9 fm cutoff. Excluding some of the interior region is seen to improve the fit to the data in that the first minimum moves out in angle and the bump near  $40^\circ$  c.m. is reduced in magnitude relative to the  $0^\circ$  peak.

A better estimate of finite range effects can be obtained by the finite range program FANNY.<sup>22</sup> Results with a finite-range parameter of 1.0 fm are shown as the solid curve in Fig. 7 and confirm the general effects observed by introducing an inner radial cutoff in the zero-range calculation.

As pointed out by Henley *et al.*,<sup>4</sup> this reaction offers a unique opportunity for comparison with elastic scattering. The comparison is contained in Eqs. (3) and (6) and is based on the assumption that the reaction is dominated by pickup at forward angles and charge exchange at back angles.

To estimate an experimental value for the ratio of pickup in the reaction to pickup in the elastic scattering we use the reaction data in the angular range  $30$  to  $45^\circ$  c.m. and the elastic scattering data in the range  $150$  to  $135^\circ$  c.m. In both angular regions the data are slowly varying in angle and have similar shapes. We obtain an experimental ratio for Eq. (6) of  $0.037 \pm 0.005$  MeV<sup>-1</sup>, where the error gives the spread in the values of the ratio for data in this region. This may be compared to the theoretical value for Eq. (6) of  $0.037$  MeV<sup>-1</sup> for a Gaussian deuteron wave function and  $0.042$  MeV<sup>-1</sup> for a Hulthén deuteron wave function. The excellent agreement between theory and experiment may be regarded as further strong evidence that pickup is the dominant mechanism at forward angles. Furthermore, this agreement emphasizes the importance of the pickup process in contributing to elastic scattering at back angles.

The contribution of a single-nucleon-pickup process to elastic scattering has also been demonstrated for  ${}^3\text{He} + {}^4\text{He}$  elastic scattering<sup>23,24</sup> and for  ${}^{12}\text{C} + {}^{13}\text{C}$  scattering.<sup>25</sup>

Difficulties arise when we attempt a similar comparison for the ratio of the charge-exchange cross section at back angles to the cross section for elastic scattering at forward angles [Eq. (3)]. In this case the shapes of the curves are not the same, and a meaningful comparison cannot be made because the ratio gives very different values depending on the angle chosen. We interpret this as indicating that there is no single reaction mechanism which is dominant in the reaction data at back angles, whereas Eq. (3) assumes the overriding importance of charge exchange.

## VI. SUMMARY AND CONCLUSIONS

The purpose of this work was to gain information on the reaction  ${}^3\text{He}(d, t)2p$  in the medium-energy range. We have thus measured the absolute triton energy spectra from this reaction at  $24$  angles from  $10.2$  to  $180^\circ$  c.m. at an energy of  $23.5$  MeV c.m.

Using the impulse approximation,<sup>4</sup> our data at  $10.2^\circ$  enable us to determine a value for the range parameter in the  ${}^3\text{He}$  wave function. Our result is  $\gamma = 0.36 \pm 0.02$  fm<sup>-1</sup>, which agrees with the result obtained from electron scattering.<sup>19</sup> It may be pointed out that the theory of Watson and Migdal<sup>15</sup> did not fit our triton spectra for reasonable values of the proton-proton scattering length. We attribute this disagreement to the assumption in Watson-Migdal theory that the spatial extent of the  ${}^3\text{He}$  wave function is small when compared with that of the diproton.

This reaction allows a unique comparison with measured  $d + {}^3\text{He}$  elastic scattering, provided that a single mechanism dominates the reaction in a given angular range. The angular distribution for the reaction at forward angles has the same shape as that for elastic scattering at back angles. The agreement with theoretical calculations indicates that pickup dominates the reaction at forward angles and is an important contribution to elastic scattering at back angles. A lack of similar agreement with elastic scattering in the charge-exchange region ( $\theta_{\text{c.m.}} \approx 180^\circ$ ) is an indication of a mixture of reaction mechanisms at these angles. The minimum in our data near  $\theta_{\text{c.m.}} = 90^\circ$  indicates destructive interference between the pickup and charge-exchange mechanisms.

The authors wish to thank E. V. Hungerford, J. J. Malanify, E. Newman, and A. Zucker for their encouragement and support, especially in the

experimental phases of the work. We also thank R. M. Haybron, E. M. Henley, and G. R. Satchler for many enlightening conversations. Finally, we

thank the nuclear plate readers and cyclotron crew of the Oak Ridge Cyclotron Laboratory for their most necessary contributions.

\*Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.

†Oak Ridge Graduate Fellow from the University of Tennessee under appointment from Oak Ridge Associated Universities. Present address: Technical Information Center, U. S. Energy Research and Development Administration, Oak Ridge, Tennessee.

<sup>1</sup>O. M. Bilaniuk and R. J. Slobodrian, *Phys. Lett.* **7**, 77 (1963).

<sup>2</sup>E. Baumgartner, H. E. Conzett, E. Shield, and R. J. Slobodrian, *Phys. Rev. Lett.* **16**, 105 (1966).

<sup>3</sup>M. Jakobson, J. H. Manley, and R. H. Stokes, *Nucl. Phys.* **70**, 97 (1965).

<sup>4</sup>E. M. Henley, F. C. Richards, and D. U. L. Yu, *Nucl. Phys.* **A103**, 361 (1967).

<sup>5</sup>K. M. Watson, *Phys. Rev.* **88**, 1163 (1952); A. B. Migdal, *Zh. Eksp. Teor. Fiz.* **28**, 3 (1955) [*Sov. Phys.—JETP* **1**, 2 (1955)].

<sup>6</sup>R. J. N. Phillips, *Nucl. Phys.* **53**, 650 (1964).

<sup>7</sup>B. J. Morton, E. E. Gross, J. J. Malanify, and A. Zucker, *Phys. Rev. Lett.* **18**, 1007 (1967).

<sup>8</sup>B. J. Morton, E. E. Gross, E. V. Hungerford, J. J. Malanify, and A. Zucker, *Phys. Rev.* **169**, 825 (1968).

<sup>9</sup>R. M. Haybron, *Nucl. Phys.* **A112**, 594 (1968).

<sup>10</sup>R. W. Rutkowski and E. E. Gross, *Phys. Lett.* **35B**, 151 (1971).

<sup>11</sup>T. A. Tombrello and A. D. Bacher, *Phys. Lett.* **17**,

37 (1963); K. P. Artjomov *et al.*, *ibid.* **12**, 53 (1964); D. Bachelier *et al.*, *Nucl. Phys.* **A184**, 641 (1962).

<sup>12</sup>E. E. Gross, E. V. Hungerford, and J. J. Malanify, *Nucl. Phys.* **A164**, 376 (1971).

<sup>13</sup>H. T. Larson, A. D. Bacher, K. Nagatani, and T. A. Tombrello, *Nucl. Phys.* **A149**, 161 (1970).

<sup>14</sup>T. J. Devlin, University of California Radiation Laboratory Report No. UCRL-9727, 1961 (unpublished).

<sup>15</sup>J. B. Ball, *IEEE Trans. Nucl. Sci.* **NS-13**, No. 4, 340 (1966).

<sup>16</sup>E. A. Silverstein, *Nucl. Instrum. Methods* **4**, 53 (1959).

<sup>17</sup>L. Hulthén and M. Sugawara, *Handbuch der Physik* (Springer-Verlag, Berlin, 1959).

<sup>18</sup>L. I. Schiff, *Phys. Rev.* **133**, B802 (1964).

<sup>19</sup>M. J. Moravcsik, *Nucl. Phys.* **7**, 113 (1958).

<sup>20</sup>F. G. Perey, the program GENOA, private communication.

<sup>21</sup>R. M. Drisko, the program JULIE, private communication.

<sup>22</sup>R. M. Drisko, the program FANNY, private communication.

<sup>23</sup>R. E. Brown, E. E. Gross, and A. van der Woude, *Phys. Rev. Lett.* **25**, 1346 (1970).

<sup>24</sup>W. Fetscher, E. Seibt, C. Weddigen, and E. J. Kanelopoulos, *Phys. Lett.* **35B**, 31 (1971).

<sup>25</sup>W. Von Pertzen, *Nucl. Phys.* **A148**, 529 (1970).