approximation to the rearrangement energy correction gives appreciably better results than those obtained in the previous calculations. Finally, it appears probable that much of the residual error in the results can be removed by improvements in the phenomenological two-body potential upon which the calculations are based, and by improvement of the "surface" energy.

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He^3+t Reactions*†

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The energy distributions of alpha particles and of protons from the He^3+t reactions have been measured for 1.9-MeV incident tritons at laboratory angles of 30° for alphas, and both 30° and 90° for protons. Absolute cross sections are obtained. The spectra are discussed in terms of a model which assumes that uncorrelated three-body breakup and several two-stage processes all contribute independently to the cross section. The calculations based on this model are in excellent agreement with the observed spectral shapes. The neutron-proton correlation corresponding to the unbound singlet state of the deuteron is observed. The binding energy of He^6 (for breakup into a neutron and an alpha particle) was found to be $\epsilon=-0.79\pm0.03$ MeV.

INTRODUCTION

RECENTLY, there has been considerable interest in the interpretations of reactions of the type

$$a+A\rightarrow b+c+d.$$

Each of the three particles in the final state has a spectrum of energies. The shape of the spectrum depends on the nuclear forces acting in the system and for this reason has not yet been derived exactly. Nevertheless, such reactions as $d+p\rightarrow p+p+n$, $d+n\rightarrow p+n+n$, $t+d\rightarrow t+p+n$, $\alpha+d\rightarrow\alpha+p+n$, $t+t\rightarrow \alpha+n+n$, $Be^9+p\rightarrow\alpha+\alpha+d$, $K^-+p\rightarrow\bar{K}^0+\pi^-+p$, and $\Sigma^-+d\rightarrow$ (Λ^0 or Σ^0)$+n+n$[1–6,8–11] are often discussed in terms of the cluster model which suggests that three-body decay can be treated as a time sequence of two-body interactions[4–7] or in terms of final-state interactions among the reaction products.[8–15]

The $T(t,\alpha)n,n$ reaction for triton energies below 2.1 MeV has been investigated in some detail at this laboratory,[6] and the alpha-particle energy spectra were fairly well explained by a two-stage process calculation. The present experiment is a similar study of the $He^3(t,\alpha)p,n$ reaction.

When helium-3 is bombarded with tritium, the following reactions are the only ones possible at low bombarding energies:

$$He^3+t\rightarrow He^4+d, \quad (Q=14.320\text{ MeV}) \quad (1)$$

$$\rightarrow He^5+p\rightarrow\alpha+p+n, \quad (Q=11.14\text{ MeV}) \quad (2)$$

$$\rightarrow Li^5+n\rightarrow\alpha+p+n, \quad (Q=10.13\text{ MeV}) \quad (3)$$

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$$\rightarrow \alpha + p + n, \quad (Q = 12.095 \text{ MeV}) \quad (4)$$

$$\rightarrow \text{Li}^6 + \gamma, \quad (Q = 15.79 \text{ MeV}) \quad (5)$$

$$\rightarrow \text{He}^3 + t. \quad (\text{elastic scattering}) \quad (6)$$

Q values were calculated using the nuclidic masses tabulated by Everling *et al.*[16]

Reactions (1)–(4) were observed qualitatively by Almqvist *et al.*[17] Moak[18] and Youn *et al.*[19] investigated charged particles from the He^3+t reactions for incident energies below 1 MeV. Both of these experiments measured the ratios of cross sections for different branches of the reaction and the decay energy of the He^5 ground state into an alpha particle and a neutron. In addition, Youn *et al.* measured the total neutron yield. Barry *et al.*[20] have investigated the neutron spectrum from these reactions for an incident He^3 bombarding energy of 3.2 MeV.

In the present experiment, the proton and alpha spectra from these reactions were investigated by bombarding a thin He^3 gas target with 1.9-MeV tritons. The reaction products emerging at angles of 30° and 90° with respect to the triton beam were analyzed with high resolution in a 16-in. radius, 180° double-focusing magnetic spectrometer and detected by a CsI scintillation counter. The combination of momentum analysis in the magnetic spectrometer and analysis of pulse heights in the CsI crystal permitted identification of the various particles. The alpha spectrum at a laboratory angle of 30° and the proton spectra at laboratory angles of 30° and 90° are presented, and absolute cross sections are obtained. The spectra are discussed in terms of a model which assumes that uncorrelated three-body breakup and several two-stage processes all contribute independently to the cross section.

EXPERIMENTAL DETAILS

The experimental setup is identical with previous studies[6,21,22] and will not be described in detail.

The data were corrected for the distortion of the spectrum due to the energy lost by the reaction particles in traversing the target gas and exit foil, and for charge exchange of the alphas.

TABLE I. Random uncertainties of measurements.

Source	Uncertainty (%)
$\sin\theta(30°)$	±0.3
$\sin\theta(90°)$	Negligible
Spectrometer momentum resolution, R	±2
Charge-exchange and energy-loss corrections	±0.5
Target pressure	±0.5
Target temperature	±0.3
Gas concentration	±0.5
Energy scale (2 MeV)	±0.4
Energy scale (8 MeV)	±0.1

The target gas was checked mass spectrometrically and corrections were made to the data for the minute quantities of impurities that were present. An experimental check was made to ensure that no correction was needed for local heating of the gas by the beam. The He^3 gas was obtained through U. S. Atomic Energy Commission facilities.

The energy scale of the spectrometer was determined[22] by the positions of particle groups corresponding to reactions whose Q values are known to be within several keV.

The counting rates for reactions (2)–(4) were quite low (5–20 counts per min); however, a sufficient number of runs was made at each experimental point to reduce the statistical error in the number of counts observed to below 10%. The background was negligible except at low particle energies where detection of proton and alpha groups became difficult because of the large number of small background pulses from the CsI crystal. This background determined the low-energy limit of the experimental spectra. The high-energy limit of the experimental spectra was determined by the maximum current the magnetic spectrometer could carry.

SUMMARY OF ERRORS

Table I lists all of the known significant sources of error in the cross section and the uncertainties (standard

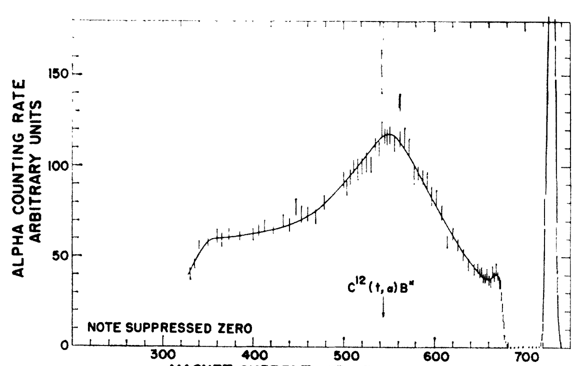

FIG. 1. The alpha-particle spectrum of the yield from the He^3+t reactions at 30° for a triton energy of 1.90 MeV. The vertical bars represent the statistical counting errors.

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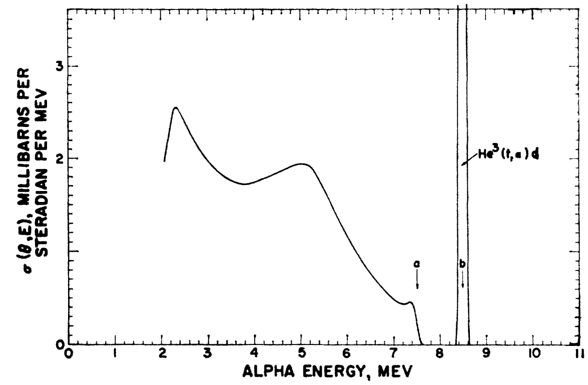

FIG. 2. Experimental alpha energy spectrum of the lab cross section $\sigma(\theta,E)$ in mb/sr at 30° for 1.90-MeV incident tritons. The vertical arrows a and b indicate the *expected* positions of the continuum end point and the peak from $He^3(t,\alpha)H^2$.

deviations) that have been assigned to each. These errors total (rms) 2.3% or less. We estimate that unknown systematic errors are no greater than 1%; therefore we assign 2.5% as a maximum random error for the cross section excluding counting statistics. The statistical errors in the number of counts observed, which in general exceeded the other random errors, ranged over several percent and are discussed as the results are presented.

As a test of the accuracy of the experiment, proton-proton scattering was done at several energies. The measured cross sections agreed within about 1% of the published values, providing an over-all check of the performance of the system.

RESULTS

Figure 1 shows an example of the data observed for alpha particles produced at 30° (lab) by 1.9-MeV tritons incident on an He^3 target. The vertical bars represent the statistical errors in the number of counts observed. These errors range from 3 to 6% for the continuum and are 2.2% for the sharp peak at abscissa 725 corresponding to alphas from the two-body reaction $He^3(t,\alpha)H^2$ [reaction (1)]. The vertical arrow indicates the expected peak position for the contaminant reaction $C^{12}(t,\alpha)B^{11}$. Similar data were observed for protons produced at both 30° and 90° by 1.9-MeV incident tritons. The counting statistics for the proton continuum ranged from 4 to 7%.

Smooth curves were drawn through the data points after subtracting the contaminant peaks. Values from these smooth curves were then used to calculate laboratory system differential cross sections by unfolding the spectrometer resolution.

Alpha Energy Spectra

Figure 2 illustrates the measured energy spectra $\sigma(\theta,E)$ versus alpha energy E, of the alphas produced at 30° by bombarding He^3 nuclei with 1.9-MeV tritons. The continuous spectrum, which was produced by alphas from reactions (2), (3), and (4), is characterized by two peaks with a knee at the high-energy cutoff.

As will be discussed later, the two peaks appear to be caused by the two-stage reactions [reactions (2) and (3)] and the knee a result of a final-state interaction of the neutron and proton. The continuum is followed by the sharp peak corresponding to $He^3(t,\alpha)H^2$ [reaction (1)]. The arrows marked a and b in Fig. 2 indicate, respectively, the *expected* positions of the continuum end point and the peak from reaction (1), both calculated from well-known nuclidic masses.[16] The excellent agreement between these calculated positions and the observed positions is evidence of the accuracy of the energy-scale calibration.

The laboratory system differential cross sections $\sigma(\theta)$ for 30° and 1.9-MeV bombarding energy were obtained by integrating the curve and the peak over the alpha-particle energy. The values thus determined were $\sigma(\theta)=2.43$ mb/sr$\pm$3.2% for the $He^3(t,\alpha)H^2$ reaction, and $\sigma(\theta)=9.69$ mb/sr$\pm$7.9% for the production of alpha particles by three-body processes [reactions (2)–(4)]. The errors indicated are standard deviations and are formed by the usual composite of the experimental uncertainties and statistical errors previously discussed and errors in the integrations involved to get $\sigma(\theta)$. The error in finding the areas graphically, using a planimeter, was no more than 0.5%. For the continuous spectrum, there was an additional uncertainty involved in extrapolating the initial part of the curve back to zero energy. It was assumed that nothing unusual occurs in this region, and a smooth extrapolation was chosen. The uncertainty resulting from this choice was estimated to be $\pm$4.5%. In the unlikely event that something unexpected happens to $\sigma(\theta,E)$ at very low energies, the values of $\sigma(\theta)$ could be in greater error.

Singlet State of the Deuteron

The knee in the continuous spectrum near the maximum alpha-particle energy corresponds to the proton

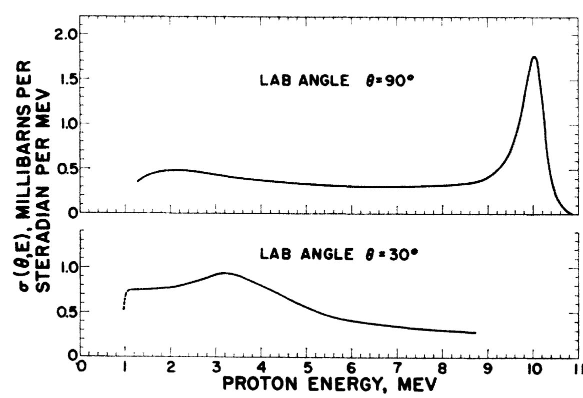

FIG. 3. Experimental proton energy spectra of the lab cross section $\sigma(\theta,E)$ in mb/sr at 30° and 90° for 1.90-MeV incident tritons.

and neutron produced in reactions (2)–(4) going off in the same direction with low relative velocity. The increased yield of alphas at this energy is due in part to the proton and the neutron interacting in the $^1S_0$ singlet state of the deuteron. This first excited state of the deuteron is a virtual state, being unstable by about 0.074 MeV; hence, the observed position of the knee should be at an alpha energy corresponding to an energy of the proton-neutron system below the energy of the unbound system. The 0.074-MeV value of the negative binding energy ϵ of this deuteron state was calculated from *n-p* scattering cross-section theory using the zero-range approximation.[23]

By measuring the energy of the alphas in the knee, an experimental value of ϵ was calculated to be $\epsilon=0.1\pm0.05$ MeV in satisfactory agreement with the theoretical value. The principal source of error lay in the fact that the peak due to the *p-n* interaction was very small and was superimposed over the end of the three-body breakup spectrum whose shape was not known. Thus, the peak position was somewhat dependent upon the assumed shape of the curve subtracted for that energy region.

Proton Energy Spectra

The energy spectra of protons produced at 30° and 90° by 1.9-MeV tritons are shown in Fig. 3. The spectrum at 30° is incomplete because the end point would appear at an energy too high to observe with the magnetic spectrometer but indicates the similarity between spectra at various angles. All of the protons seen correspond to three-body breakup processes [reactions (2)–(4)], and the laboratory system differential cross section for 90° was determined to be $\sigma(\theta)=4.40$ mb/sr$\pm8.7\%$.

He^5 Binding Energy

The large proton peak at about 10 MeV in the 90° proton spectrum corresponds to protons from the first stage of reaction (2), namely, the two-body reaction $He^3(t,p)He^5$ leaving the He^5 nucleus in its ground state. From the experimentally determined energy of the protons in this peak, the most probable He^5 binding energy (for breakup into a neutron and an alpha particle) was calculated. The value thus obtained was -0.79 ± 0.03 MeV. As in the case of the singlet state of the deuteron, some difficulty was experienced in determining the precise peak position. However, after subtracting curves having a wide range of possible shapes, it was felt that the energy value chosen for the peak position could be in error by no more than 30 keV. The value of the He^5 binding energy determined in the present experiment disagrees somewhat with the value -0.96 ± 0.02 MeV calculated from the masses compiled by Everling *et al.*[16] which were computed with least-squares methods from the significant experimental data available before 1960. The present value of -0.79 ± 0.03 MeV does, however, agree with a recent measurement by Youn *et al.*[19] who got a value of -0.8 ± 0.1 MeV.

The full width at half maximum of the proton peak represents the width of the He^5 ground state. This width was found to be 0.525 ± 0.030 MeV in agreement with published values.[24]

Total Cross Section

The total cross section for reactions (2)–(4) was calculated under the assumption of spherical symmetry of the angular distributions of the reaction products in the center-of-mass coordinate system. This assumption seems reasonable in view of the low triton bombarding energy. Both the proton spectrum and the alpha continuous spectrum were transformed into the center-of-mass system and the resulting curves were integrated over the appropriate particle energy. The center-of-mass differential cross sections thus obtained were multiplied by 4π steradian to give values of the total cross section. The values determined from the proton spectrum and from the alpha spectrum agreed within experimental errors and were averaged to give a final value of the total cross section at 1.9 MeV for reactions (2)–(4) of $\sigma=53.3$ mb$\pm8\%$. Assuming that the total cross section does not change rapidly between 0.9 and 3.5 MeV, the present value agrees reasonably well with the results of Youn *et al.*[19] and of Barry *et al.*[20] both of which disagreed by a factor of 3 with the results of Moak.[18]

DISCUSSION

A theoretical spectrum was calculated by the authors for the alpha particles emitted in the He^3+t interactions. This calculation assumed that uncorrelated three-body breakup and several two-stage processes all contribute independently to the spectrum. Only a brief description of the calculation is given: A more complete discussion appears in a forthcoming paper.

If one makes the assumption of constant density of states in phase-space as in classical statistical mechanics, the spectrum of energies for one of the particles emitted in the direct three-body breakup process is given by[18] $N(E)\propto[E(E_{\max}-E)]^{1/2}$, where N is the number density of particles having energy E, and $E_{\max}$ is the maximum possible value of the energy of the particles. This equation is the equation of an ellipse extending from zero energy to the maximum energy. This distribution would not be expected to fit the observed distribution very well since both Coulomb and nuclear effects are disregarded in such a derivation. However, since no rigorous theoretical treatment of the nuclear three-body breakup problem has yet been

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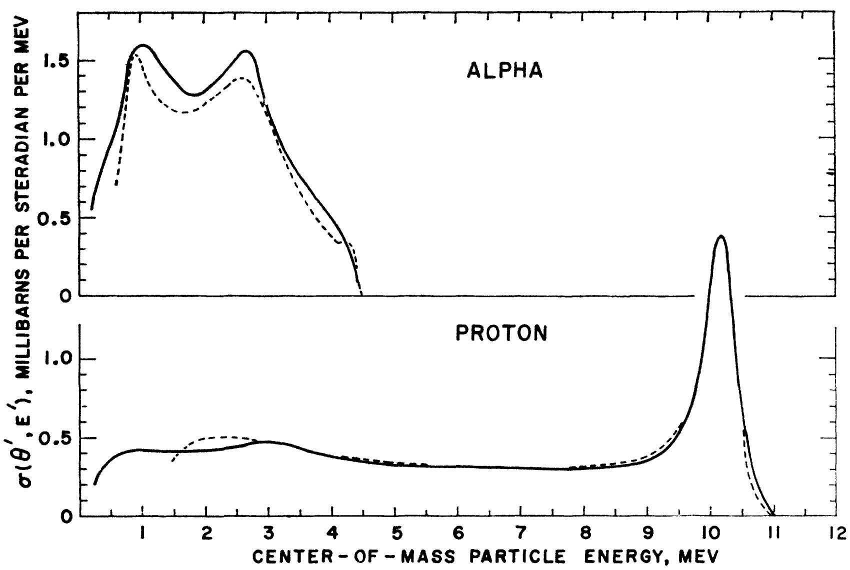

FIG. 4. Comparison of calculated and experimental spectral shapes for the c.m. cross section $\sigma(\theta',E')$ in mb/sr. The experimental spectra are indicated by the dashed curve. $E_t(\text{lab})=1.90$ MeV.

derived, this distribution was used in the present calculation for the uncorrelated three-body breakup contribution to the spectrum.

Several two-stage processes are also possible, the first stage being the collision of the He^3 nucleus and the trition to produce a proton and a He^5 nucleus *or* a neutron and a Li^5 nucleus, and the second stage being the breakup of the He^5 or the Li^5 into an alpha particle and a neutron or an alpha particle and a proton, as the case may be. It is assumed that both the He^5 and the Li^5 may be formed in either the $P_{3/2}$ ground state or the $P_{1/2}$ excited state.

In addition to these modes, the He^3 nucleus and the triton may interact to produce an alpha particle and a deuteron in its virtual ${}^1S_0$ state.

It is assumed that only the S-state component of the triton beam contributes to the interaction. This assumption implies that the mass-five (He^5 or Li^5) nucleus is emitted isotropically in the He^3-t center-of-mass system. Also, only one direction of motion of the mass-five nucleus in the He^3-t center-of-mass system need be considered to determine the *energy* distribution of the alphas in the He^3-t system. It is possible at these energies that there may be some P-state component in the triton beam. Inclusion of P state in the calculations is very complicated and was not attempted. It is interesting to note how well the S-state calculations fit the data, but it should be remembered that the sensitivity of the results to small amounts of P wave is not known.

An additional assumption is made in the calculations. Since the initial particles are not identical, they may interact in either the singlet state ($J=0$) or the triplet state ($J=1$). The ratio of singlet to triplet interaction thus becomes one of the arbitrary parameters in the calculations. However, it is assumed that once this ratio is chosen, it remains the same for all two-stage modes of interaction.

Conservation of parity considerations limit the interaction state of the first emitted nucleon and the mass-five nucleus to ${}^3P_0$ for the singlet states and to ${}^5P_1$ and ${}^1P_1$ for the triplet states.

From this knowledge of the interaction states, the angular distributions of the alpha particles in the center-of-mass system of the mass-five nucleus were calculated for each two-stage mode. For a given binding energy of the mass-five particle, this distribution was found to be isotropic for the ${}^1P_1$ state and $1+3\cos^2\Phi$ and $1+(21/13)\cos^2\Phi$ for the ${}^3P_0$ and ${}^5P_1$ states, respectively, where Φ is the angle between the direction of motion of the alpha particle in the mass-five center-of-mass system and the direction of motion of the mass-five nucleus in the He^3-t center-of-mass system. Because He^5 and Li^5 decay rapidly, both the ground states and the excited states of these nuclei are very broad, and there is a distribution of the binding energies. For this reason, the final alpha distribution is obtained for each two-stage mode by integrating over the appropriate distribution of binding energies.

The results for all modes of the He^3+t interaction were then folded together and appropriate coordinate transformations were made to give the final calculated alpha spectrum. The calculations were done on an IBM-7090 computer. The amplitude of the contribution from each mode of interaction was an unknown parameter in the folding process. These parameters along with the singlet-to-triplet interaction ratio were arbitrarily adjusted to give a good fit to the data. The results of this fit are shown in Fig. 4.

A similar calculation was carried out for the proton spectrum. These results are also shown in Fig. 4.

The results exhibit striking agreement between the

TABLE II. Interaction-mode parameters.

Mode	Value (mb/sr)
He^5+p (g.s.)	1.37
Li^5+n (g.s.)	0.90
$\alpha+p+n$ (uncorrelated)	2.40
$\alpha+d$ (singlet state)	0.05

calculated spectra and the observed spectra. It should be noted, however, that the calculations fit only the shape of the spectra and not the absolute cross section scale. The failure of the calculated curves to decrease as the experimental curves at low particle energies in the spectra is attributed to Coulomb suppression of the cross section for the breakup of the mass-five nucleus at these energies. Such Coulomb effects were not included in the calculations.

The parameters used to fit the data are shown in Table II. These parameters represent the contributions to the cross section from the various He^3+t interaction modes, and appear to be a unique set for a given set of level widths, in that other sets of parameters produced rather poor fits to the data. The fit seemed to be sensitive to the width of the He^5 ground state and, to a lesser extent, to the width of the Li^5 ground state. In the present calculation, the He^5 ground-state width was taken to be the experimental width of the peak in the proton spectrum. The Li^5 ground-state width was taken from the literature.[24] The fit was found to be sensitive to small changes in the first three parameters, permitting these parameters to be rather uniquely determined. The fit was less sensitive to the parameter corresponding to the interaction mode producing an alpha particle and a deuteron in its virtual $^1S_0$ state. This mode corresponds to the knee at the high-energy cutoff of the alpha spectrum. The parameter could be varied from zero to 0.1 mb/sr with little change in the spectral shape, but was at least not greater than 0.15 mb/sr. The parameter for the uncorrelated three-body breakup mode includes the contributions due to the He^5 and Li^5 *excited state* modes since these contributions appeared to be quite small and since, because of the breadth (3–5 MeV) of the excited states, they do not change the shape of the uncorrelated three-body breakup spectrum sufficiently to be clearly distinguished.

The ratio of singlet-to-triplet interaction of the initial particles was arbitrarily taken to be $\frac{1}{3}$. The fit appeared to be quite insensitive to the choice of this ratio.

The excellent agreement between the calculated and observed spectral shapes and the fact that the spectra could not be fitted when one or more of the interaction modes was omitted indicate that the energy spectra are not explained by any one process: The uncorrelated three-body distribution is affected to a considerable extent by final-state interactions among the particles. In addition, it appears that interference effects between the various interaction modes are not necessary to explain the spectral shapes.

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