

ALPHA-PARTICLE SPECTRA AND DIFFERENTIAL CROSS SECTIONS FOR THE  
REACTION  $H^3(t, 2n)He^4$  AT AN ANGLE OF  $90^\circ$

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Spectra of  $\alpha$  particles emitted from the  $H^3(t, 2n)He^4$  reaction at a laboratory angle of  $90^\circ$  were measured with a proportional counter and a 50-channel pulse-height analyzer. The bombarding tritium nuclei had energies ranging between 230 and 1000 keV. The differential cross section for the reaction was calculated on the basis of the spectra thus obtained and found to increase monotonically from 3 to 5.2 mb/sr as the energy increased. At all incident energies there was an appreciable contribution from the two-stage process involving the formation of a neutron and a  $He^5$  nucleus which subsequently decayed into an  $\alpha$  particle and a neutron.

### INTRODUCTION

A number of papers have been devoted to studying the T-T reaction and, in particular, the energy spectrum of the  $\alpha$  particles produced.

Allen et al.<sup>[1-3]</sup> have measured the energy spectra of  $\alpha$  particles emitted at  $90^\circ$  for bombarding triton energies of 220–240 keV. A continuous energy distribution of  $\alpha$  particles extending up to 3.8 MeV was observed, with a broad maximum in the (2.7–2.9)-MeV region; the shape of the maximum bore a good resemblance to that of the spectrum calculated under the assumption that two neutrons and an  $\alpha$  particle were simultaneously produced in the reaction. The contribution from the process corresponding to the emission of two virtually bound neutrons (a "dineutron") with a lifetime greater than  $10^{-21}$  seconds was estimated to be less than 1% of the total yield.

Using a 2.5-MeV electrostatic generator, the Los Alamos group<sup>[4]</sup> has investigated the neutron yield and  $\alpha$ -particle spectra at various angles. Preliminary indications of the existence of the dineutron were obtained.

Jarmie and Allen<sup>[5]</sup> have measured  $\alpha$ -particle spectra at a laboratory angle of  $30^\circ$  for incident tritium energies of  $E_T = 0.95 - 2.10$  MeV, and at  $30^\circ, 60^\circ, 90^\circ,$  and  $120^\circ$  for  $E_T = 1.9$  MeV. From the analysis it was concluded that these spectra could be explained approximately by the theory of a two-stage process proceeding through the formation of  $He^5$  and a neutron with the subsequent decay of the  $He^5$  into an  $\alpha$  particle and a neutron. Since the conclusions of [1-3] and [5] differ considerably as regards the mechanism of the T-T reaction, it was of interest to trace the change in character of the  $\alpha$ -particle spectrum in the unin-

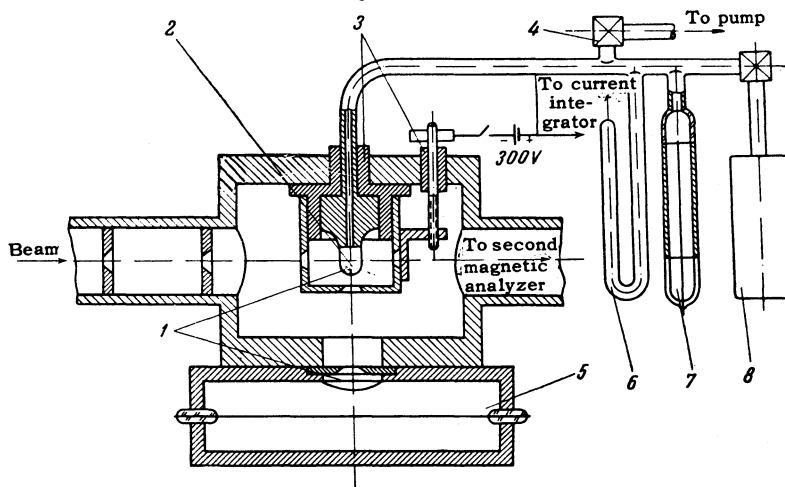


FIG. 1. Schematic diagram of the apparatus. 1 – Mica foil, 2 – gas target, 3 – insulator, 4 – valve, 5 – proportional counter, 6 – mercury manometer, 7 – ionization chamber, 8 – cylinder containing uranium tritide.

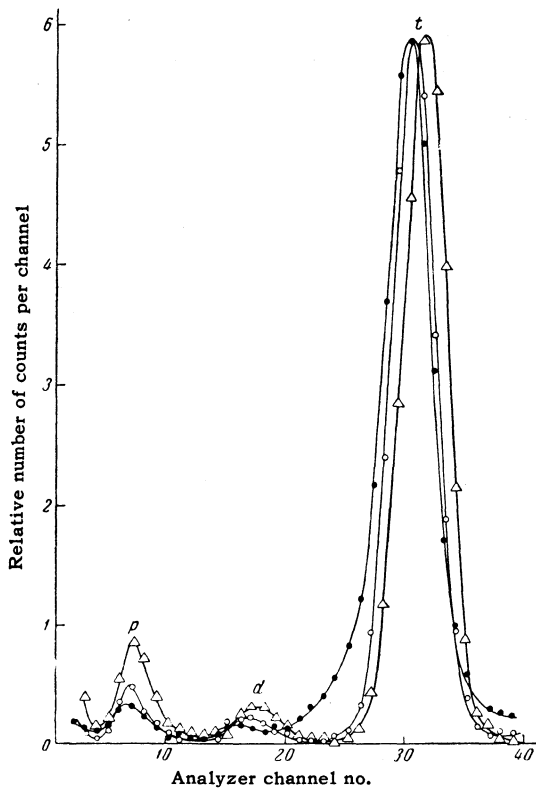


FIG. 2. Spectra of particles from the scattering of the mass 3 beam on argon.  $\Delta$  — is for a target current of 0.005  $\mu$  amp,  $\circ$  — of 0.05  $\mu$  amp, and  $\bullet$  — of 0.14  $\mu$  amp.

investigated (200–1000)-keV range of particle bombarding energies.

#### EXPERIMENTAL METHOD

After passing through the magnetic analyzer, the triton beam from the electrostatic generator

struck a thin gas target (cf. Fig. 1) surrounded by an insulated metal housing which collected the charge of the beam. A proportional counter (diameter 80 mm, length 220 mm) filled at a pressure of 5 atm with pure argon (containing a few percent  $CO_2$ ) was placed at  $90^\circ$  to the beam. The entrance and exit windows of the target were made out of a single piece of mica foil 0.10–0.14 mg/cm<sup>2</sup> thick. The counter window was closed by a 0.18 mg/cm<sup>2</sup> mica foil. The counter had an energy resolution of 4.5–5% for  $Pu^{239}$   $\alpha$  particles. After amplification, pulses from the proportional counter were fed into the 50-channel pulse-height analyzer.

The target was filled with tritium (extracted from uranium tritide) at 60 mm mercury. The concentration of tritium in the target, measured with an ionization chamber calibrated by tritium of known concentration, was about 70%. All vacuum seals of the target and filling system were made of teflon and metal. The composition of the beam of mass 3 ions was determined by scattering it on argon at  $90^\circ$  and measuring the energy spectra of the scattered particles. Figure 2 presents the spectra obtained at the triton bombarding energy of 820 keV. The highest peak corresponds to the tritons, the next one to deuterons from ionized  $DH^+$  molecules, and the third peak to protons obtained from the scattering of molecular  $HHH^+$  and  $DH^+$  ions. According to estimates which took into account the nuclear reaction cross section and multiple Coulomb scattering, the deuterium content of the beam of tritons did not exceed 0.4%, and the  $HHH^+$  ion content was always less than 0.1%. The same deuterium contamination in the beam was

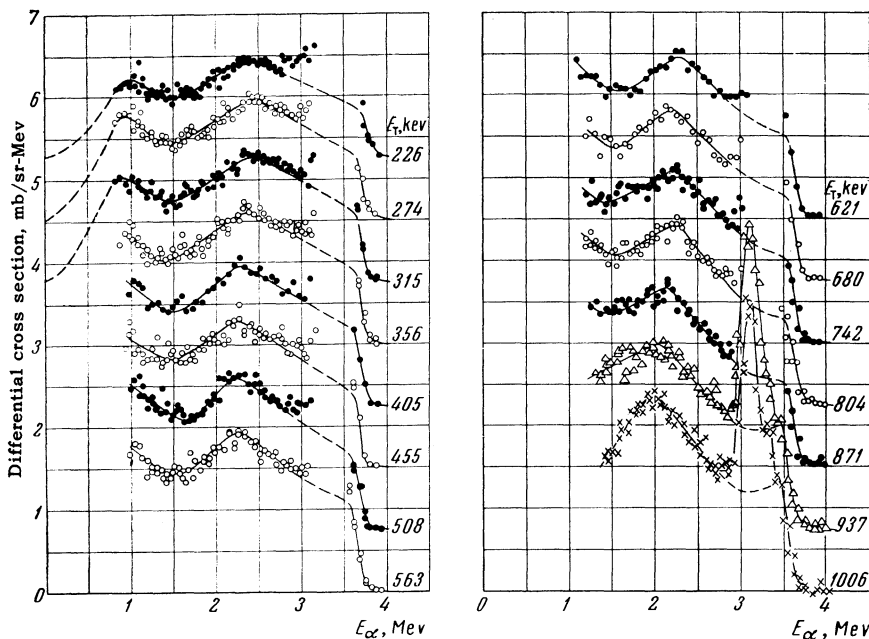


FIG. 3. Spectra of  $\alpha$  particles from the T-T reaction at an angle of  $\theta_{lab} = 90^\circ$  for various tritium nucleus energies. Consecutive curves are displaced 0.75 mb/sr-MeV along the vertical.

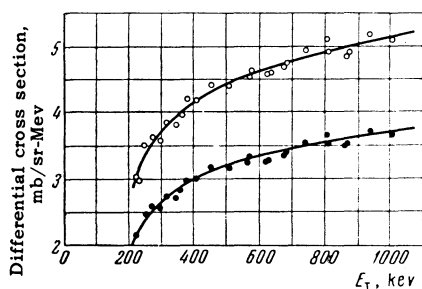


FIG. 4. Cross section for the T-T reaction at a laboratory angle of  $90^\circ$  integrated over  $\alpha$ -particle energies; O — is the cross section integrated over the whole  $\alpha$ -particle spectrum, ● — is the contribution from 61% of the  $\alpha$ -particle spectrum (according to energy scale).

also found by evaluating the contribution of the  $H^3(d, n)He^4$  reaction to the T-T reaction yield.

The energy losses of tritons in the target were determined with the aid of a second magnetic analyzer placed in the path of the beam behind the target.

#### TREATMENT AND DISCUSSION OF THE RESULTS

The experimentally obtained pulse-height distributions were transformed into energy distributions of  $\alpha$  particles by using the range-energy curve for  $\alpha$  particles in mica.<sup>[6]</sup>

The final  $\alpha$ -particle spectra for various triton bombarding energies are presented in Fig. 3. Peaks from the D-T reaction caused by the presence of deuterium in both target and beam were found in the right-hand part of each spectrum. In order not to complicate the drawing, these peaks are shown in only two spectra, for  $E_T = 937$  and 1006 keV. That part of the spectrum of  $\alpha$  particles from the T-T reaction which lies under these peaks was obtained by subtracting the contribution from the D-T reaction, whose character was determined separately by bombarding deuterium with tritons and tritium with deuterium.

The region of low  $\alpha$ -particle energies could not be investigated satisfactorily because of the background of tritons scattered on the slight nitrogen, oxygen, and mercury contaminants in the target. The latter could not be eliminated even after the necessary precautionary measures were taken. Therefore the extrapolation of the spectra to zero energy was most justified for  $E_T = 226, 274,$  and 315 keV.

The extrapolation of the  $\alpha$ -particle spectrum to zero energy adopted was based, first, on the theoretically predictable spectrum shape calculated assuming a three-particle decay of  $He^6$  and a two-stage process involving the formation of  $He^5$ , and

second, on spectrum measurements obtained by Jarmie and Allen.<sup>[5]</sup>

A wide maximum in the 2.2-Mev region and a minimum in the 1.5-Mev region are very evident in all spectra, and in the majority of the spectra the rise of the curve to a second maximum (in the region of low  $\alpha$ -particle energies) is distinctly observed. Control experiments on the scattering of tritons by the gas residues in the target (after absorption of the tritium by uranium) showed that this rise cannot be explained by scattered tritons and is due to the T-T reaction.

The shape of the spectra (position of maxima and minima) indicates that the two-stage process involving the formation of a neutron and  $He^5$  (in the ground state) with subsequent rapid decay of  $He^5$  into an  $\alpha$  particle and neutron plays an appreciable role at triton bombarding energies in the 200 — 1000 keV range.

At large incident triton energies a group of  $\alpha$  particles appears at the right-hand end of the spectra whose presence can be explained as the correlation of two neutrons in the three-particle breakup of the compound nucleus. This group of  $\alpha$  particles is obscured at low triton energies by the large peak from the D-T reaction; the shape of the right-hand side of the spectra can only be approximated here. Errors of up to 30% may occur in this part of the spectrum, while in the middle section the mean-square error of each point at all triton bombarding energies does not exceed 4 — 7%. Comparatively larger errors were considered likely in the extrapolation of spectra to zero  $\alpha$ -particle energy.

Figure 4 presents differential cross sections for the T-T reaction integrated over  $\alpha$ -particle energies. Since at  $E_T = 1006$  keV only a part of the  $\alpha$  particle spectrum was recorded (encompassing about 61% of the energy scale, counting from the right-hand end of the spectrum), these same parts were separated out on all the spectra and the corresponding areas obtained for them. In addition, the integration was carried out over the whole spectrum in the case of the first three spectra ( $E_T = 226, 274,$  and 315 keV), where a reasonable extrapolation to zero energy was possible. Assuming that the ratio of the total area of the spectrum to the area separated out of its right-hand part does not depend on the triton energy, differential cross sections were obtained which were integrated over all  $\alpha$ -particle energies for the remaining energies  $E_T$  also. Although the aforementioned assumption can not claim to be strict, the error in determining the differential

cross sections (according to the estimates made) does not exceed 20%.

In conclusion the authors express deep gratitude to F. L. Shapiro for his valuable advice, and to the collaborators from the electrostatic generator group for their aid in carrying out the experiments.

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<sup>1</sup>Allen, Almqvist, Dewan, Pepper, and Sanders, Phys. Rev. **82**, 262 (1951).

<sup>2</sup>Allen, Almqvist, Dewan, and Pepper, Phys. Rev. **81**, 315 (1951).

<sup>3</sup>Allen, Almqvist, Dewan, Pepper, and Sanders, Phys. Rev. **79**, 238 (1950).

<sup>4</sup>Los Alamos Scientific Laboratory, Phys. Rev. **79**, 238 (1950).

<sup>5</sup>N. Jarmie and R. C. Allen, Phys. Rev. **111**, 1121 (1958).

<sup>6</sup>Govorov, Li Ha Youn, Osetinskii, Salatskii, and Sizov, Preprint, Joint Institute for Nuclear Research, R-725.

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127