Experimental Evidence for the Reaction $d+T \rightarrow He^3+n+n-3$ Mev*

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A continuum of doubly charged particles has been observed from the interaction of 12- and 14-Mev deuterons with tritium. They are shown to arise from the $H^3(d,2n)He^3$ reaction. Absolute differential cross sections are obtained. No evidence for the formation of a dineutron in a bound state, or in a well-defined virtual state, was found.

During the course of an investigation of the interaction of 12- and 14-Mev deuterons with tritium, we observed a sizable cross section for the emission of low-energy nuclei which appeared to exhibit the ionization characteristics of doubly charged ions. Experiments were consequently performed to determine the charge of the ions and, having established that they were indeed doubly charged, to identify their mass.

The experimental arrangement is quite similar to that previously described[1]: a well-collimated beam of cyclotron-accelerated deuterons enters a reaction chamber in which the H^3 gas is confined to the central region, and the detectors are photographic emulsions arranged around the target in such a way as to record the charged reaction products at 2.5° intervals with an angular resolution of $\pm\frac{3}{4}°$.

The reaction products were identified as to charge on the basis of their specific ionization. In order to resolve singly and doubly charged ions, we used $E1$ emulsions which were processed by a combination of the two-solution and cold techniques.[2] A warm stage of 5-minutes duration was found to be optimum from the standpoint of discrimination between charge-1 and charge-2 particles whose range is less than 32 μ. The difficulty of identifying low-energy particles from their tracks in nuclear emulsion arises from the saturation properties of emulsion for highly ionizing particles.

Identification was accomplished by "gap-counting"[3] one or two 16-μ segments, starting from the end of each heavily ionizing track in the range interval 16–100 μ (corresponding to 4–13 Mev He^3 nuclei) and comparing these results to corresponding counts on tracks made by He^3 particles and tritons elastically scattered by deuterons. Figure 1 shows the results of gap-counts on the particles of unknown charge with those from tritons and He^3 nuclei. It is seen that, even when counts are made over the last 16 μ of track, the resolution is almost complete. We thus identify the particles under consideration as being doubly charged. It now remains to determine the source of these particles. This is done on the basis of energy and momentum conservation. The $d+T$ interaction permits the emission of both charge 1 and charge 2 particles, the energetically possible reactions being:

(1) $d+T \rightarrow d+T$ (elastic scattering),

(2) $d+T \rightarrow He^4+n+17.6$ Mev,

(3) $d+T \rightarrow T+p+n-2.2$ Mev,

(4) $d+T \rightarrow He^3+2n-3.0$ Mev,

(5) $d+T \rightarrow He^{4*}+n+Q$,

(6) $d+T \rightarrow d+d+n-6.3$ Mev.

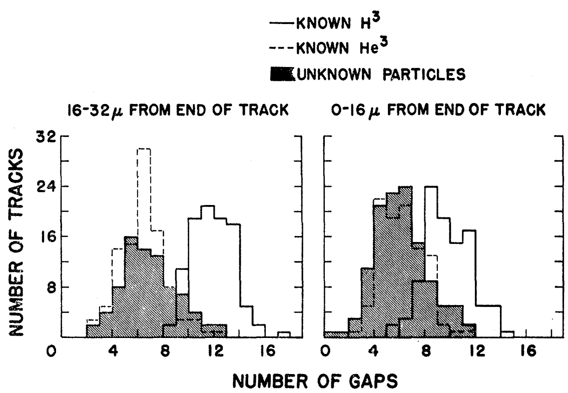

Fig. 1. Results of gap-counts on the last 32 μ of track for the "unknown" particles and for He^3 particles and tritons elastically scattered by deuterons. The ranges of all tracks gap-counted are approximately the same so that counts were made at approximately the same depth within the emulsion.

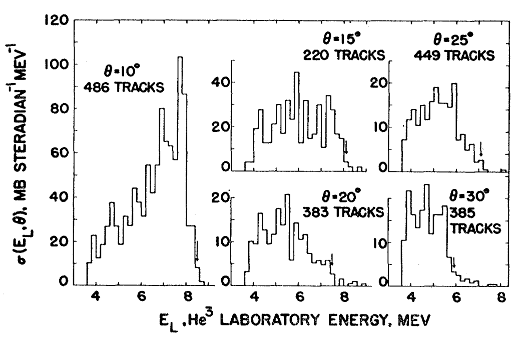

Fig. 2. Energy spectrum of continuum of doubly charged particles from 12-Mev deuterons on tritium for various laboratory angles.

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[1] Brolley, Putnam, and Rosen, Phys. Rev. **107**, 820 (1957).

[2] L. Rosen, Nucleonics **11**, No. 7, 32 (1953), and **11**, No. 8, 38 (1953).

[3] "Gap-counting" refers to the number of gaps between the resolvable track segments in a given track length. A track segment may contain one grain or a cluster of unresolved grains.

The products from reactions (1) and (2) are readily identified by virtue of their unique ranges at any given angle of observation. A continuum of doubly charged particles must therefore arise from reaction (4), assuming (4) is taken to include reaction (5) when $He^{4*} \rightarrow He^3 + n$. Figures 2 and 3 show representative energy spectra of the low-energy, doubly charged nuclei (assuming them to have a mass of 3) observed at various angles in the laboratory system. Energy considerations prohibit particle identification at laboratory angles larger than 45°. The maximum energy available to He^3 particles (corresponding to the two neutrons going off in the same direction) is indicated by the arrows. The end points of the energy distributions at the various angles are seen to correspond closely to these maximum energies. The particles are thus identified as He^3 nuclei from reaction (4). The energy distributions show no evidence that the subject reaction gives rise to dineutrons either in bound states or in well-defined virtual states. A bound state of the dineutron would be identifiable by a peak in the He^3 distribution to the right of the arrows in Figs. 2 and 3. A narrow virtual level would be associated with a similar peak to the left of the arrows. The low-energy cutoffs arise from instrumental limitations in the detection and identification of the low-energy He^3 nuclei.

At each angle of observation the cross sections for emission of He^3 particles, in each 0.2-Mev interval, were converted to the cross sections in the c.m. system at the appropriate c.m. angle and energy. For each 10°-interval in the c.m. system, the differential cross sections with respect to energy and angle were plotted as a function of He^3 energy in the c.m. system. These plots are shown in Figs. 4 and 5. The solid curves are calculated on the basis of a three-body process occurring with random probability in momentum space[4] and normalized to the area under the dotted curve. This latter curve is a visual fit to the experimental data and the known end points. Figure 6 displays the angular distributions of the He^3 particles, integrated over energy. To accomplish this the energy distributions in the c.m. system were extrapolated to zero energy.

In spite of the fact that the method of particle identification probably introduces uncertainties which are comparable to the statistical errors, it is believed that the deviations from the calculated phase-space distributions are qualitatively significant. Such deviations may be due to a variety of causes: assuming reaction (4) to be operative, they may, for example, be a manifestation of the interaction between outgoing neutrons or between one of the neutrons and the He^3 particle. Neutron-neutron forces would tend to correlate the directions of the outgoing neutrons in such a way as to impart a degree of homogeneity to the He^3 particles. Forces between the He^3 nucleus and one of the neutrons would result in homogeneity for the second neutron and, to a much lesser extent, for the He^3 particle as well. Perturbations on the phase-space distributions would also result if some of the reactions proceeded by way of a pickup process, whereby a proton from the target triton attaches itself to the passing deuteron. Such a process would result in a preponderance of high-energy He^3 particles at the forward angles, which is in fact observed (Figs. 2 and 3), as well as a forward peaking of the spatial distribution of the He^3 particles, which is also observed (Fig. 6). Finally, we cannot rule out the possibility that reaction (4) proceeds through reaction (5) and the decay of He^{4*} by neutron emission, since the evidence on the

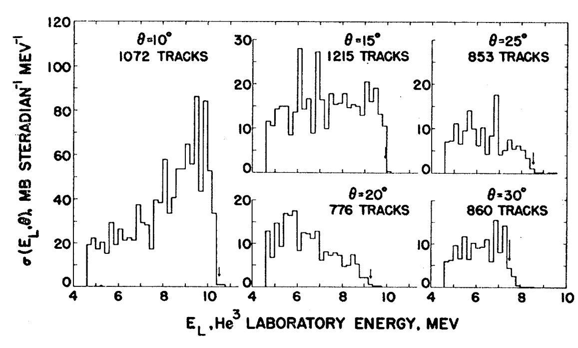

FIG. 3. Energy spectrum of continuum of doubly charged particles from 14-Mev deuterons on tritium for various laboratory angles.

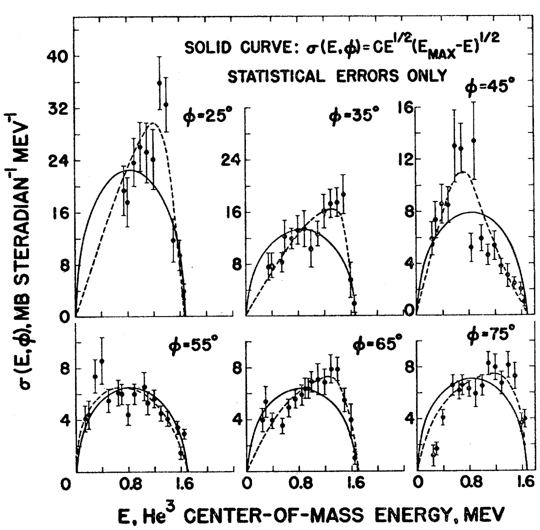

FIG. 4. c.m. energy distribution, for various c.m. angles, for the He^3 particles from the $T(d,2n)He^3$ reaction for 12-Mev deuterons.

[4] G. E. Uhlenbeck and S. Goudsmit, *Pieter Zeeman Verhandelingen* (Martinus Nijhoff, The Hague, 1935), p. 201; Fokker, Kloosterman, and Belinfante, Physica **1**, 705 (1933–34); E. Fermi, *Elementary Particles* (Yale University Press, New Haven, 1951), p. 44.

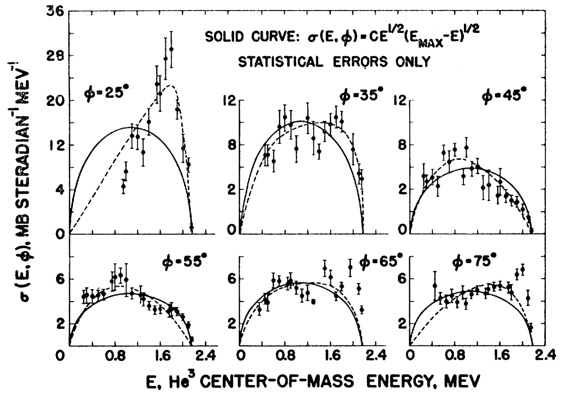

FIG. 5. c.m. energy distribution, for various c.m. angles, for the He^3 particles from the $T(d,2n)He^3$ reaction for 14-Mev deuterons.

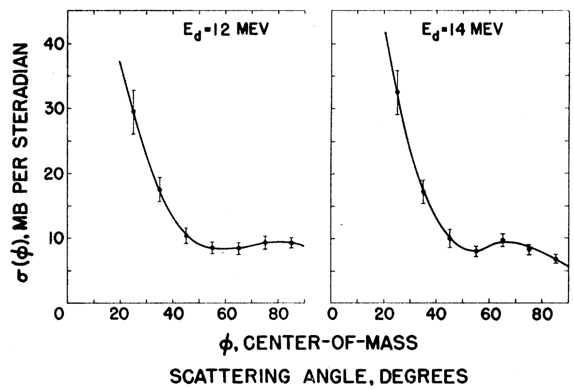

FIG. 6. c.m. angular distribution, integrated over energy, for the He^3 particles from 12- and 14-Mev deuterons on tritium.

existence or nonexistence of a well-defined level in He^4 is not conclusive.[5–13]

Reference 10 cites a comparison of the neutron spectra from 18-Mev deuterons on helium-3 and tritium as evidence for an excited state in helium-4. It may be germane to point out that the proximity, in energy, of the highest energy neutrons from the $H^3(d,2n)He^3$ reaction to those from the $H^3(d,n)He^{4*}$ (22 Mev) reaction may require a different interpretation of the results of Vlasov *et al.*, inasmuch as there is no analogous neutron emission from the $d+He^3$ interaction.

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