Evidence Against the Existence of an Excited State of He^3

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Cloud-chamber measurements have been made on the recoil protons produced by neutrons from the *d–d* reaction. The distribution of the neutron energies has been determined from 126 recoil proton tracks. No evidence for a low energy group of neutrons and consequently an excited state of He^3 was obtained.

THERE has been conflicting evidence in regard to the energies of the neutrons from the $d-d$ reaction. In particular there has been some question as to the existence of a low energy group of neutrons which would imply an excited state of He^3. Evidence for a low energy group of neutrons has been given by Bonner[1,2] and Hudspeth and Dunlap.[3] Baldinger, Huber and Staub[4] also found some evidence for a low energy group but attributed it to scattered neutrons. Kanner and Harris[5] looked for γ-radiation, delayed β's and positrons from this reaction and reported negative results. Ruhlig[6] concluded that there were no γ-rays from the reaction. The low energy group of protons which was expected from a corresponding excited state of H^3 has been investigated by Myers and Langer,[7] Hudspeth and Bonner,[8] and Myers, Huntoon, Shull and Crenshaw[9] and was not found. Schiff[10] and Share[11] independently concluded that a stable excited state of He^3 was inconsistent with the present theory.

In an attempt to clarify this situation, we have made a cloud-chamber study of the neutrons from the $d-d$ reaction.

APPARATUS

A 3-gap linear accelerating tube was used with a Crane type ion source. The high voltage was supplied by one 300-kv and two 115-kv x-ray transformers in a conventional cascade circuit. These transformers were rebuilt with new primary, and tertiary driver coils were added. A peak voltage of 630 kv above ground has been obtained with this arrangement, showing it to be a practical scheme for moderately high voltages. The addition of another transformer to this set caused a decrease in the output voltage. This decrease was doubtless due to the fact that one of the transformers became overloaded, thus causing the transformer cores to be saturated and the group to become seriously out of phase. Because of the large amount of corona at the higher voltages the tube was usually operated at about 300 to 400 kv.

For recoil proton measurements a movable piston type cloud chamber 15 cm in diameter and filled with methane was used.[12] The chamber was placed 25 cm from a heavy ice target. The chamber was placed so that a center line made an angle of 90° to the deuteron beam. Two guide wires making ±10° angles to the 90° line were placed on the chamber top plate to facilitate angular measurements. The chamber was illuminated over its depth of 3.5 cm by two 1000-watt projection bulbs. A weak α-particle source of polonium on a silver wire was mounted inside the chamber for constant calibration of the stopping power of the methane and alcohol mixture. A Sept camera making stereoscopic views on each frame by means of a mirror and direct image was used. Transformers, ion source,

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[1] T. W. Bonner, Phys. Rev. **53**, 711 (1938).

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[3] E. Hudspeth and H. Dunlap, Phys. Rev. **55**, 587 (1939).

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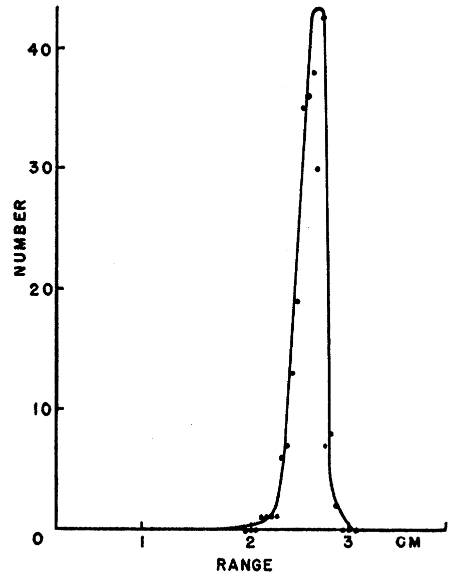

FIG. 1. Number-range curve for polonium alpha-particles from chamber calibrating source.

lights, cloud chamber expansion and camera were synchronized by a cam mechanism. This mechanism was adjusted so that good tracks could be photographed every 30 seconds. For reprojecting the pictures the camera assembly was mounted on a lathe bed equipped with a movable ground glass screen and inverted mirror. This arrangement allowed the tracks to be viewed stereoscopically.

An ionization chamber and linear amplifier were used to measure the intensity of neutrons scattered from the walls of the room. The ionization chamber consisted of a brass cylinder 5.5 cm in diameter and 12 cm long with a central collecting rod connected to the grid of the first stage of the amplifier. A paraffin disk 0.5 cm thick was placed in the end of the ionization chamber and recoil protons from the paraffin were measured. With the chamber filled with argon this arrangement was essentially directional because the pulses produced by recoil argon nuclei were very small and were indistinguishable from the background on the base line. Thus neutrons included in a solid angle of a little less than 2π could be detected. By pointing the ionization chamber directly away from the heavy ice target in the accelerating tube a measure of the neutrons scattered from the walls of the room could be obtained. A record of the pulses from the amplifier was made on 35-mm film in a magnetic oscillograph made from a permanent magnet dynamic speaker unit. The moving mirror was attached by a light rod to the voice coil of the speaker unit. This oscillograph was designed and built by Mr. William Hurst of the Duke University Instrument Shop.

MEASUREMENTS

About 1800 pairs of stereoscopic cloud-chamber pictures were examined. These pictures were taken with a deuteron beam at about 300 kv. Only tracks which started and stopped in the gas and which appeared to be due to neutrons coming from the target were accepted. This selection actually favors short tracks but no correction was made for this. The projected lengths of the tracks in the plane of the cloud chamber were noted and the angle θ (in the plane of the chamber) between the direction of the recoil proton and the incident neutron direction was measured. The majority of the accepted tracks had the angle $\theta < 35°$. The angle ϕ between the recoil proton track and the plane of the chamber was estimated visually in eleven of the 126 measured tracks. In the case of the remaining 115 tracks the angle ϕ was close to zero degrees. The actual length of a track is then $L/\cos\phi$ where L is the measured projected length. The reason for choosing such a small number of tracks which made appreciable angles with the plane of the chamber was that the criterion that the tracks had to start and stop in the chamber had to be satisfied. The cosine of the actual angle between a recoil proton and the incident neutron is easily seen to be $\cos\beta = \cos\theta\cos\phi$.

The lengths of α-particle tracks from the calibrating source were measured only when they were sensibly in the plane of the chamber. Whenever possible an α-track was measured in the frame where a measurable recoil proton was found. Fig. 1 is a plot of number as a function of the measured range of the polonium α-particles from the chamber calibrating source. The small spread in the range of the α-particles measured shows that the stopping power of the gas remained essentially constant throughout the experiment.

In order to calculate the energy of the neutrons the α-particle extrapolated range was taken from an integral curve to be 2.76 cm in our chamber. The stopping power of methane for 3.805 cm α-particles is 0.903 (relative to air) and hence the expected range in methane at 1 atmosphere is $3.805/0.903=4.21$ cm. Using mean ranges, one obtains the pressure of $4.21/2.73=1.55$ atmospheres. All proton tracks were reduced to actual lengths at one atmosphere of methane and then corrected to lengths at one atmosphere of air. Next the range-energy relation was applied and these energies were divided by $\cos^2\beta$ to give the energies of the neutrons, under the assumption that all recoil protons were due to neutrons whose direction was at 90° to the deuteron beam. In general the neutrons responsible for the recoil protons measured in the cloud chamber were not exactly perpendicular to the deuteron beam. The error thus introduced is unimportant for our purposes, as the presence of neutrons coming into the chamber at an appreciable angle would only tend to increase the number of short tracks measured in the specified direction. Consequently no corrections for it have been made.

The directional ionization chamber and linear amplifier were used to make a rough determination of the importance of neutrons scattered from the walls of the room. With the chamber pointed directly at the target and at a distance of 30 cm a counting rate of 60 counts/min. was observed. With the chamber directed away from the target and pointed at an 8-inch brick wall 70 cm from the target the counting rate was 3 counts/min. Since the beam current was fairly constant and the measurements were made under continuous operating conditions, it is estimated that the scattering measured was about 5 percent of the direct neutron beam. Because the wall 2.6 meters opposite this brick wall is a hollow tile wall from which the scattering is less it is estimated that the total scattering from all directions is something less than 10 percent of the number of neutrons coming from the target. The background count of 0.5 count/min. was taken with a deuteron beam and the whole apparatus running, the target being replaced by a clean aluminum plate. The background count of the ionization chamber when measured with the deuteron source off was also about 0.5 count/min., indicating that practically all neutrons originated at the target.

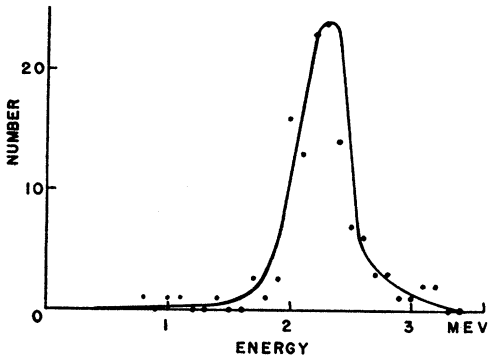

FIG. 2. Energy distribution of neutrons from the $d-d$ reaction. There is no evidence of a low energy group.

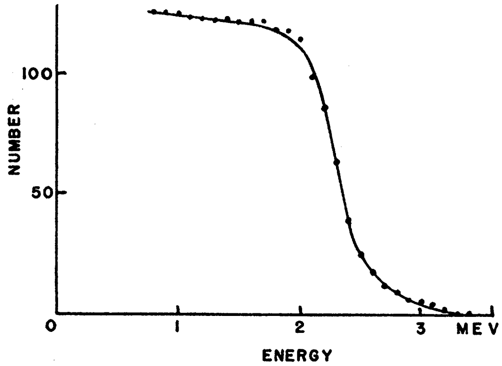

FIG. 3. Number of neutrons having energies greater than integral number-energy curve for the neutrons from the $d-d$ reaction.

RESULTS

A distribution curve of the neutron energies is plotted in Fig. 2. These energies were calculated as previously described. The most significant point about this curve is the lack of any indication of a low energy group of neutrons and consequently the absence of any evidence for the existence of an excited state of He^3. This conclusion is in agreement with the recent findings of Hudspeth and Dunlap.[13]

Because of the selection of tracks in the cloud chamber which satisfied certain conditions as to direction it is rather clear that less than 10 percent of those tracks measured were due to neutrons scattered from the walls of the room.

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From our ionization chamber measurements with the target replaced by a clean aluminum plate we conclude that the only source of neutrons in the accelerating tube was the target itself. It is conceivable, however, that with some experimental arrangements the scattering from the walls of the room might play an important role. It is also well known that in certain accelerating tubes an appreciable number of neutrons may be created at points other than the target. We feel that a low energy group of neutrons whose intensity amounts to as much as 10 percent of the main group should be evident in Fig. 2 if it exists.

We do not believe that the data presented here are sufficient to warrant a precise determination of the energy evolved in the $d-d$ reaction. We have, however, plotted an integral number-energy curve in Fig. 3. The extrapolation of this curve gives an energy of about 2.8 Mev for the neutron energy, corresponding to an extrapolated range of about 10.9 cm for the recoil protons. This agreement with Bonner's extrapolated range of 10.6 cm is satisfactory.

We wish to express our appreciation for the generous cooperation of various members of the staff in this work.

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Note on a Field Theory of Nuclear Forces*

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An interaction between nuclear particles and a field of light particles which obey Fermi-Dirac statistics is considered. It is shown that the energy of interaction between heavy and light particles can be calculated without resorting to perturbation theory in an approximation which neglects electric forces and the kinetic reaction of the heavy particles. Results which contain the effect of the rest mass of the field particles are presented for one heavy particle and for two heavy particles.

It is the purpose of this note to extend the method which has been applied to the electron-positron-field theory of nuclear forces[1] to take account of effects dependent on the rest mass of the field particles. In the previous theory, the rest mass of the light particles was negligible. If the light particle field be that of mesons which obey Fermi-Dirac statistics, however, it is necessary to take the rest mass (~ 180 electron masses) into account, even in the approximation which neglects electric forces and the recoil of the heavy particles. The method which we present may then be used, for example, to derive the nuclear forces due to the meson-field introduced by Marshak,[2] without the use of perturbation theory.

The fundamental assumptions of the present method are (I) a heavy particle (neutron or proton) interacts strongly with a light particle (meson) if the light particle occupies a state of one particular space-dependence, $u(\mathbf{x})$, but does not influence the energy of mesons in any orthogonal state; (II) the state of the heavy particle is not changed by the interaction. Both assumptions require a nonrelativistic treatment of the heavy particle and permit the simplified device of fixing a heavy particle at the origin of the coordinate system and investigating its effect on the light particle states. Condition (II) must be changed to exclude spin direction if

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