Letters to the Editor

Neutron Spectra in the Bombardment of Tritium and Deuterium by 14 mev Deuterons*

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IN preceding articles by the authors[1] and by others[2], a maximum in the cross section for the reaction $T(p,n)He^3$ was observed at proton energies of 3 mev, indicating the existence of a broad excited level of He^4 at 22 mev. In the present work an attempt was made to verify the existence of this level by investigating the neutron spectrum from the reaction $T(d,n)He^4$. Because of the existence of the level, the energy of the reaction may have, as well as the well-known value Q_0 = 17.6 mev, a second value $Q_1 = -4.4$ mev, corresponding to formation of He^4 in the excited state. Although this state of He^4 is unstable with respect to decay into $He^3 + n$ or $T + p$, a more or less compact group should be observed in the neutron spectrum corresponding to the second value of Q. The present work is devoted to the search for this group.

This work was carried out in a cyclotron, the beam of which was extracted from the chamber and focussed by a magnetic prism at a distance of 12 m from the cyclotron.

The spectra were investigated by means of a time-of-flight apparatus. The natural modulations of the cyclotron were used. The acceleration of ions in the cyclotron occurs in a narrow interval of the phase of the accelerating voltage; therefore the ions fall on the target in short pulses. According to our observations, the length of a pulse on the target does not exceed 5 mμ sec (5 $\times 10^{-9}$ sec). The frequency of the accelerating voltage is 8.9 mc; consequently, the period of pulse repetition of particles is 112 mμ sec. Neutrons were registered by a fast scintillation counter consisting of a specimen of solid solution of terphenyl in polystyrene and a photomultiplier. Pulses from the photomultiplier were shaped by a shorted cable 30 cm long (after which they had a duration of $\sim$ 3 mμ sec) and were fed to a germanium diode coincidence circuit. The second channel of the coincidence system received pulses of the same duration, synchronized with the accelerating voltage of the cyclotron. In this fashion the coincidence circuit registered the pulses of the counter, arising at some definite phase of the accelerating voltage. The value of this phase was changed by changing the length of cable in one of the lines of the coincidence system, as a result of which γ-rays or neutrons, having various times-of-flight from target to counter, were registered. The instant that the charged particles impinge on the target, that is, the instant of neutron production, was defined by the position of the peak of γ-rays, produced in the target as a result of various nuclear reactions; therefore there was no necessity for a special phasing of the system.

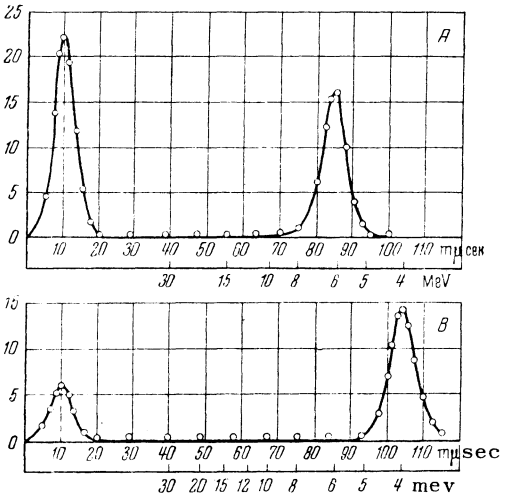

FIG. 1 Distribution with time of counter pulses in the bombardment of a tritium-zirconium target by protons. *A* corresponds to E_p = 7.1 mev, *B* to E_p = 4.9 mev.

In all measurements the neutron counter was placed in the direction of the beam of charged particles, that is, at an angle of 0°.

Figure 1 shows the distribution in time of the counters pulses, registering radiation from a tritium-zirconium target, bombarded by protons of energy 7.1 mev (curve *A*) and 4.9 mev (curve *B*). The curves were taken with the counter 2.9 m from the target. The first peak at t = 10 mμ sec came from γ-rays, accompanying the reaction in zirconium. They were observed both from the target (tritium + zirconium) and from the unmounted backing-container (zirconium only). The second peak was brought about by neutrons from the reaction $T(p,n)He^3$. Upon decreasing the proton energy from 7.1

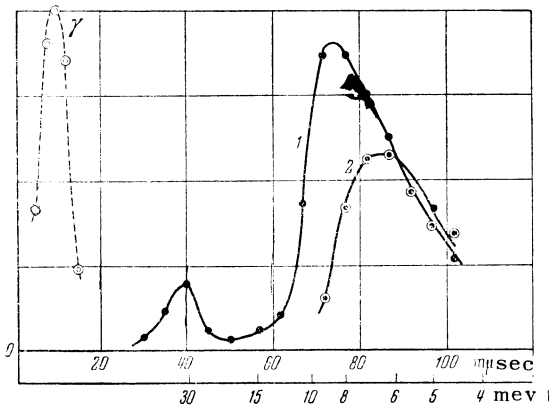

FIG. 2. Spectrum of neutrons in the bombardment of tritium by deuterons of energy: 1, 14.4 mev; 2, 12.4 mev. The γ-ray peak is displayed.

to 4.9 mev the energy of neutrons decreased from 6.3 to 4.1 mev and their time-of-flight increased; therefore, the peak was displaced to the right to a larger value of t. The width of the γ-peak is defined by the resolution of the system and is made up of the widths of pulses of the counter, of the master pulse and of the interval of working phase of the accelerating voltage of the cyclotron. The width of the neutron peak is somewhat larger; in the target 7 mev protons lose 0.5 mev and, consequently, the neutrons have approximately the same spread in energy.

The spectrum of neutrons from the bombardment of tritium by 14.4 mev deuterons is shown on Fig. 2. It is obtained at a distance of the counter from the target of 3 m, employing the same tritium-zirconium target. On the same figure is displayed the γ-peak, the magnitude of which is the same with the target and for the empty container is the same. The peak at $t = 40$ mμ sec is formed by neutrons of energy ~ 30 mev, corresponding to $Q_0 = 17.6$ mev in the reaction $T(d,n)He^4$, that is, to the formation of He^4 in the ground state. The wide peak with maximum at $t = 75$ mμ sec is formed by neutrons of mean energy ~ 8 mev. This neutron energy corresponds to the energy of the reaction $T(d,n)He^4$, $Q_1 = -5$mev. Reduction of the deuteron energy (by means of a platinum foil) to 12.4 mev leads to a displacement of the neutron group (see Fig. 2), agreeing with the value $Q_1 = -5$mev.

The curves (Figs 2 and 3) are corrected for the dependence of the efficiency of the detector on the neutron energy. It is assumed that this dependence has the form $\epsilon \sim \sigma(1 - B/E)$, where σ is the cross section of n-p scattering, E the energy of neutrons and B the threshold of the detector, which is defined by comparison of the observed intensities in the reaction $T(p,n)He^3$ of the neutron groups for

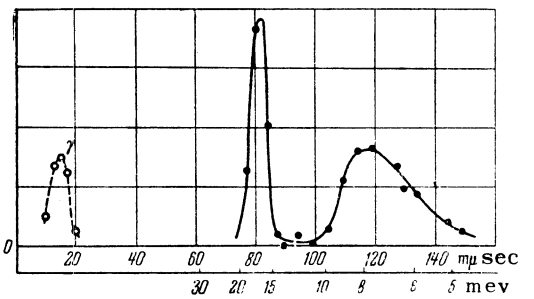

FIG. 3. Spectrum of neutrons in the bombardment of deuterium by deuterons of energy 13.0 mev. The γ-ray peak is displayed.

two values of the energies of protons with intensities known from excitation curves[1]. In the region of energy studied, the efficiency was several per cent with thicknesses of the phosphor of 16 mm.

These results might be considered as a confirmation of the existence of a broad excited level of He^4 at ~ 22 mev. It should be noted, however, that the production of neutrons in the bombardment of tritium by deuterons is possible also in the reactions $T(d, pn)T$ and $T(d, 2n)He^3$. There is not enough basis to deny the possibility of production of the observed neutron groups in one of these reactions. To resolve this question, further experiments and calculations are necessary.

One such experiment has been carried out. It consisted in the investigation of the spectrum of neutrons produced in bombarding deuterium by deuterons of energy 13.0 mev. A gas target was used, in which the pressure of the deuterium was 3 atm, and the thickness (length along the deuteron beam) was 4 cm. The same target without gas was used as an 'empty target'. The results of the experiment are shown on Fig. 3. The distance from the target to the counter was 4.5 m. The peak at $t = 80$ mμ sec was formed by 16 mev neutrons, corresponding to $Q = 3.3$ mev in the reaction $D(d,n)He^3$. Besides this group, a second wide group of slower neutrons is visible. The maximum of intensity of this group corresponds to $t = 115$ mμ sec and, consequently, to an energy of 8.0 mev. These neutrons could be produced in the reaction $D(d,pn)D$, or by disintegration of both deuterons, or, finally, in the reaction $D(d,n)He^3$ with formation of He^3 in an excited state. In the last case $Q_1 = -3.5$ mev, which corresponds to an energy of ~ 7 mev of excited He^3.

The similarity of the spectra in the two reactions supports the fact that the second group of neutrons is produced rather by the breakup of the deuteron than by the ordinary reaction with formation of a final nucleus (He^4 or He^3) in an excited state.

Whatever the mechanism is, its large probability should be noted. Comparing the intensities of the

neutron groups and taking into account the behavior of the detector efficiency with energy, it is possible to say that the cross section of production of a neutron of the second group at 0°, relative to the deuteron beam in the case T + d(E_d = 14.4 mev) is approximately 300 millibarn/sterad, and, in the case D + d(E_d = 13.0 mev), 100 millibarn/sterad.

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[2] H. B. Willard, T. K. Baira and J. D. Kington, Phys. Rev. **90**, 865 (1953).

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Gamma and Photoluminescence Yields in Organic Crystals

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THE spectrum of luminescence due to gamma ray excitation coincides with the spectrum of photoluminescence [1]. This means that the last step in the process of the excitation of gamma luminescence is the transition from the same excited state that is involved in photoexcitation. Therefore, the energy yield for gamma luminescence can be represented as $B_\gamma = \rho B_\phi^q$, where B_ϕ^q is the absolute quantum yield of photoluminescence, depending on the correlation between the transitions with and without radiation; ρ can be called the effectiveness of the excitation. The magnitude of ρ shows what fraction of the energy absorbed in the substance is used for the excitation of the molecules which are effective in luminescence.

The aim of the present paper was to see if the magnitude of ρ is the same or differs appreciably for a number of substances. For this purpose the relative yields during gamma and photoexcitations were measured. Aromatic carbohydrates in the shape of monocrystals (dimensions $1.5 \times 1.2 \times 0.7$ cm^3) were investigated, and for comparison purposes the alkali-halide crystals NaI and KI, activated by Tl. Co^{60} was used as the source of gamma rays.

During the gamma excitation the amounts of energy absorbed in the crystals were determined from the relative absorption coefficients of gamma rays. As is known, during the passage of gamma rays through the substance the electrons are freed, and these electrons cause luminescence. The absorption of gamma rays with an energy of the order of 1 mev in organic substances takes place at the expense of the formation of Compton electrons; in NaI and KI crystals the probability for the Compton effect is 95% and the remaining 5% are due to the photoeffect. The probability of the Compton effect is proportional to the number of electrons; the number of electrons in P grams of the substance is $(PZ/M)N$, where Z is the number of electrons in a molecule, M – molecular weight, N – Avogadro's number.

Relative yields for gamma excitation were measured by two methods: a) by the observation of the average intensity of luminescence, b) by the observation of individual scintillations. For the measurement of the average intensity of luminescence, the crystal was placed in a photometric sphere which was covered on the inside with MgO. The light of the luminescence, excited in the crystal by gamma rays, went through an opening in the sphere and was incident on the window of the photomultiplier FEU-19. The values obtained for the photocurrent were divided by $(PZ/M)N$. A scintillation counter with an integral discriminator was used for the determination of the relative magnitude of the scintillations. For a comparison of the magnitude of the impulses it is necessary to reduce the distribution curves to such a scale that the total number of impulses contributing be the same; for this reason the ordinates of each curve were divided by $(PZ/M)N$. For the comparison of the relative magnitudes of the impulses the method of constant counting rates was used, i.e., the magnitudes of the displacements were compared, when the counting rate was the same for different crystals.

Measurements of the relative yields of photoluminescence were made during excitation by the 254 mμ line. This line was separated from the light emitted by the PRK-2 lamp by means of a monochromatic quartz and was focussed on the surface of the crystal which was placed in the photometric sphere. The sphere had two windows: one for the entrance of the excitation light, and one for the photomultiplier. The absorption of 254 mμ line in organic crystals is known to be complete,