Interaction of Protons with Tritium and the Excited State of He^4

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Experiments are described in which the reactions $T(pn)He^3$ and $T(p\gamma)He^4$ were investigated in the proton energy range up to 7 Mev. The energy of the protons in the beam emerging from the cyclotron chamber was varied by means of lead filters. An "all-wave" counter and a uranium chamber served as neutron detectors, while a scintillation counter with a crystal of NaI(Tl) was used as a γ-ray detector. The curve of $\sigma(E_p)$ for the first reaction has a maximum at $E_p = 3$ Mev. The cross section for the second reaction increases monotonically in the entire energyinterval. Angular distributions of the neutrons and the γ-rays were also investigated. The characteristics of the excited state of He^4 are discussed.

THE first indications of the existence of an excited state of He^4 were obtained in the work of Taschek and collaborators[1,2] in which it wasfound that the cross section for the reaction $T(pn)He^3$ increases monotonically in the proton energy range E_p from the threshold (1.019 Mev) to 2.8 Mev, and in which γ-rays with energy > 20 Mev, formed as a result of radiative capture of a proton by tritium, i.e., the reaction $T(p\gamma)He^4$ were observed. The absence of a horizontal portion in the curve of $\sigma(E_p)$ for the reaction $T(pn)He^3$ at energies higher than 1.5 - 2 Mev, exceeding the potential barrier, was explained by the existence of a resonance maximum of the cross section outside the energy range which was investigated, connected with an excited state of He^4. The discovery of γ-rays from the reaction $T(p\gamma)He^4$ and the increase in their yield with E_p were regarded as a confirmation of this hypothesis.

In order to observe the resonance with certainty and to decide the question as to the existence or non existence of an excited state of He^4, it was obviously necessary to investigate the cross sections for the reactions $T(pn)He^3$ and $T(p\gamma)He^4$ in a wider energy range. It was in this connection that the present investigation was undertaken. The main results were obtained early in 1953 and reported to the Academy of Sciences of the USSR in March of 1953. At this time only the short communication of Willard and Bair[3] was available, stating that the cross section for the reaction $T(pn)He^3$ increases monotonically up to $E_p = 5$ Mev. This was in contradiction to our results which indicated the existence of a cross section maximum at $E_p = 3$ Mev. Later, Willard, Bair and Kington[4] published a detailed report of their work giving results which are in satisfactory agreement with ours in the common energy interval.

The present paper contains a description of our experiments and gives the results obtained. Excitation curves of the reactions $T(pn)He^3$ and $T(p\gamma)He^4$ were investigated in the proton energy interval up to 7 Mev. For the first reaction the absolute value of the cross section was found, for the second only the lower limit of the cross section. The angular distribution of the neutrons was investigated for several values of E_p, as well as the angular distribution of the γ-rays at $E_p = 6.7$ Mev.

THE REACTION $T(pn)He^3$

For the investigation of the excitation curves a beam of protons was used which was brought out of the cyclotron and focused by means of a magnetic prism at a distance of 12 meters from the cyclotron chamber. The energy of the protons in the beam was determined by Rybakov[5] on the basis of their range in aluminum, using Smith's[6] curve and was found to be 7.3 ± .1 Mev.

Proton energy was varied by passing the beam through retarding filters of variable thickness. The filters were placed immediately in front of the target in order to minimize changes in intensity of the beam due to scattering in them. In order to minimize neutron background due to (p, n) reactions, lead, instead of aluminum, was used as

[1] G. A. Jarvis, A. Hemmendinger, H. V. Argo and R. E. Taschek, Phys. Rev. **79**, 929 (1950)

[2] H. V. Argo, H. T. Gittings, A. Hemmendinger, G. A. Jarvis and R. E. Taschek, Phys. Rev. **78**, 691(1950)

[3] H. B. Willard and J. K. Bair, Phys. Rev. **86**, 629 (1952)

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

[5] B. V. Rybakov, J. Exper. Theoret. Phys. USSR **28**, 651 (June, 1951); Soviet Phys. **1**, 435 (1955)

[6] J. H. Smith, Phys. Rev. **71**, 32 (1947)

filter material. The curve giving the dependence of proton energy on the thickness of the lead filter obtained by Rybakov[5] was used.

A zirconium foil saturated with tritium was used as target. The mean energy loss in the target for protons with energy of 7 Mev was 0.6 Mev; with decrease of mean proton energy it increased, reaching 1.1 Mev at $E_p = 3$ Mev. Because of this, the low energy end of the excitation curve was obtained under conditions of poor resolution in energy, and the maximum of neutron yield at angle of emergence $\theta = 0°$ with above-threshold proton energy was not observed. In Fig. 1 the energy spread of the proton beam passing through the target is represented by horizontal line segments about the points, Nevertheless, the width of the maximum sought was markedly greater than this instrumental width, and the shape of the curve obrained in our experiments in the region of the maximum and beyond is, apparently, not far from the true one.

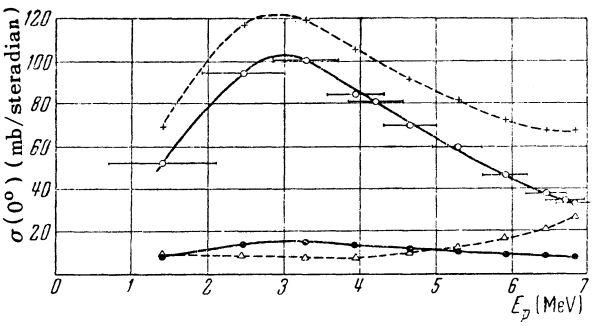

Fig. 1. Differential cross section for the reaction $T(pn)He^3$ at the angle of 0°. O $=\sigma(0°)$ for the reaction $T(pn)He^3$, + = target, Δ = control, ● = background of scattered neutrons.

In order to estimate the considerable neutron background due principally to (pn) reactions in zirconium, the measurements were made alternately with the tritium-zirconium target and with a zirconium target (without tritium) which will be referred to in what follows, for brevity, as the control. The zirconium foil on the control was of the same thickness as on the target. Subtracting the effect of the control from the effect due to the target gave, therefore, the effect due to the tritium. Change from target to control and vice versa was made very quickly by means of remote control mechanisms. A similar mechanism was used for changing filters, hence measurements under different conditions could be repeated many times and be alternated with each other without disconnecting the cyclotron and the measuring apparatus.

As the basic neutron detector, the "all-wave" counter described in reference 7 was used. A fission chamber with a layer of natural uranium was used as a control detector. The detector was attached to the remotely-controlled turntable and could be placed so as to make any angle θ with the proton beam from 0° to 140°.

The detector counts were related to a definite proton beam current which was measured by means of a current integrator. In order to exclude the distorting influence of electron emission from the target on measurements of proton current, the target was covered with a thin sheet of mica coated on both sides with a thin layer of aluminum. The front layer of aluminum (facing the beam) was grounded, while the rear layer was in contact with the target and together with it, was electrically insulated. This construction of the target results in a slight lowering of the initial energy of the protons because of slowing down in the mica (under our conditions 200 kev at $E = 7$ Mev), but is very simple and convenient to work with.

Figure 1 gives the curve showing the dependence of the differential cross section at $\theta = 0°$ on the energy of the protons (upper solid curve); it is based on the mean of several series of measurements. Dotted curves represent, to a corresponding scale, the magnitude of neutron flux from target and control. The absolute value of the cross section was found by means of special measurements of neutron flux by comparing it with the flux from a calibrated (with accuracy of 5%) Ra + Be source in the same position as the target. The amount of tritium in the target was known from the preparer's certificate and in addition was measured by a calorimetric method with accuracy of ±4%*. The two results coincided within the limits of experimental error. Errors in the absolute value of the differential cross section (±10%) result from errors in calibration of the Ra + Be source given above and the determinations of the amount of tritium in the target, as well as from errors in the measurements of proton flux (±2%). Statistical errors of all measurements did not exceed 1%.

In the adjustment of the results of measurements, it was assumed that the sensitivity of the all-wave detector was the same in the entire neutron

* The authors are grateful to A. I. Shal'nikov for the preparation of the target and to N. S. Shimanskaia for calorimetric measurements.

[7] A. O. Hanson and J. H. McKibben, Phys. Rev. 72, 673 (1947)

energy range (up to 6 Mev). Control measurements with a proportional counter telescope showed that the sensitivity of the "all-wave" counter to neutrons with energy of 4.4 and 6.3 Mev differs by not more than 10%. In addition, the excitation curve of the reaction under investigation was also determined by using the uranium fission chamber. After correcting for the energy dependence of the uranium fission cross section[8], satisfactory agreement was found between this curve and the curve obtained with the "all-wave" counter in the interval $2.5 < E_p < 7$ Mev. At $E_p < 2.5$ Mev the results of the comparison are less certain because of rapid variation in the uranium fission cross section.

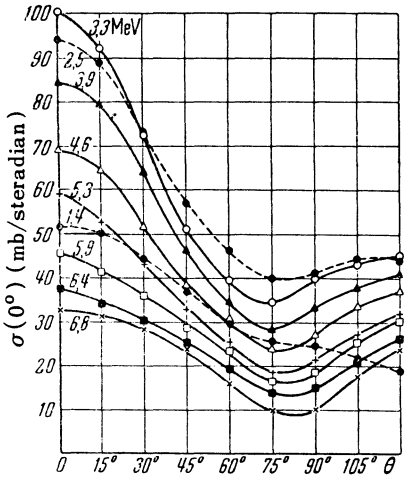

Fig. 2. Angular distribution of the neutrons in the reaction $T(pn)He^3$ in the laboratory coordinate system.

Figure 2 gives the results of the measurements of angular distribution of the neutrons for several values of proton energy. Each curve is the result of several series of measurements, the results of which were averaged. The values of the differential cross sections were found by means of a joining to the absolutized excitation curve for $\theta = 0$. In angular distribution measurements, besides the effect of the control, the background of neutrons scattered from the walls of the room was taken into account. For this prupose, a paraffin cone 40 cm long was placed between target and counter, the distance between which was 1 meter (to the front side of the counter). The direct flux of neutrons from the reaction under investigation for each value of the angle was calculated on the basis of four measurements, according to the formula

$$N(\theta) = M_0(\theta) - \Phi_0(\theta) + \Phi_к(\theta) - M_к(\theta),$$

where M_0 is the number of counts with target in the beam without the paraffin cone, Φ_0 the same with control but without the cone, M_k with target but without cone, Φ_k with control and cone. In order to give an idea of the relative values of these four quantities, Fig. 3 gives their angular distributions corresponding to $E_p = 7$ Mev. With large angles (greater than 130°) the background of scattered neutrons increases greatly; therefore, the results in this region are less depdedable than with $\theta < 130°$.

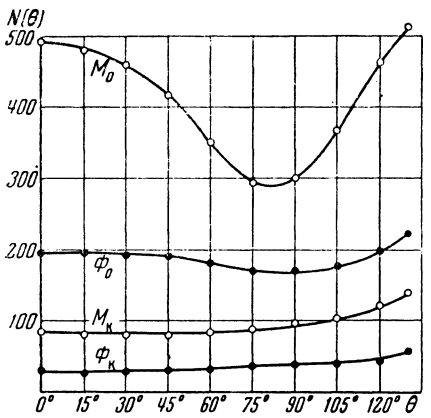

Fig. 3. Relative values of the quantities $M_0(\theta)$, $\Phi_0(\theta)$, $\Phi_k(\theta)$ and $M_k(\theta)$ for $E_p = 7$ Mev in the laboratory coordinate system.

Figure 4 gives the differential cross sections reduced to the center of mass system. The curves were represented in the form of polynomials:

$$N(\vartheta) = A + B\cos\vartheta + C\cos^2\vartheta + D\cos^3\vartheta + E\cos^4\vartheta,$$

whose coefficients were found by the method of least squares from the experimental points for θ from 0° to 120° (θ is the angle in the center of mass system). Figure 5 gives the dependence of the coefficients on the proton energy. By integrating the polynomials the total reaction cross section for the reaction $T(pn)He^3$ was obtained for each value of E_p. Figure 6 gives the dependence of the total cross section on E_p.

Measurements were also made of the spectrum of neutrons emerging from the tritium-zirconium

[8] Canad. J. Phys. **29**, 204 (1951)

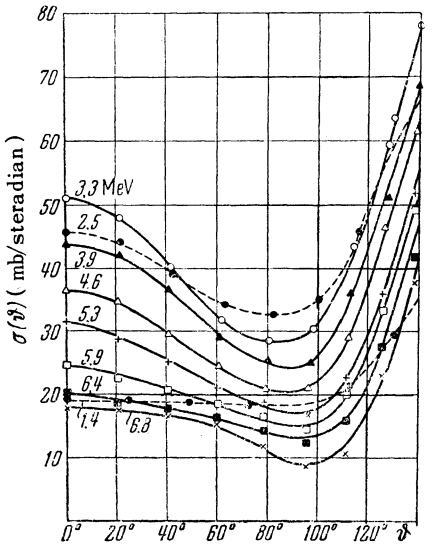

Fig. 4. Angular distribution of the neutrons in the reaction $T(pn)He^3$ in the center-of-mass system.

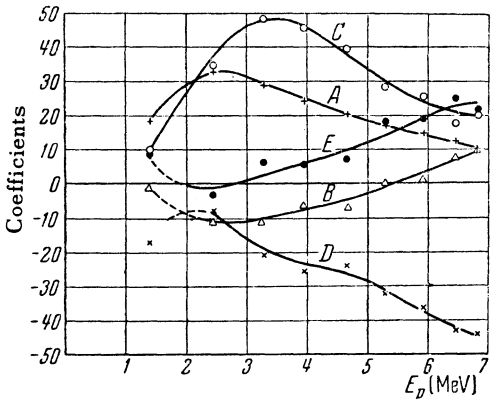

Fig. 5. Coefficients of the expansion: $\sigma(\vartheta) = A + B\cos\vartheta + C\cos^2\vartheta + D\cos^3\vartheta + E\cos^4\vartheta$

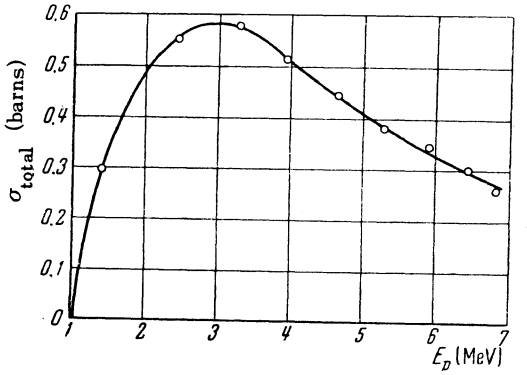

Fig. 6. Total cross section for the reaction $T(pn)He^3$.

target by means of the proportional counter telescope. The measurements were made with $\theta = 0°$ at $E_p = 7.1$ and 5.2 Mev. The telescope consisted of three counters. The first two were in coincidence, while the third was in anticoincidence with respect to the first two. Recoil protons, knocked forward at a narrow angle from a paraffin radiator 10.4 mg/cm^2 thick, were slowed down in aluminum filters of variable thickness placed beyond the radiator. Simultaneously, the number of coincidences and of the anticoincidences were recorded as a function of filter thickness. Passage from filter thickness to energy of recoil proton, equal to energy of neutron, was made with the aid of Smith's [6] curve, referred to above. The number of recoil protons in the energy interval ΔE, depending on the thickness of the filter between the second and third counter, is equal to the number of anticoincidences. Under our conditions, $\Delta E = 650$ kev at $E_n = 6$ Mev. Figure 7 gives the dependence of the numbers of coincidences and anticoincidences on neutron energy, estimated from filter thickness. The curve of anticoincidences with a maximum at $E = 6$ Mev represents the spectrum of the neutrons. The width of the maximum depends not only on the scatter of neutrons in energy, but also on the resolving power of the telescope. The natural line width of the telescope calculated from geometrical conditions and the thicknesses of radiator and absorber between second and third counters was .85 Mev (at half-height), while the observed width was 1.0 Mev. The small number of anticoincidences at $E_n < 5$ Mev is due, apparently, chiefly to the geometrical imperfection of the telescope, and, to a lesser extent, to scattered neutrons.

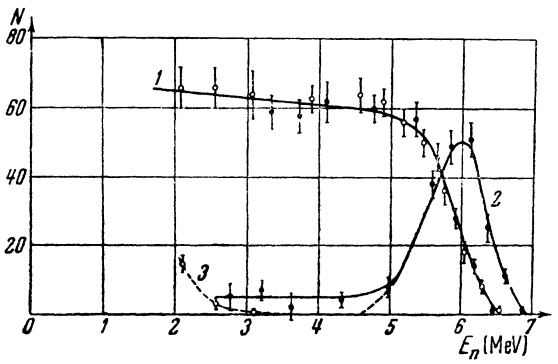

Fig. 7. Neutron spectrum in the reaction $T(pn)He^3$ at $E_p = 7.1$ Mev. *1.* Integral spectrum (coincidences), *2.* Differential spectrum (anticoincidences).

These measurements indicate that a monochromatic group of neutrons is emitted from the target with mean energy of 6 Mev, which coincides with the calculated value, if one uses proton energy of 7.1 Mev and reaction energy $Q = -.764$ Mev. If other groups of neutrons are formed in this reaction, the probability of their formation must be relatively small. When the zirconium control is placed in the beam of protons, recoil protons in the telescope are observed only with energy less than 3 Mev (dotted curve in Fig. 7). This indicates that neutrons formed in (pn) reactions in zirconium have energy less than 3 Mev.

Analogous results were obtianed also at $E_p = 5.2$ Mev. In this case the maximum of the neutron spectrum corresponds to an energy of 4 Mev.

Using the known values of scattering cross sections of neutrons on protons[9] and knowing the known geometrical parameters of the telescope, it is possible to calculate the absolute intensity of the flux of neutrons of the main group, and hence the absolute value of the differential cross section of the reaction $T(pn)He^3$ at the angle $\theta = 0$. Measurements of the proton current in this experiment were made by the same methods as in the preceding ones. The values of the cross section calculated in this way are in satisfactory agreement with values obtained by comparison of the neutron flux from the target with the flux from the Ra + Be source with the aid of the all-wave counter.

REACTION $T(p\gamma)He^4$

Studies of the reaction $T(p\gamma)He^4$ were made following the same procedure as described above, except that a scintillation counter with a NaI(Tl) crystal and FEU-19 photomultiplier was used as a γ-ray detector. It was known[2], and confirmed by our very first experiments, that the intensity of γ-rays is low, and hence to register them a highly effective detector is necessary. In addition, in our experimental conditions, an intensive background of γ-rays was present around the target, due to reactions and radioactivity produced by protons and neutrons. It is possible to eliminate this background, using the fact that the γ-rays in question have energy not less than 20 Mev, while the background γ-rays have a markedly lower energy. For this a detector-spectrometer is necessary, which can make an energy analysis of the γ-rays. It was because of these considerations that the crystal of NaI(Tl) was chosen as detector. The counter pulses were registered by an 8-channel pulse height analyzer adapted for switching the working interval into different regions of the spectrum. The crystal had the form of a rectangular prism about 4 cm high and with a 2×2 cm cross section. It was placed directly on the photomultiplier column and was coated with a layer of magnesium oxide. Optical contact between the crystal and the FEU was made by means of a layer of oil.

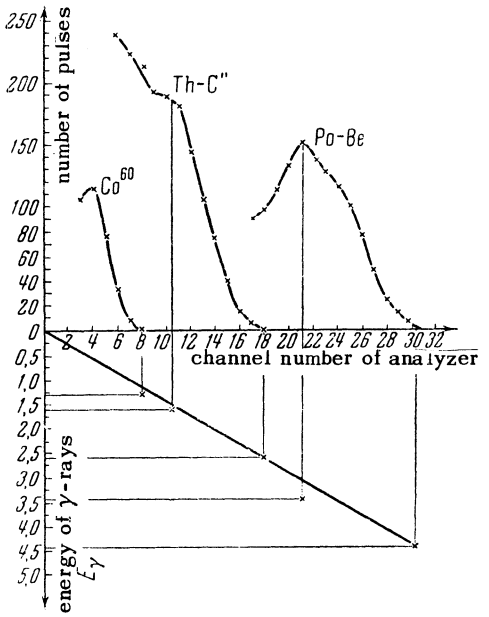

Fig. 8. Spectral characteristics of the γ-ray detector.

The spectrometric properties of our detector are represented by the curves of Fig. 8, which give the differential spectra of the pulses produced by γ-rays of Co^{60} (1.3 Mev), ThC'' (2.6 Mev) and C^{12*} (4.4 Mev, Po + Be source). The curves do not show distinct peaks corresponding to photoelectrons, Compton-electrons or pairs, formed in the crystal, but the limits of the spectra are rather sharp. If the pulse heights corresponding to them are taken as proportional to the total energy of the quanta, the dependence of the pulse height on energy turns out to be linear. This dependence is pictured in the lower part of Fig. 8. If the upper limit of the spectrum of γ-rays from the target is regarded as being due to the γ-rays of the reaction $T(p\gamma)He^4$ whose energy should be equal to 25 Mev, and the corresponding point be plotted in the lower half of Fig. 8, it is

[9] C. Bailey, W. Bennett, T. Bergstralh, R. Nukkols, H. Richards and J. Williams, Phys. Rev. 70, 583 (1946)

found to fall satisfactorily on the straight line through the other points. This indicates that high pulses in the counter were actually produced by γ-rays from the reaction $T(p\gamma)He^4$. It is to be remarked that in order to maintain the linear relation between spectral limit and γ-ray energy it was necessary to increase the potential difference between the last dynodes of the multiplier. With a uniform distribution of potential between dynodes, the linearity was not maintained, and this occurred the sooner, the higher the total voltage.

It is clear that if one registers only the high pulses it is possible to separate out the γ-rays sought. In fact, experiments showed that with a discrimination level corresponding to γ-ray energy exceeding 15 Mev, the background from the zirconium control remained low. Hence during all measurements the analyzer was tuned for the energy interval from 14 to 25 Mev. Spectra of the pulses from target and control at $E_p = 6.8$ Mev and 5.7 Mev are given in Fig. 9.

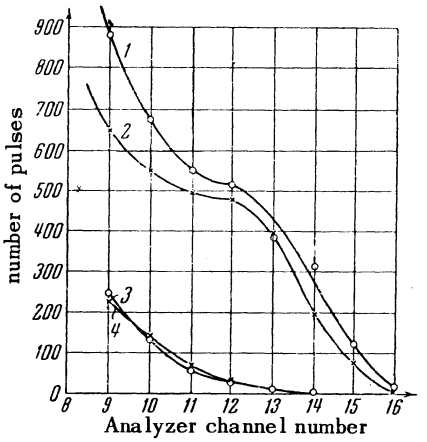

Fig. 9. Detector pulse spectra from target γ-rays. *1.* $E_p = 6.8$; *2.* $E_p = 5.7$ Mev; *3.* background of γ-rays from the control; $E_p = 6.8$; *4.* the same, $E_p = 5.7$ Mev.

The excitation curve for the reaction $T(p\gamma)He^4$ was taken as follows. The counter was placed at an angle $\theta = 90°$ to the proton beam at a distance of 50 cm from the target, and the number of counts was recorded in each of the eight channels of the analyzer, at the maximum proton energy and one of the lower energies in turn. In this way the intensities of the γ-ray flux at $\theta = 90°$ and various energies of bombarding protons were compared with the intensity at $E_p = 6.8$ Mev. This method of making the measurements was necessary in order to exclude the effect of detector instability. All counts, as in the experiments described above, were related to a definite proton current measured with an integrator.

Passage from the number of counts to γ-ray intensity is complicated by the circumstance that γ-ray energy varies with proton energy. As a result the limits of pulse spectra are displaced toward the region of smaller pulse heights with decreasing proton energy. The results of our experiments showed that the displacement of spectral limit is correlated with change of γ-ray energy calculated according to the formula

$$E_\gamma + \frac{E_\gamma^2}{2M_{He}c^2} = Q + \frac{M_t}{M_t + M_p} E_p,$$

where M_{He}, M_t and M_p are the masses of He^4, T and H^1 and $Q = 19.8$ Mev is the binding energy of the proton in He^4. Since the pulse spectra have neither a maximum nor even a clearly defined plateau, it would be incorrect to regard the intensity of the γ-rays as proportional to the number of counts in a given channel of the analyzer at any proton energy. Therefore, in order to determine the ratios of γ-ray intensity at two values of E_p, we calculated the ratios of the spectrum areas bounded on the left by ordinates proportionally distant from the upper limit. Depending on the magnitude of the portion of the proportionally cut out areas these ratios fluctuated about a mean value, which was taken as the true one. This method of reduction assumes similarity of spectra at all values of E_p. Absence of systematic variation of the ratios studied with increase of portions compared confirms this supposition.

Ratios of areas obtained in this way are not, in general, equal to the ratio of intensities of the γ-rays at corresponding E_p, since, first, the probability of absorption of the quantum in the crystal, and second, the probability of complete slowing down in the crystal of electrons produced by the quantum in the crystal, both depend on the energy of the γ-rays. But since these effects have opposite sign and, in our conditions, are small and approximately equal in magnitude, the ratios of areas were taken to be equal to the ratios of intensities.

Figure 10 gives the dependence of the intensity of γ-rays at the angle of 90° on proton energy, obtained in this way. As is shown below, the angular distribution of γ-rays varies little in the entire interval of E_p under investigation. Hence it can be assumed that the total reaction cross section for $T(p\gamma)He^4$ varies similarly.

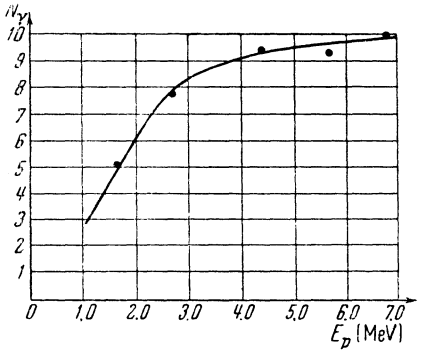

Fig. 10. Relative yield of γ-rays N_γ in the reaction $T(p\gamma)He^4$ at angle of 90° as a function of proton energy E_p.

To determine the absolute value of the effective cross section of the reaction on the basis of the available data is impossible. One can estimate only the lower bound of the cross section by the following method. The pulse spectra from the γ-rays of the target have a slight shelf not far from the limit. If one drops an ordinate from the middle of the shelf and assumes that the total number of pairs formed in the crystal is given by twice the area to the right of the ordinate, then, using this number and knowing the cross section for pair formation as well as the flux of protons to the target and the amount of tritium in it, it is possible to calculate the differential cross section of the reaction $T(p\gamma)He^4$ for the angle of 90°. It is obvious that the area of the spectrum bounded in this way does not include all pairs formed in the crystal, since pairs with nonsymmetrically distributed energy have a greater probability to carry off out of the crystal part of the energy, and give a pulse markedly lass than maximal. Hence the calculated value of the cross section is only a lower bound. For $E_p = 6.8$ Mev the value $\sigma(90°) > 0.006$ mb/steradian was obtained.

Taking the angular distribution of the γ-rays to have the form $\sigma(\theta) = \sin^2\theta + 0.05$, we obtain as the lower bound of the total cross section $\sigma_{total} > 0.04$ mbn. These results are in agreement with those of Perry and Bame[10], obtained with $E_p < 4.3$ Mev. The angular distribution of γ-quanta was not systematically investigated at all angles, since the construction of the target was such that the flux of γ-rays was diminished differently (up to 40%) in different directions due to variable thicknesses of material. It is impossible to obtain a dependable estimate of this decrease by calculation. Hence, in order to check the angular distribution, we carried out a comparison of the γ-ray intensities for several pairs of angles relative to which the target could be placed symmetrically. Thus, e.g., in order to compare the intensities at 0° and 90°, the target was placed at 45° to the proton beam; hence equal thicknesses of material were in the path of the γ-rays in both directions. The comparison was made for the following pairs of angles: 0 - 90°, 0 - 30°, 0 - 60° with maximal energy of protons.

The angular distribution of γ-rays at lower proton energies was investigated previously[2]. It was found to have the form

$$\sigma(\theta) = \sin^2\theta + a,$$

where $a = 0.11$ at $E_p = 1.52$ Mev and $a = 0.09$ at $E_p = 2.16$ Mev. We assumed that it has the same form also at high E_p, and compared the results of intensity measurements at each pair of angles, finding the suitable value of a from the relation

$$a = \frac{I_1 \sin^2\theta_2 - I_2 \sin^2\theta_1}{I_2 - I_1}.$$

For the various pairs of angles the following values were obtained:

$$\theta = 0 - 90°, \quad a = 0.06;$$
$$\theta = 0 - 60°, \quad a = 0.04;$$
$$\theta = 0 - 30°, \quad a = 0.03.$$

Although the scatter of the values of a obtained is rather large, which is natural since the result depends on the difference of two quantities of the same order of magnitude, nevertheless, these results indicate that the given formula satisfactorily describes the angular distribution of the γ-quanta at $E_p = 6.8$ Mev. The value of the quantity a is most reliably found from a comparison of the intensities ot 0° and 90°. The measurements for this pair of angles were made with greater care than for other angles; hence for the quantity a at $E_p = 6.8$ Mev the value $a = 0.05$ can be taken.

Measurements at 120° showed that the distribution is approximately symmetrical relative to the 90° direction. In comparing intensity at 120° with intensities at smaller angles, the absorption of γ-rays in the details of the target was taken into account. In reducing the results of angular

[10] J. E. Perry and S. J. Bame, Phys. Rev. **90**, 380 (1953)

distribution measurements, the displacement of the spectra was not taken into account, since the energy of the γ-quanta varies comparatively little with angle of emission.

DISCUSSION OF RESULTS

The curve giving the dependence of the cross section on proton energy, for the reaction $T(pn)He^3$, has a broad maximum at $E_p = 3$ Mev. (cf. Fig. 6). The width of the maximum is markedly greater than the instrumental width due to measuring apparatus. In reference 4 a similar curve was obtained in the energy range up to 5 Mev under better conditions of resolution in energy. The results of this paper (reference 4) are more accurate at low energy. In the region of the maximum and beyond they agree satisfactorily with ours in respect to both the absolute value of σ and its variation with energy.

In spite of the large width of the maximum, the shape of the curve $\sigma(E_p)$ indicates a resonance in the reaction, connected with an excited state of He^4. The position of the resonance and the energy of the level cannot be determined with high accuracy for two reasons. First, the level is very broad, and second, besides the state responsible for resonance, large but undetermined contributions to the cross section are made by nonresonant states, as follows from a consideration of the angular distribution of the neutrons (cf. below). Hence an analysis of the curve $\sigma(E_p)$ by means of the Breit-Wigner formula cannot give unique results. Using directly the value $E_p = 3$ Mev, corresponding to the maximum of the curve of $\sigma(E_p)$, it is possible to give the value of the energy of the excited state of He^4 as 22 Mev. This level exceeds by 2.2 Mev the energy of dissociation of He^4 into $T + p$ and by 1.5 Mev the energy of dissociation into $He^3 + n$. It is therefore to be expected that the level should be wide and that the lifetime of He^4 in the corresponding state is very short.

Attempts to observe the excited states of He^4 by other methods[11,12] did not give positive results. They indicate only that He^4 does not have excited states at lower energies. In reference 12 in which the scattering of protons with energy of 32 Mev on He^4 was investigated, no inelastic scattering was found. However, the proton energy corresponding to excitation of He^4 to the 22 Mev level is near the lower limit of the spectrum observed in the experiment, and the large width of the level unquestionably leads to a marked blurring of the spectrum of the inelastically scattered protons; hence, the results of reference 12 cannot be regarded as contradicting our results.

The absolute value of the cross section for the reaction $T(pn)He^3$ at maximum, equal to 0.58 bn, is rather large. According to a remark of Baz' and Smorodinskii[13], this indicates that the resonance corresponds to a 2^- state, since the maximum value of the resonance cross section cannot exceed $^1/_4 \pi\lambda\!\!\!^{-2}(2I+1)$ ($\lambda\!\!\!^{-} = \lambda/2\pi$ is the wavelength of the proton in the center of mass system). At $E_p = 3$ Mev, $^1/_4 \pi\lambda\!\!\!^{-2} = 0.36$ bn and comparison with the experimental cross section of 0.58 bn gives $I > 1$. It is to be remarked that with a large contribution to the cross section by nonresonant states this condition does not apply too rigorously, but if one takes $I = 1$, more than half of the cross section has to be attributed to nonresonant states, which seems improbable. The supposition that the resonance corresponds to a 1^- state is also contradicted by the excitation curve of the reaction $T(p\gamma)He^4$ which does not show a resonance in the region of 3 Mev. In this reaction the intermediate state is undoubtedly the 1^- state from which an electric dipole transition to the ground state 0^+ takes place. That the radiative transition is in fact electric dipole is indicated by the angular distribution of the γ-rays which has the form $\sigma(\theta) = \sin^2\theta + a$ where $a \ll 1$. The transition from the state 2^- to the ground state 0^+ must be a magnetic quadrupole transition. The probability of such a transition is much less than for an electric dipole transition, and it is, therefore, not surprising that no resonance is visible in the reaction $T(p\gamma)He^4$.

The supposition that the resonance is connected with the 2^- state is also in accord with the predictions of nuclear shell theory, according to which, above states s_0, there should be $p_{3/2}$ and $p_{1/2}$, the first of these corresponding to lower energy as is observed in He^5 and Li^5. The 2^- state in He^4 can be formed only from the $p_{3/2}$ proton state, and the angular momenta of the proton and of the tritium must be parallel. If the 2^- state is in fact the lowest excited state of He^4, this is in agreement not only with the level order predicted by shell theory, the levels being split by spin-orbit interaction, but with the fact that

[11] J. C. Allred, Phys. Rev. **84**, 695 (1951)

[12] J. Benveniste and B. Cork, Phys. Rev. **89**, 422 (1953)

[13] A. I. Baz' and Ia. A. Smorodinskii, J. Exper. Theoret. Phys. USSR **27**, 382 (1954)

the lowest levels are those with the maximum value of the spin, since from the $p_{3/2}$ proton state two states of He^4 can be formed, viz., 2^- and 1^-. In the latter state the spins of proton and tritium are antiparallel.

The angular distribution of the neutrons in the reaction $T(pn)He^3$ is characterized by a strong asymmetry (cf. Fig. 4). In the first place, the ratio of intensities at 0 and 180° to intensity at 90° (in the center-of-mass system) is rather large. As was pointed out by Baz' and Smorodinskii[13], the large value of the ratio $\frac{1}{2}[\sigma(0°) + \sigma(180°)]/\sigma(90°)$ indicates a large contribution to the cross section of the 1^- state. It is to be noted that this ratio continues to increase up to $E_p = 7$ Mev. If the level 1^- exists, this indicates that it is situated at $E_p > 7$ Mev, and, therefore, the magnitude of the splitting between the levels 2^- and 1^- exceeds 3 Mev in this case. Second, the asymmetry of the angular distribution relative to the angle of 90° is very great. If one calculates the ratio $\sigma(180°)/\sigma(0°)$, using empirical formulas in which the cross section is expanded in a series of cosines, the ratio turns out to be equal to 2.3 at $E_p = 3.3$ Mev and 4.9 at $E_p = 7$ Mev. The very large probability of the neutron emerging backward is a characteristic peculiarity of the reaction $T(pn)He^3$. This peculiarity distinguishes it from many other reactions. Formally this peculiarity of the reaction can be easily explained by the interference of waves of different parity, e.g., p-wave with s-wave. With the value of the ratio $\sigma(180°)/\sigma(0°) = 4$, the amplitude of the even wave must not be less than 1/3 the amplitude of the odd (p) wave. From this it is seen that the relative contribution of the even states to the reaction cross section is rather large. This is confirmed by the following: 1) The cross section of the inverse reaction $He^3(np)T$ with thermal neutrons is very large (5000 bn) and 2) The coefficient E of the $\cos^4\vartheta$ term (Fig. 5) whose magnitude is apparently chiefly determined by the contribution of the d-state, reaches a large value at $E_p = 7$ Mev. The angular distribution obtained in the experiments of Willard et al. is in satisfactory agreement with the one obtained by us in the common energy interval.

The excitation curve for the reaction $T(p\gamma)He^4$, as already noted above, does not show resonance behavior, hence the state 1^- is not related to resonance in the reaction $T(pn)He^3$.

The radiative capture of the proton can be explained also with the assumption of the existence of a definite 1^- state. A formula is given by Flowers and Mandle[14] which gives the variation with energy of the cross section for non-resonant radiative capture for an electric dipole transition. Comparison of this formula with the experimentally determined variation of the cross section shows that agreement can be obtained if the constant ϵ in the formula of Flowers and Mandle[14], which represents the mean binding energy per nucleon in He^4, is set equal to 5 Mev, and if the range R of nuclear forces, used in calculating the penetrability of the potential barrier, is set equal to $R = 5 \times 10^{-13}$ cm. It should be noted that the shape of the theoretical curve is very sensitive to the magnitude of R.

The angular distribution of the γ-rays at $E_p = 7$ Mev turned out to be close to the one observed earlier[2]:

$$\sigma(\theta) \approx \sin^2\theta + a.$$

For the quantity a our results lead to the value $a = 0.05 \pm 0.01$, somewhat less than at $E_p = 1.52$ and 2.16 Mev ($a = 0.11$ and 0.09 resp). Apparently, the decrease of the magnitude of a with energy is beyond the limits of experimental error, even though the precision of the determination of this quantity is not great. It is not possible to explain the fact that $a \neq 0$ by the finiteness of the angular width of the apparatus and the scattering of protons in the target. Hence, the departure of the angular distribution from $\sin^2\theta$ must be regarded as real, but as one which decreases with proton energy. From an examination of the angular distribution of the neutrons it follows that the relative role of the 1^- state in the reaction $T(pn)He^3$ increases with E_p. The same is observed in the reaction $T(p\gamma)He^4$ if one assumes that the component connected with $a \neq 0$ is due to a different intermediate state.

The demonstration of the existence of the excited state of He^4 makes it possible to make certain conclusions concerning the states of the isobaric nuclei H^4 and Li^4. Since no levels lower than 22 Mev have been found in He^4, H^4 and Li^4 cannot have bound states. If the excited state of He^4 with energy near 22 Mev has isotopic spin $T = 1$, corresponding (similar) states, shifted by the difference in Coulomb energies, can also be present in H^4 and Li^4. Although the lifetimes of these states must be very small,

[14] B. H. Flowers and F. Mandle, Proc. Roy. Soc. (London) 206 A, 131 (1951)

nevertheless it would be possible to detect them in various nuclear reactions, e.g., $T(dp)H^4$, $He^3(dn)Li^4$. If, however, the 22 Mev level of He^4 is characterized by isotopic spin $T = 0$, as is supposed by Baz' and Smorodinskii [13], then corresponding states of H^4 and Li^4 cannot exist, and the question as to the existence of H^4 and Li^4 is decided in the negative sense.

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