YIELD AND ANGULAR DISTRIBUTION OF FAST PHOTONEUTRONS FROM DEUTERIUM AND CARBON

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Submitted to JETP editor May 20, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1123-1130 (November, 1957)

The yield and angular distribution of fast photoneutrons (of energy > 20.6 Mev) from carbon and deuterium were investigated on the 265 Mev synchrotron of the Physics Institute, Academy of Sciences. Results of the experiments are interpreted from the point of view of the two-nucleon model for photon energies both below and above the threshold for meson production.

1. INTRODUCTION

PHOTODISINTEGRATION of the deuteron is the simplest example of the interaction of γ-rays with nuclei. At one time the study of this reaction near threshold gave various information about the interaction of protons with neutrons and quantiatively established two types of dipole absorption of γ-rays, photoelectric and photomagnetic absorption.

In recent years the photodisintegration of the deuteron has been studied in especial detail for photons of high energy — near to and above the threshold for meson production — in so far as it was of interest to establish whether an essential change in the mechanism of γ-ray absorption occurred in this energy region. However, up to the present there has not been a theory which completely explains the experimental data on photodisintegration of the deuteron for photons of energy exceeding 50 Mev. Besides this, the investigation of photodisintegration of the deuteron by high-energy photons is necessary for an analysis of the interaction of γ-rays with complex nuclei which depends, according to the two-nucleon model[1,2] on the absorption of γ-rays by pairs of nucleons in the nuclei, in particular, proton-neutron pairs (quasi deuterons).

At present, a considerable number of experiments on photodisintegration of the deuteron have been carried out from threshold for the reaction $\gamma + d \rightarrow n + p$ up to energies of approximately to 450 Mev. In all experiments on the photodisintegration of the deuteron with high-energy photons, the emitted protons were counted. Data on the emission of photo neutrons could serve as a check on these experiments. In addition, in order to verify the two-nucleon model, it is of interest to compare the yield and angular distribution of fast neutrons from deuterium for photon energies below and above the threshold for meson production with analogous data obtained by the same method for complex nuclei.

2. EXPERIMENTAL ARRANGEMENT

In the present work, carried out on the 265 Mev synchrotron of the Physics Institute of the Academy of Sciences, the photodisintegration of the deuteron by photons of energies greater than 50 Mev was studied by counting the neutrons. For this we employed a high-threshold scintillation neutron detector[3] based on producing the reaction $C^{12}(n, 2n)C^{11}$ with threshold of 20.6 Mev in a liquid scintillator. The C^{11} activity was detected by fluorescence of the scintillator coming from decay positrons, using FEU-19 M photomultipliers connected in coincidence ($\tau \approx 3 \times 10^{-8}$ sec).

In order to increase the efficiency of counting positrons from the decay of C^{11}, the dependence of this efficiency on the form and volume of the container of the scintillation counter and on the voltage of the photo-multiplier was studied in special experiments. As a result of this investigation, a solution of terphenyl in xylene of volume 50 cm^3 in a spherical glass container was used as a scintillator. The voltage on the photomultiplier was about 2100 v. Under these conditions the effective number of atoms of carbon in the scintillator comprised $N \approx 7.2 \times 10^{24}$, which allowed detection of a neutron beam of 20 neutrons/cm^2 sec (for neutrons of high energy this beam corresponds to the tolerance dose) with an accuracy of $\sim 6\%$ for activation by neutrons for 30 min and a counting time of the scintillator of 40 min.

Using such a detector, the yield and angular distribution of photoneutrons from deuterium was studied by the difference of D_2O and H_2O yields under bremsstrahlung radiation of maximum energy 255 Mev. The experimental arrangement is given in Fig. 1. The neutron sources D_2O and H_2O, in cubical containers with walls of 15 μ copper foil, were placed in the center of the γ-ray beam. The mass of the irradiated liquid was ~ 200 g; here the thickness of material did not exceed ~ 0.2 radiation units and ~ 0.1 mean free paths of 30 Mev neutrons relative to inelastic scattering. Such dimensions of the target did not lead to a noticeable distortion in the angular distribution of the neutrons or in the form of the excitation function.

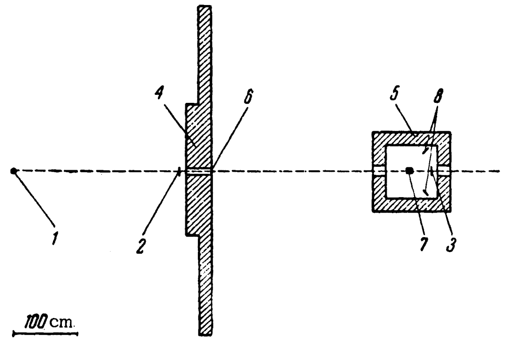

FIG. 1. Experimental arrangement. 1 — target of the synchrotron, 2 and 3 — carbon monitors of the photon beam, 4 and 5 — lead shielding, 6 — collimator of diameter 40 mm, 7 — target of D_2O or H_2O, 8 — neutron detector.

The liquid organic scintillator which served as a neutron detector was placed during the irradiation at a definite angle relative to the direction of the photon beam in five containers ($2 \times 5 \times 10$ cm^3). The use of several containers made it possible to improve the statistics without worsening the angular resolution, which constituted ± 6° in our experiments. The beam of γ-rays proceeded through a lead collimator of diameter 4 cm. The thickness of the lead shields for the neutron detectors on the side of the synchrotron target was 40 cm. In addition, the entire apparatus was shielded on all sides by lead walls of thickness 20 cm.

In order to separate off accessory activation of the detectors on account of the reactions $C^{12}(p, pn)C^{11}$ and $C^{12}(\gamma, n)C^{11}$, by particles emitted from the targets (D_2O and H_2O), we also screened the neutron detectors on all sides with sheets of lead of thickness 1 cm. A check showed that with raising the thickness of the shields to several millimeters, the activation of the detectors decreased rapidly and was practically independent of the further increase in thickness of the target above several millimeters, i.e., it was determined at the thickness of shielding noted.

An absolute value for the photon beam was determined by activation of graphite plates ($0.2 \times 3 \times 6$ cm^3) using the reaction $C^{12}(\gamma, n)C^{11}$. The accuracy of absolute measurement of the photoneutron beam was ~ 15% and was basically determined by the accuracy with which the cross section for the reaction $C^{12}(n, 2n)C^{11}$ is known (see, for example, Ref. 3) in the range of neutron energies from 30 to 60 Mev.

3. EXPERIMENTAL RESULTS

We obtained the angular distribution of photoneutrons from deuterium for maximum bremsstrahlung energies $E_{\gamma m} = 170$ Mev and $E_{\gamma m} = 255$ Mev and the dependence of the yields on the maximum photon energy at 75° in the laboratory system (l.s.), corresponding in this energy interval to approximately 90° in the center-of-mass system (c.m.s.). This dependence is shown on Fig. 2, on which there is also given the analogous dependence obtained by way of evaluating the neutron yields from the results of recent results on photodisintegration of the deuteron.[4-10] The evaluation was carried out in the following way. The differential cross section for emission of photoprotons in the disintegration of the deuteron in the c.m.s. was transposed by replacing the angle θ by $\pi - \theta$ (transition from protons to neutrons). Going to the l.s., we integrated over the spectrum of bremsstrahlung, and took into account the energy dependence of the reaction $C^{12}(n, 2n)C^{11}$. From Fig. 2 it can be seen that our data for photons with energies up to ~ 200 Mev agree well with the other experiments.

For photon energies greater than 200 Mev the yield of neutrons increased sharply. This growth was connected with meson production in the photodisintegration. Consideration of photoproduction of mesons in deuterium in the impulse approximation shows that only two reactions can lead to production of neutrons with energies > 20 Mev in our energy interval: photoproduction of π^0 mesons on the neutron and of π^+ mesons on the proton. Photoproduction of a π^0 meson on the proton in deuterium does not lead in the impulse approximation to the production of fast neutrons.

In production of a meson on a nucleon at rest by photons of energy up to 255 Mev it is impossible to have a nucleon of energy ≳ 20 Mev emitted at an angle ≳ 40°. However, already at the energies of motion of the nucleons in deuterium (E ≳ 12 Mev) the emission of neutrons of energy 20 Mev is possible up to

90° (l.s.) for $E_{\gamma m}$ = 255 Mev and at angles up to 70° for $E_{\gamma m}$ = 200 Mev.

The angular distribution of neutrons in the l.s. obtained by us for $E_{\gamma m}$ = 170 Mev is given on Fig. 3. Curve 1 corresponds to the data of Refs. 4 — 10 (transposed for neutrons), which can be approximated in the c.m.s. by a curve of the form

$$\sigma(\theta) = (A + B\sin^2\theta)(1 - C\cos\theta),$$

where θ is the angle of emission of neutrons in the c.m.s. and A = 4.5 × 10^{-30} cm^2/sterad · Q, B = 3.8 × 10^{-30} cm^2/sterad · Q, C = 0.35. As follows from Fig. 3, our data for $E_{\gamma m}$ = 170 Mev agree with the results of these other experiments within the accuracy of the experiments.

For $E_{\gamma m}$ = 255 Mev, as can be seen from Fig. 3, the angular distribution obtained by us differs markedly from the results of transposing data for the photodisintegration of deuterium without the production of mesons (curve 2). It is clear that the contribution of photoproduction of mesons leads to a noticeable increase in the general yield of fast photoneutrons from deuterium and to a marked change in the form of their angular distribution — to the appearance of an additional group of neutrons, sharply peaked forward.

It should be noted that although we employed a difference method which gives, instead of the yield of fast neutrons from deuterium, the difference in yields from deuterium and hydrogen, the yield from hydrogen is different from zero only for angles ≤ 40°, so that its contribution at 30° constitutes 25% of the yield from deuterium at 30° and, after integration over angles, 5% of the total yield.

The integral yield of neutrons of energy > 20 Mev from deuterium in processes of production of π^+ mesons and π^0 mesons can be determined as the difference between the total yield of neutrons from deuterium measured by us and the yield, taken from the literature, of neutrons from deuterium in processes without production of photomesons. The magnitude of this difference constitutes 8 × 10^{-29} cm^2/sterad · Q and, within the limits of experimental error, agrees with the estimate of the yield of neutrons in reactions with the production of π^+ and π^0 mesons from deuterium obtained by superposition of data in the literature[11] on the photoproduction of mesons on nucleons.

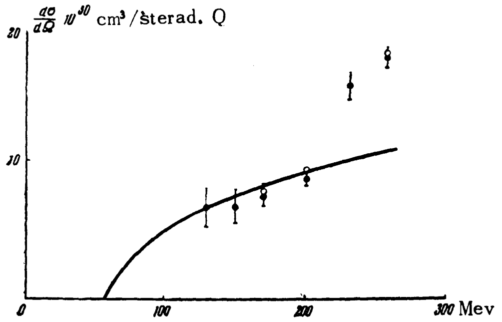

FIG. 2. Yield of fast photo neutrons from deuterium at 75° in the l.s. vs. maximum energy of the photon bremsstrahlung spectrum. The solid curve gives the results of the experiments, Refs. 4 — 10, transposed for neutrons; ● — yield of fast neutrons from deuterium, ○ — yield of fast neutrons from carbon.

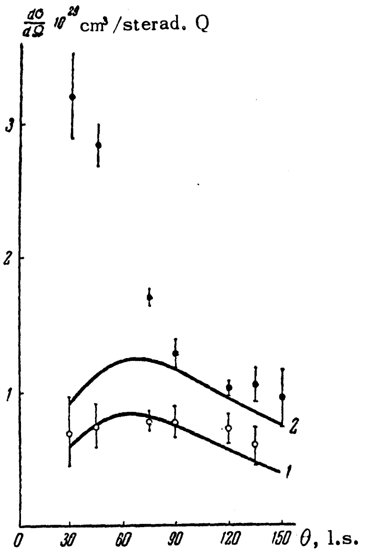

FIG. 3. Angular distributions of photoneutrons of energy > 20 Mev from deuterium; ○ — $E_{\gamma m}$ = 170 Mev, ● — $E_{\gamma m}$ = 255 Mev. The solid curve gives the results of the experiments, Refs. 4 — 10, transposed for neutrons: 1 — for $E_{\gamma m}$ = 170 Mev, 2 — for $E_{\gamma m}$ = 255 Mev.

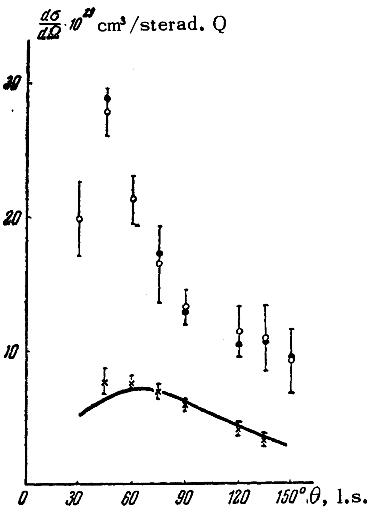

FIG. 4. Angular distributions of neutrons of energy > 20 Mev from carbon and deuterium. ○ — yield of neutrons from carbon for $E_{\gamma m}$ = 225 Mev;[15] × — the same for $E_{\gamma m}$ = 170 Mev; ● — yield of neutrons from deuterium for $E_{\gamma m}$ = 255 Mev. The solid curve gives the angular distribution of neutrons from deuterium for $E_{\gamma m}$ = 170 Mev, obtained from the results, Refs. 4 — 10, transposed for neutrons.

From the point of view of the quasi-deuteron model[1] it is of particular interest to compare our data on the yield and angular distribution of fast neutrons from deuterium with analogous data obtained earlier by the same method for complex nuclei. The two-nucleon model was verified qualitatively in direct experiments on n – p coincidences[12-14] of photonucleons from complex nuclei. These experiments showed that a considerable number of protons from the nucleus have that angular correlation with photoneutrons determined by photodisintegration of the deuteron.

In Fig. 4 we show the angular distribution of fast neutrons from carbon for a maximum photon energy $E_{\gamma m}$ = 255 Mev, obtained earlier,[15]* and our data for carbon for $E_{\gamma m}$ = 170 Mev. In addition, the yields of neutrons from deuterium for the same maximum photon energies are given on Fig. 4. The data for carbon and deuterium were normalized using the total cross section.

From Fig. 4 it can be seen that the angular distributions of neutrons from carbon and deuterium are similar both for $E_{\gamma m}$ = 170 Mev and $E_{\gamma m}$ = 255 Mev. Some difference occurs only for 30° and $E_{\gamma m}$ = 255 Mev. It is possible that the difference is connected with the Pauli principle, which allows only those processes of photodisintegration of quasi deuterons and production of mesons on them in which the energy of both nucleons exceeds the Fermi energy (20 Mev). Several differences between the nucleon yield at small angles from complex nuclei and deuterium were noticed also in the experiments of Odian et al.,[13] in which the correlations in the emission of neutrons and protons from lithium, nitrogen and deuterium were studied.

TABLE I. Yield of photoneutrons of energy $\gtrsim$ 20 Mev from deuterium and carbon

$E_{\gamma m}$ (Mev)	Yield from deuterium (without meson production) according to Refs. 4-10 10^{28} cm$^2/Q$	Total yield from deuterium $\sigma_D \times 10^{28}$ cm$^2/Q$	Total cross section from carbon $\sigma_C \times 10^{28}$ cm$^2/Q$	σ_C/σ_D
170	0.82	0.84±0.07	7,2±0.25	8,58±0.66
255	1,27	2.06±0,06	18,9±1,35	9.18±1,44

In Table I we give the total yields of fast neutrons from carbon and deuterium for $E_{\gamma m}$ = 170 and 255 Mev and the data in the literature on photodisintegration of deuterium without meson production.

From Table I it can be see that the ratio of yields of fast neutrons from carbon and deuterium is the same for $E_{\gamma m}$ = 170 Mev, where such neutrons are emitted exclusively in the process of photodisintegration of deuterium without meson production, as for $E_{\gamma m}$ = 255 Mev where the process of meson production is essential.

4. DISCUSSION OF RESULTS

The connection between the emission of photonucleons from complex nuclei and deuterium is usually described in the framework of Levinger's two-nucleon theory,[1] according to which the cross section σ_A for photodisintegration of a nucleus with mass number A and the cross section for photodisintegration of deuterium σ_D are connected by the relation

$$\sigma_A = 6.4\,(NZ/A)\,\sigma_D, \quad (1)$$

where Z is the number of protons and N = A – Z is the number of neutrons in the nucleus. In the work of Odian et al.[13] in which it was assumed that the quasi deuteron is in a $^3S_1$ state and the nuclear radius is taken equal to $R = 1.2\,A^{1/3} \times 10^{-13}$ cm (instead of $R = 1.4\,A^{1/3} \times 10^{-13}$ cm) and the Hulthén wave function for deuteron was used, it was found that

$$\sigma_A = 3.8\,(NZ/A)\,\sigma_D. \quad (2)$$

The two-nucleon model has been verified in a series of experiments in which the yield of high-energy photoprotons from the nucleus and the angular correlation of photoprotons and photoneutrons were observed. However, in all of these, the experimental conditions were such that only processes of two-nucleon disintegration without meson production were counted. Correspondingly, the verification of the validity of the predictions of the two-nucleon model was carried out by comparison of results for complex nuclei with data on the photodisintegration of deuterium into protons and neutrons without meson production. In the present work it was possible to compare total cross sections and angular distributions of neutrons in photodisintegration of deuterium both without and with meson production. From Table I it can

*The data of Ref. 15 should be decreased by 10% because of a more accurate measurement of the intensity of the photon beam and its absorption in the target.

be seen that for photon energies below the threshold of meson production, as well as for higher energies, the relation satisfied for carbon is

$$\sigma_c \approx 3\,(NZ/A)\,\sigma_D,$$

in good agreement with the calculations and experimental data of reference 13, obtained for only the non-mesonic processes.

In order to interpret the results, it is useful to turn to the concept of Wilson[16,17] about the disintegration of deuterium by photons of energy 40 — 500 Mev, extending it to the disintegration of quasi deuterons. According to Wilson, photodisintegration of deuterium proceeds, together with disintegration not connected with mesonic processes, with reabsorption of virtual and real mesons. In the interaction in deuterium of γ-rays with one of the two nucleons, a virtual or real π-meson is produced. If the second nucleon is then close to the first one ($r \lesssim \hbar/\mu c$), the meson will be reabsorbed with a probability close to unity and there will be photodisintegration of deuterium without meson production (the probability of repeated emission of mesons in the disintegration is very small). The larger the distance between the nucleons, the smaller is the probability of reabsorption of a meson produced on one of them by the other one, and the larger is the probability of photoproduction of a meson (if, of course, it is allowed by conservation laws).

We will assume, for simplicity, that if the nucleons are found closer to each other than $r \leq \kappa\hbar/\mu c$, then reabsorption occurs with unit probability; if $r \geq \kappa\hbar/\mu c$, then there is no absorption. Then the probability of reabsorption ω can be determined as the probability of finding the nucleons in the deuteron or quasi deuteron at distances $r \leq \kappa\hbar/\mu c$.

The cross section for photodisintegration of the deuteron or quasi deuteron without production of real mesons can be written in the form

$$\sigma_{np} = \sigma_1\omega + \sigma_2, \tag{3}$$

where σ_1 is the cross section for absorption of a γ-ray with production of a π^+, π^- or π^0 meson on the neutron or proton of the deuteron or quasi deuteron; σ_2 is the cross section for photodisintegration of the deuteron or quasi deuteron not connected with meson processes. Then the cross section for photodisintegration with production of real mesons can be written in the form

$$\sigma_\pi = \sigma_1(1 - \omega), \tag{4}$$

and the total cross section is equal to

$$\sigma_t = \sigma_{np} + \sigma_\pi. \tag{5}$$

From Eqs. (3), (4), and (5) it follows that $\omega \leq \sigma_{np}/\sigma_t$ and $1 - \omega \geq \sigma_\pi/\sigma_t$. In the case of a complex nucleus these inequalities are strengthened because the σ_π observed can be below the true one on account of reabsorption of mesons by other nucleons of the nucleus.

From our and other experimental data it is possible to evaluate the upper limits of the probability of reabsorption of mesons in deuterium $\omega = \omega_D$ and in the quasi deuterons $\omega = \omega_C$ in the carbon nucleus. These are given in Table II.

The values of the quantities in Table II were obtained by using the results of the work, Refs. 4 — 10, for the cross section of photodisintegration of deuterium without production of real mesons, cross sections for photoproduction of mesons on nucleons from Ref. 11, the data from Ref. 18 $\sigma\pi^{\pm} = 7.3\sigma_{\gamma p \to \pi^+ n}$ for $E_{\gamma m} = 310$ Mev and [23] $\sigma_{\pi^0} = 12\sigma_{\gamma p \to \pi^0 + p}$ for $E_{\gamma m} = 256$ Mev for a rough estimate of the cross section of production of mesons on carbon and, finally, our data on the ratios of the total cross sections of carbon and deuterium: $\sigma_C \approx 9\sigma_D$. From the table it can be seen that the quantity ω_D is, in the range of photon energies ~ 250 Mev, near to that calculated by Austern[20] using the isobar model ($\omega_D = 0.11$), which corresponds to a value $r = 0.7\,\hbar/\mu c$ (for the wave function of Hulthén).

TABLE II. Probability of reabsorption of mesons in deuterium and in quasi deuterons in carbon.

E_γ (Mev)	160	180	200	220	240	260	280	300	320	360	400	450
$\omega_D \leqslant$	0.39	0.24	0.17	0.13	0.11	0.09	0.07	0.053	0.041	0.039	0.039	0.038
$\omega_C \leqslant$	0.74	0.68	0.64	0.61	0.58	0.55	0.52	0.49	0.47	0.47	0.49	0.50

The quantity ω_C for the quasi deuterons in the carbon nucleus is substantially less than unity. This indicates that in the production of mesons in the carbon nucleus the probability of their reabsorption in the same quasi deuteron in which they were formed is sufficiently small.

A qualitative indication that the value of ω_C should be even less than the upper limits given in Table II comes from the similar angular distributions of photoneutrons from deuterium and carbon noted in our experiments. The angular distribution of photoneutrons for $E_{\gamma m}$ = 255 Mev is the sum of two completely different distributions arising from the photodisintegration of deuterium without photoproduction of mesons and photodisintegration with meson production (see Figs. 3 and 4). Under the conditions $\omega_D \ll 1$ and $\omega_C \gg \omega_D$ (because of the much greater compactness of the carbon nucleus compared with deuterium) similar angular distributions would result only if $\omega_C \ll 1$.

In connection with the results obtained we note that the increase in yield of fast photoneutrons as $\sim A^{4/3}$ from carbon to lead noted in Ref. 15 for $E_{\gamma m}$ = 255 Mev, and also the somewhat larger fraction of neutrons emitted from heavy nuclei (for example, from lead) at large angles, is apparently caused by secondary processes (interaction of the nucleons and absorption of mesons in the nucleus) leading to the production of stars with emission of fast neutrons.

CONCLUSIONS

1. The yield and angular distribution of fast photoneutrons emitted by deuterium and carbon interacting with bremsstrahlung γ-rays with maximum energies 170 and 255 Mev were studied. An effective scintillation counter for fast neutrons, based on the reaction $C^{12}(n, 2n)C^{11}$ (threshold 20.6 Mev) in a volume of liquid scintillator, was used.

2. For γ-rays of maximum energy 170 Mev, the results obtained for deuterium agree with the results of experiments in which the photodisintegration of deuterium was studied by registering protons. For a maximum γ-ray energy of 255 Mev the angular distribution of fast photoneutrons from deuterium changed markedly on account of the appearance of a substantial yield of photoneutrons produced in the process of photoproduction of mesons and emitted in the forward direction.

3. Both for a maximum γ-ray energy of 170 Mev, where the detector did not count neutrons connected with meson production, and for 255 Mev, where these processes were essential, the ratio of total yields was

$$\sigma_C/\sigma_D \approx 3\,(NZ/A) = 9$$

Thus, this consequence of the two-nucleon model was verified not only for the disintegration of deuterium and carbon without mesons, but also for the photomeson processes in these nuclei. For both maximum energies the same angular distributions of fast neutrons result for deuterium and carbon, in spite of the marked change in their form in the transition from one maximum energy to the other.

4. Comparison of the results obtained with data on the photoproduction of mesons from deuterium and carbon makes it possible to evaluate the upper limit of the probability of reabsorption of the meson produced on one nucleon of the deuteron or quasi deuteron in carbon by the second nucleon. In the energy range $\sim$ 250 Mev and above this probability is < 0.1 for deuterium and, apparantly, less than 0.5 for carbon.

In conclusion, we express our gratitude to A. M. Baldin and V. A. Petrun'kin for taking part in the discussion of our results.

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Translated by G. E. Brown
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SOVIET PHYSICS JETP VOLUME 6 (33), NUMBER 5 MAY, 1958

α-PARTICLES EMITTED BY HEAVY EMULSION NUCLEI IN EMULSIONS BOMBARDED BY HIGH-ENERGY PROTONS

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Submitted to JETP editor May 25, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 1131-1139 (November, 1957)

An investigation has been made of the energy spectra of α-particles emitted by heavy nuclei in emulsions bombarded by protons with energies of 360, 560, and 660 Mev, assuming different excitation energies for these nuclei. The calculated evaporation spectrum is found to be in satisfactory agreement with experiment in the α-particle range up to 14 Mev without requiring any reduction of the Coulomb barrier as proposed by Le Couteur. By subtracting the calculated evaporation spectrum from the experimental spectrum the energy distribution for the cascade α-particles and the relative number of such particles which appear in one disintegration event at the three experimental energies cited above have been obtained.

INTRODUCTION

THE α-particles emitted in the disintegration of nuclei in emulsions bombarded by high-energy nucleons have been studied by many investigators.[1-14] However, most of these studies have been carried out with non-monoenergetic fast-particle sources (cosmic rays); thus there is a high degree of uncertainty in the interpretation of the results. In addition, the methods used for distinguishing between stars due to heavy nuclei and light nuclei are not always effective. Finally, in most cases the investigators did not have at their disposal a sufficient number of events to ensure good statistics for studying the α-particle energy spectra at different excitation energies.

In a number of papers[1,3-5,12-14] it has been noted that among the α-particles emitted from silver and bromine nuclei there is an anomolously large (from the point of view of nuclear evaporation theory) number of slow α-particles. Le Couter[15] and Fujimoto and Yamaguchi,[16] on the basis of an idea suggested by