PHOTONUCLEAR REACTIONS INVOLVING THE EMISSION OF DEUTERONS AND TRITONS WITH ENERGIES BELOW 15 *MeV*

Yu. M. VOLKOV and L. A. KUL'CHITSKII

Leningrad Physico-Technical Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor August 24, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **42**, 108-114 (January, 1962)

The cross sections per effective quantum are obtained for the (γ, p), (γ, d), and (γ, t) reactions on Li^6 and Li^7 nuclei. The relative yields $Y(\gamma, d)/Y(\gamma, p)$ and $Y(\gamma, t)/Y(\gamma, p)$ for Li^6, Li^7, B^{11}, and Cu as a function of the energy $E_{\gamma max}$ are measured. Angular distributions of photoprotons, photodeuterons, and phototritons for Li^7 and the excitation function for the $Li^7(\gamma, t)$ reaction are presented. It is shown that photodeuterons are produced predominantly in reactions in which one or several particles are emitted in addition to the deuterons. The results of measurement of the excitation function of the $Li^7(\gamma, t)$ reaction and of the triton angular distribution are shown to agree with the concept of direct dipole absorption of γ quanta by Li^7 as a "triton + α-particle" system.

INTRODUCTION

THE yields of photodeuterons of energy below 15 MeV emitted in the photodisintegration of medium and heavy nuclei induced by bremsstrahlung with $E_{\gamma max}$ = 30 and 70 MeV were investigated by a number of workers (see [1]). The results obtained were clearly contradictory. The relative yields of photodeuterons and photoprotons $Y(\gamma, d)/Y(\gamma, p)$ for nuclei of the same elements were, according to the data of different authors, between zero and several tens per cent. Such disagreement between the experimental results as well as their nonreproducibility, as noted by Forkman,[2] is apparently a consequence of the shortcomings of the methods used to separate the particles on the basis of their masses (method of grain counting on tracks of particles in nuclear emulsions) and to identify the reactions (γ, d) and (γ, np) (activization method). Apparently, only the results of experiments carried out with the aid of the deflection of charged particles in a magnetic field and their registration in nuclear emulsion[2,3] can be regarded as free from coarse errors. In these experiments the ratio $Y(\gamma, d)/Y(\gamma, p)$ for Al, S, Co, and Cu were found to be of the order 10^{-2}—10^{-3}, which is in agreement with calculations[2] based on the statistical theory of nuclear reactions.

Further investigations are necessary to lay the basis for conclusions on the mechanism of photonuclear reactions in medium and heavy nuclei from which low-energy deuterons are emitted. In particular, studies of the dependence of the relative photodeuteron yields on the γ-quantum energy fall in this category. It is also of interest to compare the results of the study of photoreactions in which compound particles are emitted by heavy and light nuclei.

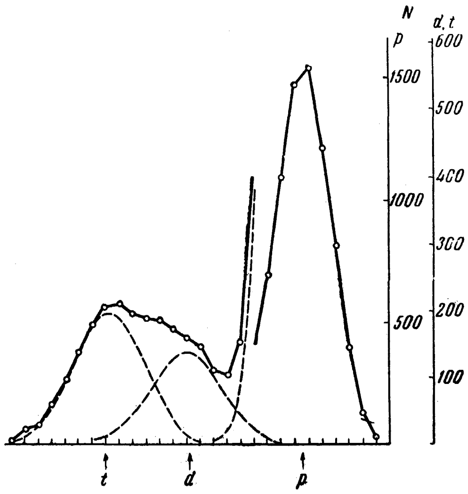

FIG. 1. Distribution according to zones for the experimental points of particles emitted in the photodisintegration of Li^7 ($E_{\gamma max}$ = 63 MeV). The quantity N is the number of particles in a given zone. The ordinate axis for zones 1 to 12 (protons) has a reduced scale. The dotted lines indicate the calculated Gaussian distributions for protons, deuterons, and tritons; the positions of the corresponding maxima are indicated by arrows.

It should be noted that an investigation[4] of the photodisintegration of some light nuclei gave large

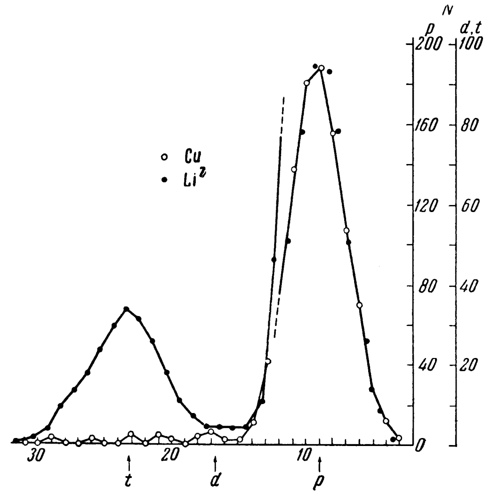

FIG. 2. Distribution according to zones for the experimental points in the photodisintegrations of Cu ($E_{\gamma max}$ = 34 MeV) and Li^7 ($E_{\gamma max}$ = 25 MeV). The ordinate axis for zones 1 to 12 is shown in half scale.

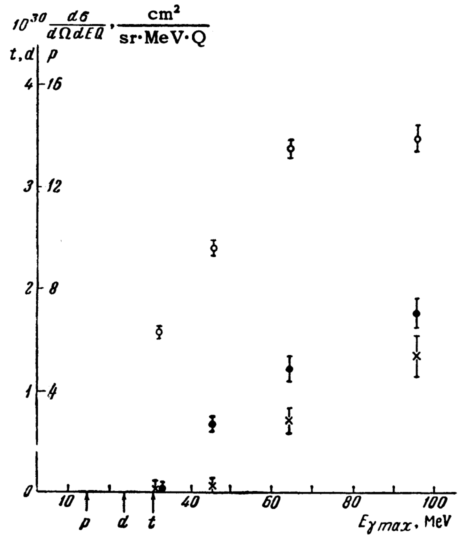

FIG. 3. Cross sections per effective quantum as a function of the energy $E_{\gamma max}$ for the reactions: o – $Li^6(\gamma, p)$; × – $Li^6(\gamma, d)$; and • – $Li^7(\gamma, t)$. The scale on the ordinate axis for cross sections of the $Li^6(\gamma, p)$ reaction is reduced fourfold; the arrows p, d, and t denote the thresholds for the reactions $Li^6(\gamma, p)He^5$, $Li^6(\gamma, d)He^4$, and $Li^6(\gamma, t)He^3$ for recording particles of energy 7.5 MeV.

values for the relative deuteron and triton yields with E > 15 MeV. A comparative study of the (γ, d) and (γ, t) reactions can, of course, give additional information on the mechanisms of reactions from which compound particles are emitted.

In the present experiment we obtained values of the absolute and relative yields of photodeuterons and phototritons of energy below 15 MeV emitted in the photodisintegration of Li^6, Li^7, B^{11}, and Cu induced by bremsstrahlung of different values of $E_{\gamma max}$. Moreover, the angular distributions of protons, deuterons, and tritons emitted in the photodisintegration of Li^7 induced by bremsstrahlung with $E_{\gamma max}$ = 63 MeV were studied.

EXPERIMENTAL METHOD

The charged products of the photonuclear reactions were recorded and identified with the aid of a telescope of scintillation counters by measurement of pulse amplitudes, one of which was proportional to the energy loss $\Delta E \sim dE/dx$ in a thin crystal in the front counter of the "telescope" and a second proportional to the energy of the particle E given up in the crystal of the rear counter. A similar method has been described earlier.[4,5]

A NaI(Tl) crystal was placed in a vacuum chamber together with the irradiated targets. Pulses (from FÉU photomultipliers) proportional to ΔE and E were applied, after amplification and shaping, to pairs of horizontal and vertical plates of a cathode-ray tube and were photographed. The cathode-ray beam was visible only in the case of a coincidence of pulses from both channels during a period of ~ 0.2 μsec. Hence, we obtained on the film a family of points distributed over the rectangular coordinates ΔE and E. To improve the stability of the counters we used circuits for the stabilization of the photomultiplier gain and of the amplification channels with the aid of pulses from Cs^{137} γ quanta, which continually irradiated the rear-counter crystal of the "telescope" and a small additional crystal (cube with 3-mm sides) placed inside the light guide of the front counter with the thin crystal.[6]

The energy scale of the "telescope" was established by measurement of the pulse amplitudes from photoprotons of ranges equal to the thickness of the rear crystals, namely, 0.2, 0.4, 0.8, and 1.0 mm prepared from the same standard crystal together with the crystals used in the main measurements. The accuracy of the calibration was about 5%.

Element	$E_{\gamma max}$, MeV	Particle energy interval, MeV	$Y(\gamma, d)/Y(\gamma, p)$	$Y(\gamma, t)/Y(\gamma, p)$
Li^6	30 43 90	7.5–15	0.003+0.006 0.007±0.005 0.097±0.014	0.000+0.007 0.067±0.007 0.116±0.009
Li^7	25 43 90	7.5–15	0.02+0.03 0.056±0.018 0.160±0.054	0.342±0.025 0.256±0.013 0.338±0.024
Bi^{11}	40	7.5–19	0.006±0.002	0.036±0.005
$Cu^{63,65}$	34 34 90	4.5–15 7.5–15 7–19	0.007±0.003 0.007±0.003 0.021±0.005	0.005±0.002 0.005±0.003 0.013±0.004

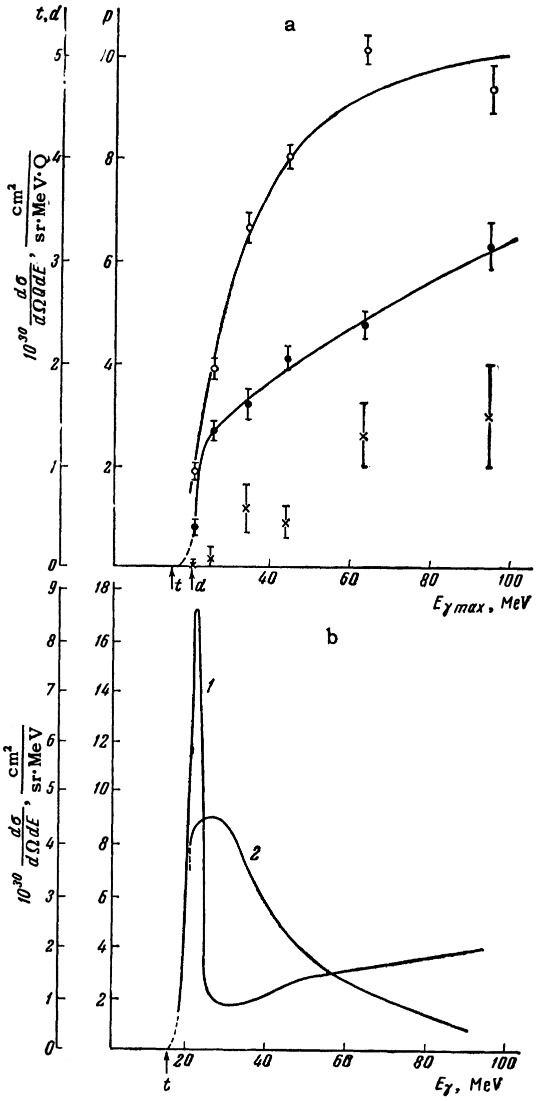

FIG. 4. a) Dependence of cross sections per effective quantum as a function of the energy: o – $Li^7(\gamma, p)$, x – $Li^7(\gamma\, d)$, and • – $Li^7(\gamma, t)$. The scale along the ordinate axis for the $Li^7(\gamma, p)$ reaction is decreased in half. The arrows d and t denote the thresholds for the $Li^7(\gamma, d)He^5$ and $Li^7(\gamma, t)He^4$ reactions for recording particles of energy 7.5 MeV. b) Excitation function for the reactions $Li^7(\gamma, t)$ (curve 1) and $Li^7(\gamma, p)$ (curve 2).

The absolute intensity of the γ-ray flux was measured with a thick-walled ionization chamber calibrated by a calorimetric method. [7]

The particles were separated according to their masses in the following way. On the distribution of points on the ΔE and E coordinates we plotted calculated curves relating the values of ΔE to the values of E for protons and tritons. We then plotted intermediate curves between the other curves in such a way that lines parallel to the ordinate axis divided them into equal segments. Using the obtained "zone grid" also extended below the upper limits for the protons, we constructed the experimental distribution of the points as a function of the zone number (see Figs. 1 and 2). The experimentally obtained distribution of points over the zones is shown in the form of a sum of three Gaussian distributions.

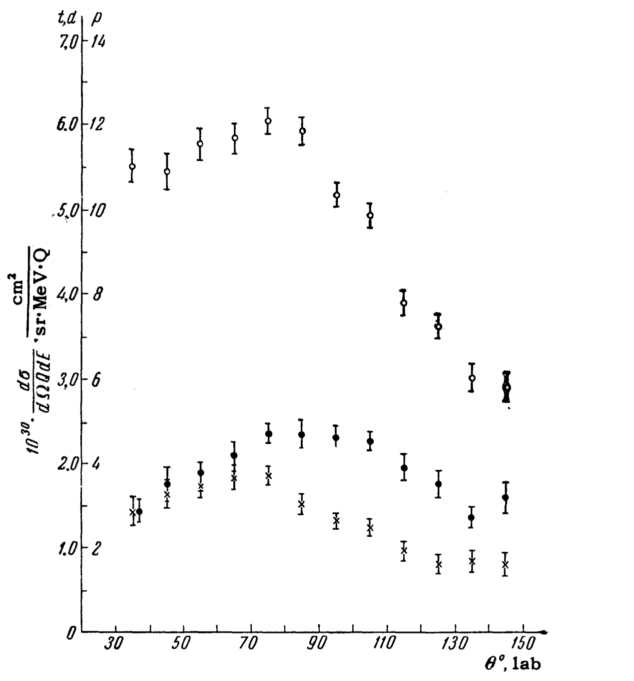

FIG. 5. Angular distribution of protons (o), deuterons (x), and tritons (•) of energy between 7.5 and 15 MeV emitted in the photodisintegration of Li^7 induced by bremsstrahlung with $E_{\gamma max}$ = 63 MeV. For protons the ordinate axis is shown in half scale.

Figure 1 shows the distribution according to zones for the experimental points representing particles emitted from the photodisintegration of the Li^7 nuclei with $E_{\gamma max}$ = 63 MeV. Three Gaussian distributions for protons, deuterons, and tritons, with half-widths of 24, 22, and 20%, correspond to this distribution.

Figure 2 shows the distribution according to zones for points obtained during the study of the photodisintegration of Li^7 by bremsstrahlung with $E_{\gamma max}$ = 25 MeV and Cu with $E_{\gamma max}$ = 34 MeV. Each of the distributions shown in Fig. 2 represents about a thousand points due to protons. The relative yields of particles given below were obtained from measurements of several thousand points corresponding to the protons.

The errors associated with the method of separating the particles vary within the limits of 5–20%, depending on the number of recorded particles and the relative number of particles of different mass. For all the experimental results reported here, the errors cited are equal to the sum of the statistical errors and the errors associated with the method of separation of the particles.

EXPERIMENTAL RESULTS AND DISCUSSION

The cross sections for the reactions $Li^6(\gamma, p)$, $Li^6(\gamma, d)$, and $Li^6(\gamma, t)$ per effective quantum in the energy region 7.5—15 Mev at $\theta = 90°$ are plotted in Fig. 3 as a function of $E_{\gamma max}$. It is seen in Fig. 3 that the cross section for the $Li^6(\gamma, d)$ reaction is appreciable only for γ-quantum energies considerably exceeding the energy threshold for the $Li^6(\gamma, d)He^4$ reaction. This fact was observed earlier in the case of photodeuterons of energy above 15 MeV and was explained on the basis of the isospin selection rules.[4] However, it was later shown[8] that the "anomalous" threshold of the photoreaction involving the emission of deuterons is also observed in the photodisintegration of B^{10} and B^9. It was noted in the same work that the (γ, d) reaction apparently occurs in all light nuclei primarily under conditions in which the emission of the deuteron can be accompanied by the emission of one or several nucleons.

The results of similar investigations of the Li^7 photodisintegration are shown in Fig. 4a. The $Li^7(\gamma, d)$ reaction, as can be seen from Fig. 4a, is not characterized by a marked "anomalous" threshold. This, however, does not contradict the foregoing remark (see [8]) on the character of the (γ, d) reaction in light nuclei, since the $Li^7(\gamma, d)$ reaction, owing to the unstable residual nucleus He^5, is a multiparticle reaction at all γ-quantum energies beginning with the threshold.

The relative yields of deuterons $Y(\gamma, d)/Y(\gamma, p)$ obtained in the photodisintegration of Li^6, Li^7, B^{11}, and Cu produced by bremsstrahlung with different end-point energies $E_{\gamma max}$ ($\theta = 90°$) are shown in the table. It is seen from the table that the relative yields of the photodeuterons are very small for $E_{\gamma max} \approx 30$—40 MeV and increase sharply with $E_{\gamma max}$. This indicates that in the (γ, d) process we have to do with processes in which the residual nucleus with a high excitation energy plays a considerably greater role than in the (γ, p) reaction.

The values of the relative yields of deuterons for Cu with $E_{\gamma max} = 34$ Mev (see table) are of the order 10^{-3} and are not in agreement with the results of a number of authors (see [1]). Taking into account the results of the present work and those of Forkman[2] and Makhnovskii,[3] we can definitely state that the results of the investigations in which large values of $Y(\gamma, d)/Y(\gamma, p)$ were established earlier for low-energy particles with $E_{\gamma max} < 30$ MeV are erroneous. As noted in [2], the observed ratio of $Y(\gamma, d)/Y(\gamma, p)$ for low-energy particles corresponds to values calculated with the aid of the statistical theory of nuclear reactions. On the basis of this fact alone, one cannot, of course, make unambiguous conclusions on the mechanism of the production of low-energy photodeuterons, while additional investigations are extremely difficult owing to the low deuteron yield.

However, on the basis of the experimental results shown in the table, we can draw some conclusions on certain features of the (γ, d) reaction involving the emission of low-energy deuterons observed in experiments with $E_{\gamma max} \approx 90$ MeV. The relative deuteron yield $Y(\gamma, d)/Y(\gamma, p)$ for Cu with $E_{\gamma max} = 90$ MeV is considerably larger than $Y(\gamma, d)/Y(\gamma, p)$ for particles of the same energy with $E_{\gamma max} = 34$ MeV. Consequently, the basic part of the photodeuterons is due to transitions occurring under the action of γ quanta of energy between 30 and 90 MeV. Here, of course, the residual nuclei have an excitation energy sufficient for the emission of two particles accompanying the deuterons. Hence, we can conclude that the low-energy photodeuterons emitted in the photodisintegration of Cu induced by bremsstrahlung with $E_{\gamma max} = 90$ MeV are produced primarily in complex reactions involving the emission of several particles. This is in agreement with the results of the investigations of the excitation functions of (γ, d) reactions in light nuclei.[8]

The angular distributions for deuterons and protons (E = 7.5—15 MeV) emitted in the photodisintegration of Li^7 induced by bremsstrahlung with $E_{\gamma max} = 63$ MeV (Fig. 5) display very similar variations of the cross section for the (γ, p) and the (γ, d) reactions with the angle of emission of the particles. They possess the same characteristics which were observed in the angular distributions of deuterons and protons of energy greater than 15 MeV.[4]

The excitation function for the $Li^7(\gamma, t)$ reaction with the emission of tritons with energy in the interval 7.5—15 MeV is shown in Fig. 4b. The mean triton energy of this interval, with allowance for the shape of the energy distribution, is approximately 9.6 MeV. The excitation function was obtained from the smoothing of the curve for the cross section per effective quantum under the assumption that the bremsstrahlung spectrum has the form

$$n(E_\gamma)\,dE_\gamma = Q\,dE_\gamma/E_\gamma.$$

The excitation function has a sharp maximum at a γ-quantum energy corresponding to the energy threshold of the $Li^7(\gamma, t)He^4$ reaction for tritons of energy $E \approx 9.6$ MeV, which is the mean value of the energy of the recorded tritons. The smooth increase in the cross section with the γ-quantum energy in the region past the maximum (where it is assumed that the He^4 residual nucleus has no excited levels) can be explained by the contribution of processes in which the emission of tritons is accompanied by the emission of other particles.

Figure 5 shows the angular distributions of tritons of the above-mentioned energy interval emitted in the photodisintegration of Li^7 induced by bremsstrahlung with $E_{\gamma max} = 63$ MeV. The recorded tritons are primarily products of the $Li^7(\gamma, t)He^4$ reaction. The contribution from tritons produced in reactions in which several particles are emitted, as is indicated by an estimate based on the results of the measurement of the excitation function for the $Li^7(\gamma, t)$ reaction and the shape of the bremsstrahlung spectrum, is no greater than 15%.

The triton angular distribution has the form $A + B \sin^2 \theta$. This fact can be regarded as evidence that the phototritons are produced in the direct process of dipole absorption of γ quanta by the Li^7 nucleus as a "triton + α-particle" system.

The authors express their gratitude to V. P. Chizhov for discussion of the results and a number of comments and to the synchrotron crew of the Physico-Technical Institute under the direction of N. N. Chernov for aid in setting up the experiment.

[1] M. E. Toms, Bibliography of Photonuclear Reactions, U.S. Naval Research Laboratory, Washington, D.C., 1960.

[2] B. Forkman, Nuclear Phys. **23**, 269 (1961).

[3] E. D. Makhnovskii, JETP **41**, 1091 (1961), Soviet Phys. JETP **14**, 779 (1962).

[4] V. P. Chizhov, JETP **38**, 809 (1960), Soviet Phys. JETP **11**, 587 (1960).

[5] V. P. Chizhov and L. A. Kul'chitskii, JETP **36**, 345 (1959), Soviet Phys. JETP **9**, 239 (1959).

[6] A. V. Kulikov and Yu. M. Volkov, PTÉ (Instrum. and Exptl. Techniques) in press.

[7] S. P. Kruglov, ZhTF **28**, 2310 (1958), Soviet Phys.-Tech. Phys. **3**, 2120 (1959).

[8] Volkov, Kulikov, and Chizhov, JETP **42**, 61 (1962), this issue, p. 42.

Translated by E. Marquit
17