V. M. Dukel' skii and O. B. Firsov for discussion of the work and for useful critical comments.

[1] H. F. Newhall, Phys. Rev. **62**, 11 (1942).
[2] D. R. Bates and A. Dalgarno, Proc. Phys. Soc. **A66**, 972 (1953).
[3] J. D. Jackson and H. Schiff, Phys. Rev. **89**, 359 (1953).
[4] T. Pradhan, Phys. Rev. **105**, 1250 (1957).
[5] D. R. Bates and G. Griffing, Proc. Phys. Soc. **A66**, 961 (1953).
[6] H. Bartels, Ann. Physik **13**, 373 (1932).
[7] J. P. Keene, Phil. Mag. **40**, 369 (1949).
[8] F. L. Ribe, Phys. Rev. **83**, 1217 (1951).
[9] Fogel', Krupnik, and Safonov, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 589 (1955), Soviet Phys. JETP **1**, 415 (1955).
[10] J. B. H. Stedeford and J. B. Hasted, Proc. Roy. Soc. **A227**, 466 (1955).
[11] H. B. Golbody and J. B. Hasted, Proc. Roy. Soc. **A240**, 382 (1957).
[12] E. Lindholm, Proc. Phys. Soc. **A66**, 1068 (1953).
[13] H. S. W. Massey and E. H. S. Burhop, Electronic and Ionic Impact Phenomena, Oxford, 1952.
[14] Fedorenko, Afrosimov, and Kaminker, J. Tech. Phys. (U.S.S.R.) **26** 1929 (1956), Soviet Phys. JTP **1**, 1861 (1956).
[15] N. V. Fedorenko and V. V. Afrosimov, J. Tech. Phys. (U.S.S.R.) **26**, 1941 (1956), Soviet Phys. JTP **1**, 1872 (1956).
[16] V. V. Afrosimov and N. V. Fedorenko, J. Tech. Phys. (U.S.S.R.) **27**, 2557 (1957), Soviet Phys. JTP **2**, 2378 (1957).

Translated by J. G. Adashko
288

SOVIET PHYSICS JETP VOLUME 34(7), NUMBER 6 DECEMBER, 1958

SOME PHOTOREACTIONS ON LIGHT NUCLEI

V. N. MAIKOV

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor January 8, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 1406-1419 (June, 1958)

The reactions $C^{12}(\gamma, 3\alpha)$, $O^{16}(\gamma, 4\alpha)$; $(\gamma, p\alpha)$ on C^{12}, N^{14}, and O^{16}; and $C^{12}(\gamma, pt)2\alpha$ were investigated with photographic emulsions. The dependence of the γ-ray energy on the reaction cross section and the energy and angular characteristics of the disintegration products were obtained. The contribution of the reactions $C^{12}(\gamma, p\alpha)Li^7$ and $C^{12}(\gamma, pt)2\alpha$ to the total cross section for star production in the photon energy region from 30 to 80 Mev is estimated. Some possible mechanisms for the $(\gamma, p\alpha)$ processes are discussed.

THE interaction of photons with light nuclei, leading to the emission of three or more particles, has been little investigated in the region of γ-ray energy above 30 Mev. Yet observation of stars in photographic emulsions[1,2] shows that similar "complex" reactions give, with increased γ-ray energy a substantial contribution to the total photon-absorption cross section. Investigation of such processes can, therefore, furnish information about the interaction of γ-rays with light nuclei, which becomes substantial at high energies.

In the present work we consider several types of photonuclear reactions in C^{12}, N^{14} and O^{16}. The method of photographic emulsions we used, making it possible to register charged disintegration products. The work was carried out with type Ia-2 NIKFI plates 500 μ thick, in which tracks of singly- and multiply-charged particles could be separated without difficulty. The experimental conditions were the same in the study of all reactions. Emulsions were irradiated by a bremsstrahlung beam from the synchrotron target at maximum energies of 150 and 250 Mev at an angle of 90° to the direction of the γ-rays. Electrons were removed from the beam by a magnetic field of strength 7000 oersteds. During irradiation, the plates were shielded from scattered radiation by carbon blocks. A graphite ionization chamber directly behind the plates measured the γ-ray beam going through the emulsions.

I. ALPHA-PARTICLE REACTIONS ON CARBON AND OXYGEN

Much work has been devoted to the study of the photodisintegration of carbon into three α-particles

$$C^{12} + \gamma \rightarrow 3He^4 - 7.28 \text{ Mev} \qquad \text{(I)}$$

and of oxygen into four α-particles

$$O^{16} + \gamma \rightarrow 4He^4 - 14.4 \text{ Mev} \qquad \text{(II)}$$

Experiments were carried out both with Li radiation and with bremsstrahlung at maximum energies ~30 and 70 Mev. At present it can be considered established that the reaction (I) goes, in the region of energy studied up to ~40 Mev, mainly through different excited intermediate states of the Be^8 nuclide. Analysis of reaction (II) is more difficult.

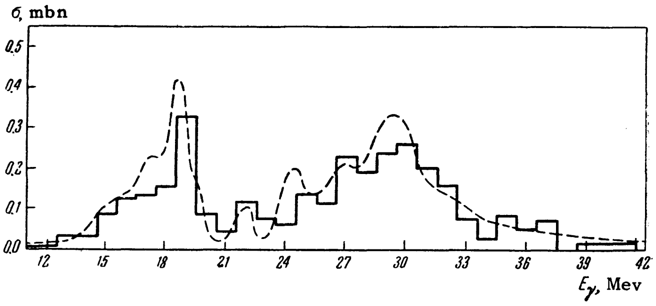

FIG. 1. Dependence of the cross section for reaction (I) on γ-ray energy. The solid line gives our data, the dashed one the data of reference 3.

However, there is reason to believe that intermediate states of C^{12} and Be^8 take part in the process.

In experiments on the synchrotron with maximum energy 70 Mev,[3,4] the reactions (I) and (II) were observed right up to photon energies ~45 Mev. Even prior to publication of these results in 1951, an attempt to observe reactions (I) and (II) at higher energies was made in our laboratory (thesis project by Iu. V. Nikol' skii). Photoemulsions were irradiated on the Physics Institute synchrotron at a maximum energy of 250 Mev. Although no noticeable yield from these reactions was observed above 45 Mev, the statistical accuracy in this experiment was not high. Somewhat later, an experiment with maximum energies 150 and 250 Mev was set up. However, as previously, the reactions $C^{12}(\gamma, 3\alpha)$ and $O^{16}(\gamma, 4\alpha)$ were observed only in the photon energy region up to ~45 Mev. The results of the experiment are given below.

In the photographic emulsions, three- and four-pronged stars were selected, all tracks of which, according to visual determination, belonged to α-particles. The laws of conservation of energy and momentum were used to distinguish between reactions (I) and (II). As criteria of the fulfilment of these laws we introduced the quantities

$$\Delta p = |\Delta \mathbf{p}| = \left|\mathbf{P}_\gamma - \sum_i \mathbf{P}_i\right|$$

and

$$(\Delta p)_{xy} = |(\Delta \mathbf{p})_{xy}| = \left|\sum_i (\mathbf{P}_i)_{xy}\right|,$$

where $\mathbf{P}_i$ is the momentum of the α-particle, determined from the relation $P_i = \sqrt{2M_iE_i}$, with the proton mass taken to be unity; $E_\gamma = \sum_i E_i + E_Q$, $P_\gamma = E_\gamma/30.6$ are the energy and momentum of the photon responsible for the disintegration; E_Q is the binding energy; $(P_i)_{xy}$ is the projection of the α-particle momentum on the xy plane, perpendicular to the direction of the γ-ray. One can show that the spread in values of Δp and $(\Delta p)_{xy}$ produced by exclusively experimental errors should follow the Maxwellian distributions $(\Delta p)^2 \times \exp\{-h^2(\Delta p)^2\}$ and $(\Delta p)_{xy} \exp\{-h^2(\Delta p)^2_{xy}\}$ respectively.

Values of Δp and $(\Delta p)_{xy}$ were calculated for each three-pronged star. Their distributions were quite close to the expected distribution law. An analogous result was obtained for four-pronged stars. In addition, each case displayed a "tail" for large values of Δp, due apparently to an admixture of extraneous reactions. The distributions were cut off at $\Delta p = 1.8$ and $(\Delta p)_{xy} = 1.3$, corresponding to 98% of the areas under the curves.

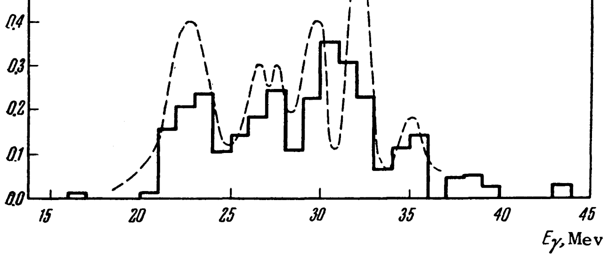

FIG. 2. Dependence of the cross section for reaction (II) on the γ-ray energy. The solid curve gives our data, the dashed one the data of reference 4.

In the analysis of the momentum balance 340 stars were employed for reaction (I) and 180 stars for reaction (II).

The cross sections for reactions (I) and (II) are given, as functions of photon energy, in Figs. 1 and 2. Experimental data obtained by irradiation at maximum energies of 150 and 250 Mev were grouped together, since no difference was observed in the cross-section behavior in these two cases. In spite of the high maximum energy of the spectrum not a single case with γ-ray energy > 50 Mev was observed. The dependence of the cross section for reactions (I) and (II) on the obtained photon energy agreed satisfactorily with the results of references 3 and 4. The sharp drop in the cross section of the studied reactions in the high-energy region is seemingly connected with the competition of various processes entailing a more complete break-up of the nucleus. Thus, the $(\gamma, p\alpha)$ reaction cross sections in carbon and oxygen, with higher thresholds, have maxima in the region ~ 35 Mev.

II. $(\gamma, p\alpha)$-REACTIONS IN C^{12}, N^{14} AND O^{16}

Another typical photonuclear reaction in C^{12}, N^{14} and O^{16} was investigated in the same emulsions:

$$C^{12} + \gamma \to H^1 + He^4 + Li^7 - 24.6 \text{ Mev}, \quad \text{(III)}$$
$$N^{14} + \gamma \to H^1 + He^4 + Be^9 - 18.3 \text{ Mev}, \quad \text{(IV)}$$
$$O^{16} + \gamma \to H^1 + He^4 + B^{11} - 23.1 \text{ Mev}. \quad \text{(V)}$$

Up to the present there has been no information about the mechanism of such a process.

1. Separation of the Reactions

A quantitative method of separating the reactions (III), (IV) and (V) was described in reference 5, where the experimental range-energy relations for Li^7, Be^9 and B^{11} nuclei in emulsion were obtained. Using these, it is possible to carry out a quantitative separation of stars with respect to reaction, using the laws of conservation of energy and momentum. In each case of disintegration, three values of Δp corresponding to the three reactions were calculated, leaving out of consideration the qualitative separation already carried out. Each of the stars was related to that reaction for which the following conditions were satisfied:

$$\left.\begin{array}{r}\Delta p \leqslant 1.8\\ (\Delta p)_{xy} \leqslant 1.3\end{array}\right\} \text{ in the case } R_0 > 3\mu.$$

If these criteria were satisfied at the same time by two "neighboring" reactions, then the star was related to that reaction for which Δp had a minimum value. In the case where the recoil of the nucleus is $R_0 < 3\mu$, the distributions of Δp for two "neighboring" reactions begin to overlap all the more, since the distances between the range-energy curves become comparable with the errors in the measurement of the ranges. In this case, the character of the disintegration cannot be determined with sufficient reliability for all stars. The following (not quite rigorous) criteria were employed

$$\left.\begin{array}{r}\Delta p - \text{minimal}\\ (\Delta p)_{xy} \leqslant 1.3\end{array}\right\} \text{ in the case } R_0 < 3\mu.$$

In spite of the insufficient accuracy of this condition, it may, however, be considered that reactions (III) and (V) were separated correctly in 70 to 80% of the cases (in the region $R_0 < 3\mu$) if the Gaussian character of the distribution of range errors is taken into account.

In 20% of the cases, the track of the singly charged particle went out of the emulsion. Application of the conservation laws to these stars made it possible to separate them with respect to reaction and to define the energies of these particles, assuming that the tracks were produced by protons. As a check on the correctness of the assumption, the energies of the particles going out were determined by counting grains, and the values obtained were compared with the energies determined by the conservation laws. Within the limits of experimental error, the same proton energies were obtained by these two independent means.

As a result of the analysis carried out, 1088 stars were sorted out as listed below:*

Reaction	(III)	(IV)	(V)
Number of stars	545	197	346

In the work of reference 6, the same reactions were considered and separated by an analogous method. However, the yield of reaction (V) turned out to be insignificant compared with (III) and (IV). This fact contradicts our results, and seems doubtful, since the oxygen content of Ilford emulsions is twice that of nitrogen. The small relative yield of reaction (V) was due, it would seem, to the fact that in the theoretical curves for Be and B were used to separate the reactions (IV) and (V). As already noted,[5] in the region of small energies these curves are not in agreement with experiment and their use can lead to an increase in the number of cases of reaction (IV) and a decrease in those of (V).

*A supplementary analysis of these stars showed that the possible admixture of several alternative reactions $(\gamma, d\alpha)$, (γ, pHe^3), giving stars of the same type, did not exceed ~ 5% in the case of reaction (III) and ~ 10% in the case of reactions (IV) and (V).

TABLE I. Integral cross sections for reactions (III) and (V) in mbn-Mev

E_γ, Mev	25—40	40—55	55—70	70—85
(III)	3.85±0.20	1.78±0.17	0.82±0.13	0.38±0.11
(V)	3.11±0.21	1.64±0.18	0.64±0.14	0.16±0.08

2. Experimental Results

The photographic method made it possible to determine all basic properties of the reaction products. In our experiment the energy of the particle was determined by the range, using the dependence E = f(R). The error in measuring the length of short tracks (α-particles and recoil nuclei) comprised $\sim 0.5\,\mu$. In the case where the track of the proton left the emulsion, the energy of the particle was determined from the conditions of conservation of momentum in the reaction. Here the error in the energy depended to large degree on the form of the star, but did not exceed 15%. The energy of the photon in each case of disintegration was determined from the relation $E_\gamma = \sum_i E_i + E_Q$, where E_i is the kinetic energy of the particle and E_Q is the binding energy. In the case of tracks remaining in the emulsion, the error in determination of E_γ constituted ~ 1 Mev.

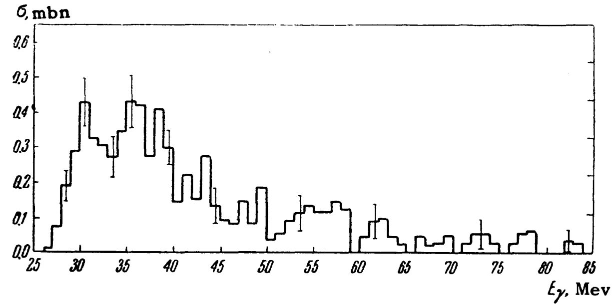

FIG. 3. Dependence of the cross section for reaction (III) on γ-ray energy.

Figure 3 shows the dependence of the cross section of process (III) on γ-ray energy. Integral cross sections for various energy ranges are given in Table I. In our work the cross section for reaction (III) in the range of photon energies from 25 to 40 Mev was found to be 2.9 times larger than in reference 6. The reasons for this large discrepancy are not clear. We note only that in our experiment the statistics were approximately 5 times larger than in the work cited.

The energy distributions of protons and α-particles are given in Fig. 4. In the proton spectrum, a high energy "tail" ($E_p > 15$ Mev, 16%) was observed. Stars in which $E_p > 15$ Mev arose mainly (75%) from photons with energy > 45 Mev. In this case the protons carried, on the average, $\sim 75\%$ of the energy $E_0 = E_\gamma - E_Q$.

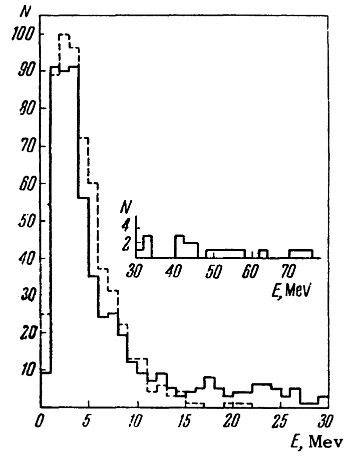

FIG. 4. Energy distributions: solid lines – protons, dashed lines – α-particles from reaction (III).

The angular distributions of protons and α-particles showed a noticeable anisotropy relative to the direction of the γ-rays in the carbon c.m. system. For protons, in addition, a displacement of the maximum into the forward hemisphere was observed.

The cross section for reaction (V) as a function of γ-ray energy is shown in Fig. 6, and the integral cross sections are listed in Table I. The energy distributions of protons, α-particles, and the nuclide B^{11} have the same character as the analogous distributions in the case of reaction (III). A great similarity is also observed in the angular characteristics.

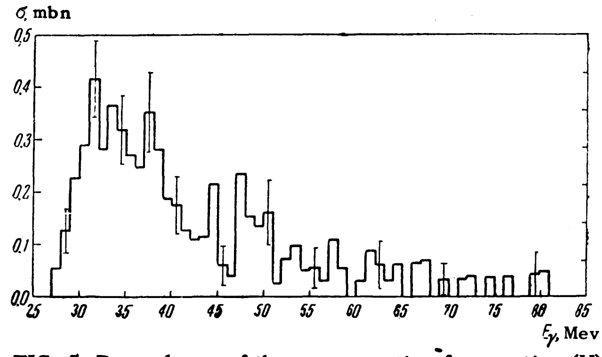

FIG. 5. Dependence of the cross section for reaction (V) on γ-ray energy.

In Fig. 5 the dependence of the yield of reaction (IV) on the γ-ray energy is given. The integral cross section of the reaction in the region E_γ = 30 to 80 Mev was 7.35 ± 0.56 mb-Mev.

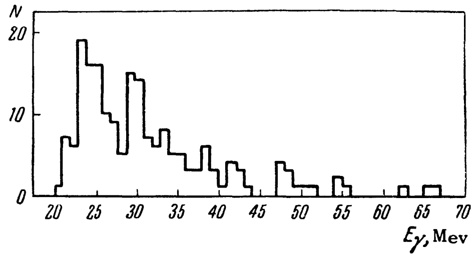

FIG. 6. Dependence of the yield for reaction (IV) on γ-ray energy.

3. Analysis of Experimental Data and Discussion of the Results

The similarity of basic characteristics of the reactions (III) and (V) noted above is apparently not accidental, since the initial nuclei have a number of common characteristics, and the reactions considered are of the same type and occur in the same region of γ-ray energy. It might be expected, therefore, that the mechanisms of interaction of the photon with the nuclei C^{12} and O^{16}, which lead respectively to reactions (III) and (V), are the same. At present, there is no concrete theoretical representation of the process of this "complete" break-up. We shall try, therefore, within the experimental framework, to clarify the most characteristic features of the process.

We consider how the energy of the photon that produces the disintegration is distributed among the products of the reaction in different intervals of the γ-ray energy. We shall compare the energy distributions of the particles with those calculated under the assumption of a symmetrical distribution of the energy among the products of the disintegration. The latter do not depend on the nature of the initial interaction. It will be assumed that there is no interaction between particles in the final state, and the distributions will be determined only by the corresponding volume in phase space. The energy distribution of the particles has in this case the form

$$P(E)\,dE \sim E^{1/2}(E_m - E)^{1/2}\,dE \qquad (1)$$

and the mean value of the energy is

$$\bar{E} = {}^1/_2 E_m, \qquad (2)$$

where $E_m = E_0(A - M)/A$ is the maximum possible energy of a particle of mass M; $E_0 = E_\gamma - E_Q$ is the energy distributed among the reaction products; A and M are the masses of the initial nucleus and studied particle, respectively. The diagram in Fig. 7 shows the mean values of the proton

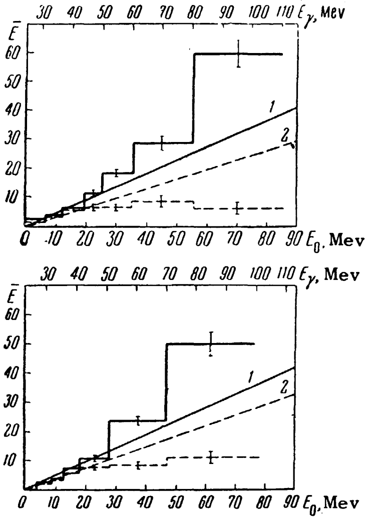

FIG. 7. Dependence of the mean energy: solid line – protons, dashed line – α-particles, plotted against energies E_0 and E_γ, in the case of reactions: (III) above and (V) below; 1 and 2 are the theoretical distributions corresponding to Eq. (2).

energies (solid line) and α-particle energies (dashed line) for different intervals in E_0 (and E_γ) for reactions (III) and (V). The experimental results are compared with the data calculated from Eq. (2). As can be seen from the figure, there is satisfactory agreement, in both cases, in the region of photon energies up to ~ 50 Mev. Above this energy we observe a progressive deviation from the theory. In view of the insufficient statistics, we shall consider the energetic and angular characteristics of the reaction products separately for two intervals of photon energy: E_γ < 50 Mev and E_γ > 50 Mev (the choice of these intervals is arbitrary).

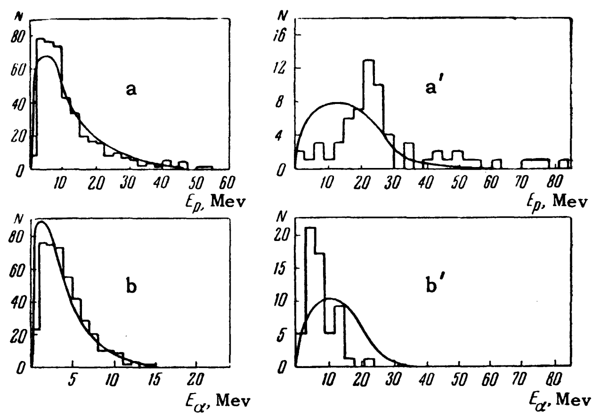

FIG. 8. Energy distributions: a, a′ – protons; b, b′ – α-particles from reaction (III) in two intervals of photon energy: a, b – E_γ < 50 Mev,aand a′, b′ – E_γ > 50 Mev. The smooth curve gives the distribution (1).

Figure 8 shows the energy distributions of protons and α-particles from reaction (III) for these two intervals of γ-ray energy. The smooth curve shows the distribution (1) with account of the dependence of the particle yield on the photon energy. Although the agreement might be considered satisfactory, for cases a and b, for $E_\gamma > 50$ Mev the form of the energy spectrum differs markedly from the theoretical curve. The energy spectrum of protons from oxygen has the same character.

We consider further the experimental results from the point of view of possible interaction of the particles in final states. We introduce the relative energy of two particles T, equal to the sum of energies of these particles in their c.m. system, and relate it to the total energy E_0 distributed among all particles. Were there no interaction between the pair of particles considered, the distribution of the quantity T/E_0 would have, in our case, the form

$$P(T/E_0) \sim (T/E_0)^{1/2}(1 - T/E_0)^{1/2}. \quad (3)$$

Equation (3) is obtained from Eq. (1) on the basis of kinematic transformations, and has the same form.

Nuclear interaction may also occur between particles in final states. The general theory of this process has been given by Watson[7] for particles of small relative momenta. Unfortunately, a quantitative comparison with the theory is not possible, at present, because of the low statistical accuracy of the results in the region of applicability of the theory. Finally, both in Eq. (3) and in the nuclear interaction, it is necessary to take into account the Coulomb interaction of the disintegration products, which may play an important role in our case of multiply charged particles. This interaction should lead, in both cases, to a decreased yield of particles with both small and large relative energies.

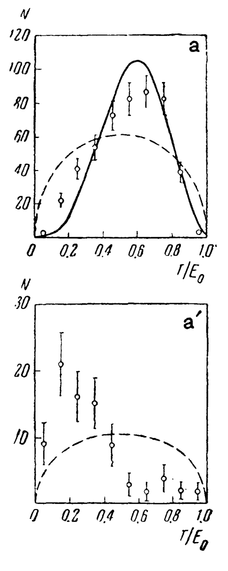

FIG. 9. Distribution of relative energy of the pair (α-particle plus recoil nucleus) in reaction (III). a – $E_\gamma < 50$ Mev; a' – $E_\gamma > 50$ Mev.

Distributions of the quantity T/E_0 for the pair (α-particle plus recoil nucleus) are given in Fig. 9 for two intervals of photon energy in reaction (III) [in the case of reaction (V), the distribution has the same character]. The same figure shows the distribution (3) for noninteracting particles (dashed curve). It can be seen from Fig. 9 that the experimental results corresponding to $E_\gamma <$ 50 Mev do not completely agree with Eq. (3). However, even a rough calculation of the Coulomb interaction between all three particles (solid curve in Fig. 9) gives a fair agreement with experiment. For photon energies $E_\gamma > 50$ Mev, the analogous experimental data are in clear contradiction to the distribution of Eq. (3). Account of the Coulomb interaction in Eq. (3) would make the divergence even greater. Thus, a very characteristic peculiarity of the process is the occurrence of small relative energies of the pair (α-particle plus recoil nucleus) or the predominant emission of protons with energies near to the maximum possible.

We consider further the angular characteristics of the processes (III) and (V) in the same intervals of γ-ray energy. Figure 10 shows the angular distributions of protons from reaction (III) for $E_\gamma <$ 50 Mev and $E_\gamma > 50$ Mev. The statistical errors are indicated parallel to the ordinate; ϑ is the angle between proton and direction of the γ-ray in the center-of-mass system of carbon. The angular distributions were approximated in the form

$$f(\vartheta) \sim (\alpha + \sin^2\vartheta)(1 + \beta\cos\vartheta). \quad (4)$$

The coefficients, determined by the method of least squares, are given in Table II. In Fig. 10 the curve corresponding to Eq. (4) is drawn as the solid line. From consideration of the coefficients in Table II it can be seen that the angular distributions of protons from reactions (III) and (V) have the following general properties: the isotropic part of the angular distribution changes markedly in going from $E_\gamma < 50$ Mev to $E_\gamma > 50$ Mev, and the change in the position of the maximum of the distribution relative to 90°, if present, is not substan-

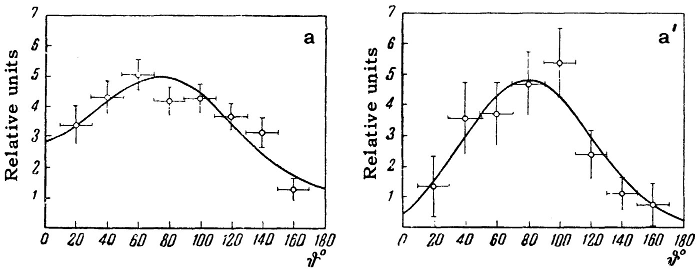

FIG. 10. Angular distribution of protons in reaction (III): a – $E_\gamma < 50$ Mev, a' – $E_\gamma > 50$ Mev.

tial, constituting $\sim 10°$ in both cases.

An attempt was made to observe experimentally the presence of an intermediate state in the reactions considered. It is well known that various intermediate nuclei have been observed in several disintegration processes, such as $C^{12}(\gamma, 3\alpha)$, and also in several other reactions on B and Be. This has led to the idea that the disintegration does not proceed in a single act, but is a complex process of successive emission of particles with formation and decay of excited states of several intermediate nuclei. It should be noted, however, that such a character has been observed mainly in the region of comparatively low photon energies and low excitation energies. Under our conditions, such a process is not completely obvious and experimental verification is required. Let us consider, for example, the reaction (III). One could propose at least three ways in which the reaction might proceed:

$$C^{12} + \gamma \to H^1 + B^{11*}; \quad B^{11*} \to He^4 + Li^7; \qquad \text{(IIIa)}$$
$$C^{12} + \gamma \to He^4 + Be^{8*}; \quad Be^{8*} \to H^1 + Li^2; \qquad \text{(IIIb)}$$
$$C^{12} + \gamma \to Li^7 + Li^{5*}; \quad Li^{5*} \to H^1 + He^4. \qquad \text{(IIIc)}$$

In order to distinguish the paths of decay noted above, an analysis of the excitation energy E^* of the intermediate nucleus was employed. The excitation energies of B^{11}, Be^8, and Li^5 were calculated for all stars relating to the reaction (III) under assumptions corresponding to the three modes of decay:

$$E^* = \sum_i^2 E_i + E_Q - E_k,$$

where E_i is the energy of the corresponding decay particle, E_Q is the binding energy of the intermediate nucleus in the decay considered, and E_k is the kinetic energy of the intermediate nucleus. If the intermediate state indicated really occurs, then an excited level of such nuclei should appear in the distribution so calculated. In our case such an analysis involved several difficulties. In fact, the expected decay should proceed through rather highly excited levels, since the threshold of disintegration is 8.5 Mev in case (IIIa) and 17.2 Mev in case (IIIb), and in this energy region the known levels of the nuclei considered are rather dense. In any case, the distance between them is not much larger than the error in determination of E^*. Comparison of our experimental results with known levels of B^{11} and Be showed that the maximum in the distribution of excitation energy came in the region of those levels, with which the decay studied is most often observed.* In the region $E_\gamma < 50$ Mev, neither of the schemes (IIIa) and (IIIb) contradicted experiment, whereas for $E_\gamma > 50$ Mev the formation of the intermediate nucleus B^{11} can be considered as preferred. Because of the poor resolving power of this method, it was not possible to separate satisfactorily the intermediate nuclear states, and therefore no definite conclusions could be drawn about the occurrence of the decay scheme proposed. Our results, however, do not contradict such a mechanism.

TABLE II. Coefficients in the distribution of Eq. (4)

Reaction	$E_\gamma > 50$ **Mev**		$E_\gamma > 50$ **Mev**	
	α	β	α	β
(III)	0.98	0.32	0.17	0.41
(V)	0.76	0.41	0.04	0.45

The above analysis of the experimental data does not, at the present time, allow us to draw definite conclusions about the type of interaction between photons and light nuclei leading to the indicated reaction. We can, however, formulate several characteristic properties of the process considered, which could serve as a basis for constructing various models to represent the mechanism of the reaction:

1. The total cross sections for reactions (III) and (V) (up to $E_\gamma = 85$ Mev) are equal, respectively, to 6.8 mbn-Mev and 5.5 mbn-Mev. The dependence of the cross section on γ-ray energy has in both cases broad maxima in the region of ~ 35 Mev. The energy distributions of protons and α-particles in carbon and oxygen have the same form. The angular distributions of protons from reactions (III) and (V) coincide, within the limits of experimental error. The great similarity of all characteristics of the reactions (III) and (V) indicates that the mechanism of interaction of photons with carbon and oxygen nuclei, leading to the indicated reactions, is apparently the same and that the individual peculiarities of these nuclei are not essential in this case.

2. The distribution of photon energy among the reaction products, and also the form of the angular distribution, change with increasing γ-ray energy, so that the fraction of the photon energy transmitted to the proton is increased and the isotropic part of the angular distribution is decreased. This characteristic is possibly connected with a change in the mechanism of γ-ray absorption by the nuclei (two intervals might be conditionally

*An analogous analysis of excitation energy was made in reference 6. The experimental results are in satisfactory agreement with our data.

separated: $E_\gamma < 50$ Mev and $E_\gamma > 50$ Mev).

3. In the region $E_\gamma = 25$ to 50 Mev no one particle in the reaction is energetically distinguished from the others. Moreover, the energy of the absorbed photon is spread among the disintegration products in a symmetrical fashion, satisfying Eq. (1) if the Coulomb interaction between particles is taken into account.

The simplest way to explain the observed character of the energy distribution is to assume that the absorption of the photon by the nucleus leads to the disintegration into three particles in a single act. In this case the equally-probable position of the particles should lead to a symmetrical division of energy [Eq. (1)]. However, such a distribution of energy can also be connected with another possible mechanism of interaction between the photon with the nucleus. In particular, it does not contradict the concept of formation and subsequent decay of a compound nucleus with a high excitation energy and high density of levels. In spite of the indefiniteness of the conclusions, it is at least possible to exclude any local interaction, since it assumes a special status for some particles.

4. For $E_\gamma > 50$ Mev the protons in reactions (III) and (V) are energetically quite distinct from other particles and carry away, on the average, from 60 to 90% of the energy E_0, depending on the photon energy. Accordingly the two other particles are emitted with small relative energies.

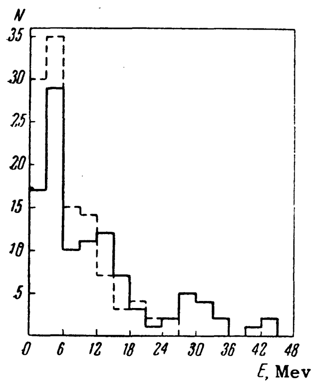

FIG. 11. Energy distributions: solid line – protons, dashed line – tritons.

Thus, the distribution of energy among the reaction products does not correspond to the concept of disintegration of the nucleus into three particles in a single act. As to the possibility of formation of the intermediate states B^{11} or N^{15}, our results, as noted above, do not contradict this concept. Several assumptions can be stated relative to the primary process of interaction of the photon with the nucleus. First, this process should be of local character. One possible process of this type is the direct photoeffect. The latter, as well known, assumes that in the interaction one of the particles is "torn loose," carrying off a large part of the photon energy and leaving the nucleus in the ground or a low excited state. In our case the remaining nucleus, if it is formed at all, should possess a comparatively high excitation, so that the decay proceeds into the particles observed. In principle such a process could, apparently, explain the results obtained in the range of photon energies above 50 Mev.

III. THE REACTION $(\gamma, pt)\,2\alpha$ ON CARBON*

Besides the reactions $C^{12}(\gamma, 3\alpha)$ and $C^{12}(\gamma, p\alpha)$ already considered, one more reaction involving the disintegration of carbon

$$C^{12} + \gamma \to H^1 + H^3 + He^4 + He^4 - 27\ \text{Mev} \qquad \text{(VI)}$$

was observed in the same emulsions for photon energies up to 150 Mev.

Detailed information about this reaction does not exist, at present, in the literature. The stars from reaction (VI) were identified visually as four pronged, consisting of two tracks of singly-charged particles and two of multiply-charged ones. However, besides (VI), it is possible to propose several other more typical, alternate reactions giving stars of an analogous form:

$$C^{12} + \gamma \to H^1 + H^1 + He^4 + He^4 + n + n; \qquad \text{(VII)}$$
$$C^{12} + \gamma \to H^1 + H^2 + He^4 + He^4 + n; \qquad \text{(VIII)}$$
$$C^{12} + \gamma \to H^2 + H^2 + He^4 + He^4. \qquad \text{(IX)}$$

It was thus difficult to separate the reactions (VI) because the tracks of the different singly-charged particles were difficult to distinguish and the external appearance of stars produced in different reactions was similar.

We chose tentatively 200 stars by visual identification. In the first step, singly-charged particles were divided into protons and tritons according to their ability to balance the momenta of the two α-particles in the plane perpendicular to the direction of the γ-rays (plane of the emulsion). The above rough division was improved upon by measuring the separate energy losses in the emulsions (method of grain counting). Each of the stars chosen in this fashion was taken to belong to reaction (VI) and this was verified by checking conservation of energy and momentum. In the case of tracks going out of the emulsion (which, as a rule, were those of singly-charged particles) the conditions were the same as in the separation of the $(\gamma, p\alpha)$ reaction. The distribution of values of Δp

*V. I. Turovtsev took part, together with the author, in this portion of the work.

for the 200 stars studied approximated well the expected Maxwellian distribution. In the selection, as earlier, the 132 stars having the values $\Delta p \leq 1.8$ and $(\Delta p)_{xy} \leq 1.3$, were segregated as belonging to reaction (VI). In addition, for all of the particles going out of the emulsion, the energy of the particle determined from energy-momentum balance was compared with that determined from its energy loss in the emulsion (method of grain counting). In this way 20 additional stars, for which the energies of the singly-charged particles lay outside the limits of experimental errors, were excluded. It can be considered that the identification of singly-charged particles was correctly made in all of the remaining cases of stars with tracks going out of the emulsion. As a check on the reliability of identification of the tracks ending in the emulsion, grains were counted in similar remaining tracks. A satisfactory division of tracks ascribed to protons and tritons was obtained. In this fashion, 112 stars were related to reaction (VI). One can consider the reactions (VII), (VIII), and (IX) to be excluded as a result of this analysis. An added proof of this was the search for the presence of reaction (IX) in stars related to (VI). All 112 stars were considered again under the assumption that they related to reaction (IX). However, not a single case among them could really be related to this reaction.

The statistics are at present insufficient for a detailed study of reaction (VI). We give, therefore, only several of the most general characteristics of the process.

The integral cross section for the reaction, in various regions of γ-ray energy, is shown below.

E_γ, Mev	30—40	40—55	55—70	70—85
σ, mbn-Mev	0.64±0.15	1.74±0.30	1.25±0.32	0.54±0.34

Figure 11 shows the energy distributions of protons and tritons. The stars in which $E_p > E_t$ constituted ~ 70% of the total. A maximum occurred in the α-particle energy distribution at ~ 2 Mev. The yield of particles with energy greater than 15 Mev was insignificant.

The angular distribution of protons in the center-of-mass system of carbon is given for $E_\gamma < 70$ Mev in Fig. 12. The distribution was approximated by the form $(\alpha + \sin^2 \vartheta)(1 + \beta \cos \vartheta)$. The coefficients, determined by the method of least squares, were: $\alpha = 0.16$, $\beta = 0.91$. Thus, the distinguishing features of the angular distribution of protons from reaction (IV) are a very small isotropic part and a displacement of the maximum relative to 90° (~ 20°).

As in the case of the $(\gamma, p\alpha)$-reaction, the distribution of the photon energy among the disintegration products was verified. A divergence from a "symmetrical" distribution of energy was observed, beginning with γ-ray energies ~ 70 Mev. The investigation of the energy and angular distributions as a function of γ-ray energies was difficult because of the small statistics. An attempt was made to consider the reaction from the point of view of the presence of intermediate states. Several different schemes for formation and subsequent decay of an excited intermediate nucleus can be imagined. We examined one of the possible chains of disintegration, i.e.,

$$C^{12} + \gamma \rightarrow H^1 + B^{11*};\ B^{11*} \rightarrow \begin{cases} H^3 + Be^{8*}; & Be^{8*} \rightarrow He^4 + He^4 \\ He^4 + Li^{7*}; & Li^{7*} \rightarrow H^3 + He^4. \end{cases}$$

Sufficiently complete information on the highly-excited levels of B^{11} does not exist. Besides this, we have already noted the difficulties connected with the analysis of the excitation energies. Our results, in any case, do not negate the possibility of formation of an intermediate state of B^{11}. A

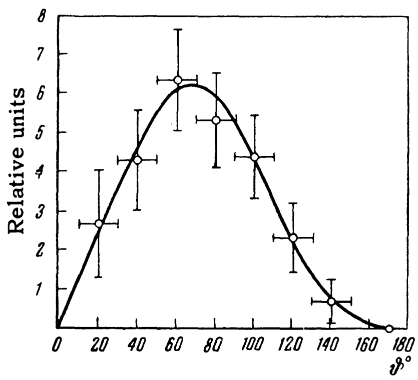

FIG. 12. Angular distribution of protons in reaction (VI) for $E_\gamma < 70$ Mev.

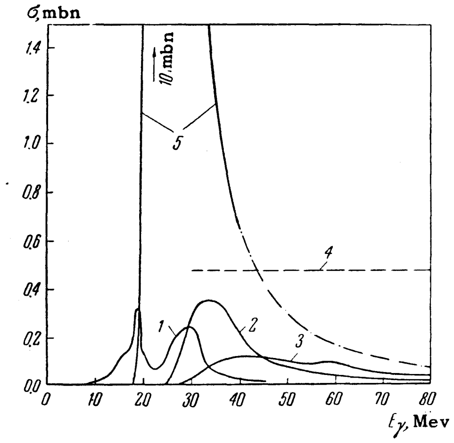

FIG. 13. Dependence of the cross sections for several reactions on the energy of the γ-ray: 1 – (I), 2 – (III), 3 – (VI), 4 – cross section for photoproduction of stars with two or more prongs in the interval $E_\gamma = 30$ to 80 Mev from reference 1, 5 – $C^{12}(\gamma, n)C^{11}$ from reference 8.

more definite conclusion can be drawn relative to the existence of Be^{8*}: the ground state and well-known 3-Mev state of Be^8 occur in many cases of reaction (VI).

The cross sections for reactions (I), (III) and (VI) in carbon are given in Fig. 13 as functions of γ-ray energy in the region up to 80 Mev. For comparison, the form of the (γn)-reaction in carbon[8] is also shown. In the work of reference 1, the integral cross section for photoproduction of stars with two and more prongs was measured for light emulsion nuclei (C^{12}, N^{14} and O^{16}) in the interval of photon energies from 30 to 80 Mev. It comprised 80-mbn-Mev.* Then the total cross section for photoproduction of stars in carbon is approximately 23 mbn-Mev, if the total cross section is divided up in the ratio of the masses of the nuclei (some basis for this is furnished by the fact that the total cross section for absorption of photons by nuclei is proportional to A). In our experiment the integral cross section for reactions (III) and (VI), in the range of γ-ray energies from 30 to 80 Mev, was $\sim$10 mbn-Mev, comprising $\sim$45% of the total cross section for star photoproduction. In the interval E_γ = 40 to 80 Mev, the total cross section for the reactions studied and for (γ, n) is $\sim$6.8 and 8 mbn-Mev. Thus, the reactions studied by us are processes which play an essential role in the photoproduction of stars and give, it would seem, an important contribution to the cross section for photon absorption in the region above the "giant" resonance.

*The reaction C^{12} (γ, 3α) was excluded here.

In conclusion, I should like to express my gratitude to Prof. V. I. Veksler and A. T. Varfolomeev for help in the work and discussion of the results obtained, and also to I. D. Bannikova and G. A. Prokhorova who took part in the work.

Note added in proof (23 May 1958). Calculations of the angular distributions of protons were made recently under the assumption of a direct photoeffect in the $S_{1/2}$ shells of C^{12} and O^{16}, with allowance for electric dipole and quadrupole absorption of γ-rays. A satisfactory agreement with the experimental angular distribution of protons from the reactions (III) and (V) was obtained for $E_\gamma >$ 50 Mev.

[1] R. M. Lebedev, Dissertation, Physics Institute, Academy of Sciences, U.S.S.R. (1953).

[2] S. Kikuchi, Phys. Rev. **86,** 41 (1952).

[3] E. K. Goward and J. J. Wilkins, Proc. Phys. Soc. **A65**, 671 (1952).

[4] W. K. Dawson and D. L. Livesey, Can. J. Phys. **34**, 241 (1956).

[5] V. N. Maikov, Приборы и техника эксперимента (Inst. and Meas. Eng.) (in press).

[6] D. L. Livesey, Can. J. Phys. **34**, 216 (1956).

[7] K. W. Watson, Phys. Rev. **88**, 1163 (1952).

[8] Barber, George, and Reagan, Phys. Rev. **98**, 73 (1955).

Translated by G. E. Brown
289

ERRATA TO VOLUME 7

Page	Reads	Should Read
533, title	Nuclear magnetic moments of Sr^{87} and Mg^{95}	Nuclear magnetic moments of Sr^{87}
645 Eq. (1)	$\ldots + \varkappa \sqrt{j_0 (j_0 + 1)}$	$\ldots - \varkappa \sqrt{j_0 (j_0 + 1)}$
647 Eq. (11)	$(L+1) \lvert B_L^- \rvert^2 - L \lvert B_L^+ \rvert^2$	$L (L+1) \left[\lvert B_L^- \rvert^2 - \lvert B_L^+ \rvert^2 \right]$
894 Eq. (12)	$\varepsilon_{11} = 1 - \sum \frac{\cdots}{\sqrt{\pi/\mu}}$	$\varepsilon_{11} = 1 - \sum \frac{\cdots}{\sqrt{\pi}\, \mu}$
897 Eq. (45)	$\sqrt{\pi/2}$	$\sqrt{\pi/8}$
979 Table II, heading	$\lvert E_\gamma > 50$ **Mev** $\lvert E_\gamma > 50$ **Mev**	$\lvert E_\gamma < 50$ **Mev** $\lvert E_\gamma > 50$ **Mev**
1023 Figure caption		a) $\omega < \omega_H$, b) $\omega > \omega_H$
1123 Eq. (2)	$\Gamma = \mu_2/\mu_1$	$\Gamma = \mu_2/\mu_1$, $\mu_\perp = (\mu_1^2 - \mu_2^2)/\mu_1$

ERRATA TO VOLUME 8

Page	Reads	Should Read
375 Figure caption	a) positrons of energy up to 0.4 ϵ, b) positrons of energy up to 0.3 ϵ.	a) positrons of energy up to 0.3 ϵ, b) positrons of energy up to 0.4 ϵ.
816 Beginning of Eq. (8)	$I_2^5 = (4\pi)^2 \ldots$	$I_2^2 = (4\pi)^5 \ldots$