EMISSION OF FAST DEUTERONS IN THE PHOTODISINTEGRATION OF O^{16}

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The relative yields of photonuclear reactions involving the emission of fast deuterons are determined. It is found that the deuterons are emitted as a result of complex photodisintegrations, with at least one more particle emitted along with the deuteron. Most of the deuteron yield is due to the $O^{16}(\gamma, dp)C^{13}$ and $O^{16}(\gamma, dn)N^{13}$ reactions. An angular correlation between the directions of emission of the deuterons and accompanying nucleons with energies $E > 2$ MeV in the $O^{16}(\gamma, dp)C^{13}$ and $O^{16}(\gamma, dn)N^{13}$ reactions is detected.

1. It was established in [1] on the basis of investigations of the excitation functions of the (γ, d) reactions on Li^6, Be^9, and B^{10} that photodeuteron yields become noticeable only at γ-quantum energies that exceed the kinematic threshold of the reaction in which one deuteron is emitted by approximately the amount of the binding energy of the nucleon in the residual nucleus. It was also shown there that an analogous effect is observed in (γ, d) reactions on B^{11} and Cu. On this basis, a hypothesis was advanced that the photodeuteron emission process is unique in that the emission of the deuterons must be accompanied in almost all cases by the emission of one or several nucleons. It is quite desirable to check the foregoing hypothesis in direct experiments and also to ascertain which particle is emitted with the photodeuterons, something of importance for the explanation of the singularities noted above in the (γ, d) reaction.

We made such experiments with a cloud chamber controlled by scintillation-counter telescopes. With the aid of the telescopes we have determined the energy and mass of the particle that causes the operation of the cloud chamber. The remaining information on each case of photodisintegration was obtained by studying the corresponding stereo photographs of the tracks in the cloud chamber. The procedure employed was already described in detail in [2].

We present below the results of an investigation of the photodisintegration of O^{16} with deuteron emission induced by γ-bremsstrahlung with maximum energy $E_{\gamma max} = 90$ MeV. The cloud chamber was filled with oxygen mixed with helium. The partial pressure of the oxygen and helium had a ratio 1 : 1.53 with a total pressure of 1.3 atm. The helium was added to increase the ranges of the recoil nuclei. The total pressure in the cloud chamber could not be less than the indicated value because of the structural features of the expansion apparatus of the chamber.

2. In the present experiments we registered deuterons with energies above 11 MeV with the aid of scintillation telescopes. The accuracy with which the deuteron energy was determined was approximately ± 5%. The energies of the recoil nuclei were determined from their ranges in the cloud chamber, which exceeded 3—4 mm as a rule. These measurements were based on a range-energy relation which we have determined experimentally for the N^{15} recoil nuclei produced in the reaction $O^{16}(\gamma, p)N^{15}$. These dependences were used to determine the range-energy curves for the neighboring nuclei by means of suitable calculations. The reactions in which two particles, of which one was a deuteron, were emitted were identified on the basis of the momentum and energy balance under the assumption that the residual nuclei are produced in the ground state. The neutron energy was determined accurate to ± 25% while the angle between the deuteron and neutron emission angles was accurate to ± 10°. The angle of emission of the proton accompanying the deuteron emission was determined accurate to ± 1°, and its energy was found with accuracy not worse than ± 20%.

3. The telescopes registered 27 photodeuterons with energies from 11 to 40 MeV. An analysis of the corresponding stereo photographs of the cloud-chamber tracks has shown that none of these cases could be identified as the $O^{16}(\gamma, d)N^{14}$ reaction. In all cases the emission of a deuteron was accompa-

Reaction	Yield, per cent	Threshold, MeV
(γ, dp)	41	28.25
(γ, dn)	41	31.2
Multiprong disintegrations	18	—

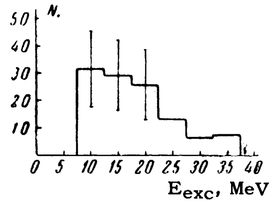

FIG. 1. Distribution of number of $O^{16}(\gamma, dp)C^{13}$ and $O^{16}(\gamma, dn)N^{13}$ reactions as a function of the excitation energy of the intermediate nucleus N^{14} (N is in arbitrary units).

nied by the emission of one or several particles. Consequently the probability of the $O^{16}(\gamma, d)N^{14}$ reaction amounts to less than $1/30$ of the probability of a reaction in which the deuteron is the result of a more complicated disintegration of O^{16}. The table lists the relative yields of various O^{16} photodisintegrations in which deuterons are emitted, and also the corresponding energy thresholds. The reactions in which the emission of a deuteron is accompanied by the emission of a single neutron cannot be distinguished in the cloud chamber from reactions in which several neutrons are emitted. However, in our conditions ($E_{\gamma max} = 90$ MeV) the contribution of the $(\gamma, d2n)$ reactions can be neglected, since the energy threshold of this reaction is approximately 20 MeV higher than the threshold of the (γ, dn) reaction.

On the basis of the data and the table we can conclude that the emission of the photodeuterons is accompanied in most cases by the emission of protons and neutrons, with the probabilities of the reactions $O^{16}(\gamma, dp)C^{13}$ and $O^{16}(\gamma, dn)N^{13}$ being approximately the same. Among the "multiprong" disintegrations indicated in the table are included reactions in which at least two particles are emitted besides the deuteron. It must be noted that the overwhelming majority of protons and neutrons accompanying the deuterons have energies from 2 to 20 MeV, with cases observed in which the nucleon energy is practically equal to the energy of the corresponding deuteron.

If we assume that the $O^{16}(\gamma, dp)C^{13}$ and $O^{16}(\gamma, dn)N^{13}$ reactions proceed in two stages, i.e., that the deuteron is emitted first, followed by the proton or neutron, then we can calculate the excitation energy of the intermediate nucleus N^{14}, assuming that the excitation energy of the residual nucleus C^{13} or N^{13} is equal to a certain average value, in the interval between 0 and 5 MeV for C^{13} and up to 2 MeV for N^{13}. The indicated upper limits for the excitation energies of C^{13} and N^{13} were chosen in accordance with the binding energies of the neutron and the C^{13} nucleus and of the proton in N^{13}. The results of these calculations are shown in Fig. 1 in the form of a histogram of the dependence of the number of observed cases on the excitation energy of the intermediate nucleus N^{14}. The histogram is constructed with allowance for the form of the bremsstrahlung spectrum.

It follows from the presented histogram that, within the limits proposed, a rather large group of highly excited levels of N^{14} participates in the suggested transitions. It is even more difficult to explain the low probability of the $O^{16}(\gamma, d)N^{14}$ reaction as being due to the suppression of the dipole transitions without a change in isotopic spin ($\Delta T = 0$) for the nuclei with $Z = N$, than it is to explain the analogous results for Li^6 and B^{10}.[1] The reason for it is that the first excited level of $N^{14}(0^+, T = 1)$ corresponds to an excitation energy 2.31 MeV, whereas in the case of the $O^{16}(\gamma, d)N^{14}$ reaction transitions to this level are not as rigorously forbidden as would follow from the momentum and parity conservation laws. However, as was already indicated above, no such transitions are observed. This fact can indicate that the process leading to the suppression of reactions in which only one deuteron is emitted is common to the nuclei Li^6, Be^9, B^{10}, and O^{16}.

A characteristic feature of the discussed reactions is the clearly pronounced correlation between the directions of emission of the deuterons and the protons and neutrons that accompany them. Figure 2 shows the dependence of the number of $O^{16}(\gamma, dp)C^{13}$ and $O^{16}(\gamma, dn)N^{13}$ reactions on the angle between the emission directions of the deuterons and the corresponding nucleons. The histogram includes all the cases with proton and neutron energies exceeding 2 MeV. A predominant backward emission of protons and neutrons is observed relative to the deuteron emission direction. It must be noted that when the nucleon energy is less than 2 MeV no analogous correlation is seemingly observed, inasmuch as three out of four registered

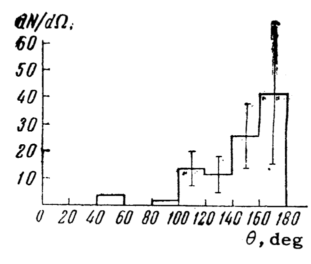

FIG. 2. Dependence of the number of reactions $O^{16}(\gamma, dp)C^{13}$ and $O^{16}(\gamma, dn)N^{13}$ on the angle θ between the directions of the emitted deuterons and their accompanying nucleons ($dN/d\Omega$ in arbitrary units).

events of this type lie in the angle range from 0 to 90°, and one lies between 90 and 180°.

The correlation in the particle-emission directions observed for most $O^{16}(\gamma, dp)C^{13}$ and $O^{16}(\gamma, dn)N^{13}$ reactions does not contradict in principle the assumption of a successive emission of particles with production of highly excited N^{14} nuclei. Such a correlation is also possible in the presence of direct processes where γ quanta are observed. Among such processes is the interaction between the γ quanta and groups of three correlated nucleons. It can be shown that the observed angular correlation is difficult to attribute to absorption of the γ quanta by pairs of nucleons and subsequent pickup. Indeed, according to this assumption, one of the np-pair nucleons which scatter in opposite directions can pick up the corresponding nucleon. As a result, deuterons should be observed and their accompanying nucleons emitted in approximately opposite directions. However, such an explanation contradicts the data which we obtained in the analysis of the $O^{16}(\gamma, pn)N^{14}$ reaction. We did not observe the required correlation in the directions of the proton and neutron emission.

[1] Chizhov, Komar, Kulikov, Kulchitsky, Makhnovsky, and Volkov, Nucl. Phys. **34**, 562 (1962).

[2] Kulikov, Chizhov, and Yavor, DAN SSSR **136**, 77 (1961), Soviet Phys. Doklady **6**, 62 (1961).

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