# PHOTODISINTEGRATION OF $Be^9$ AND $C^{12}$ BY GAMMA-BREMSSTRAHLUNG WITH MAXIMUM ENERGY UP TO 44 Mev

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We present results of an investigation of the angular and energy distributions of protons from the photodisintegration of $Be^9$ and $C^{12}$. Analysis of the results leads to the conclusion that in the region of the giant resonance the interaction of $\gamma$ quanta with these nuclei is satisfactorily explained by the resonance theory of the compound nucleus. For energies above the giant resonance, the interaction of the $\gamma$ quanta is predominantly with individual substructures within the nuclei.

In the present work we have studied the angular and energy distributions of the protons formed in the photodisintegration of $Be^9$ by $\gamma$ bremsstrahlung with a maximum energy of $E_{\gamma max}$ = 44 Mev and in the photodisintegration of $C^{12}$ by bremsstrahlung with maximum energies of 30 and 44 Mev.

The results were obtained using the method described in a previous paper.[1] The targets were a graphite plate of thickness 17 mg/cm$^2$ and a beryllium plate 15 mg/cm$^2$ in thickness. Impurities amounted to less than 0.3%. The protons were recorded in NIKFI Ia-2 emulsions of thickness 400 and 500 $\mu$.

In the irradiation of $C^{12}$ by $\gamma$ rays with $E_{\gamma max}$ = 30 Mev, only the protons from the $C^{12}(\gamma, p)B^{11}$ reaction were investigated. Other photoreactions on carbon in which protons are emitted have energy thresholds above 26 Mev, and the protons produced in these reactions (which have an energy less than 3 Mev) were not counted in our experiment. The contribution from the $C^{12}(\gamma,d)B^{10}$ reaction is very small at both energies since this reaction is forbidden by the isotropic spin selection rule.

We shall first consider the results obtained for beryllium. The angular distributions of protons from photodisintegration of $Be^9$ are shown in Fig. 1. An analysis of the distributions of the various energy groups of photoprotons shows that there is no way of explaining all of the results on the basis of a single photoreaction mechanism in this range of photon energies. The angular distribution of the 4 — 6 Mev proton group, as calculated using the model of direct interaction of $\gamma$ quanta with individual nucleons in the nucleus,[2] contradicts the experimental observations.

We therefore made calculations of angular distributions of photoprotons for transitions of various types on the basis of the compound nucleus resonance model.[3] The results of the computations for transitions to the $2^+$ ground state and $3^+$ first excited state of the $Li^8$ final nucleus are given in the table.

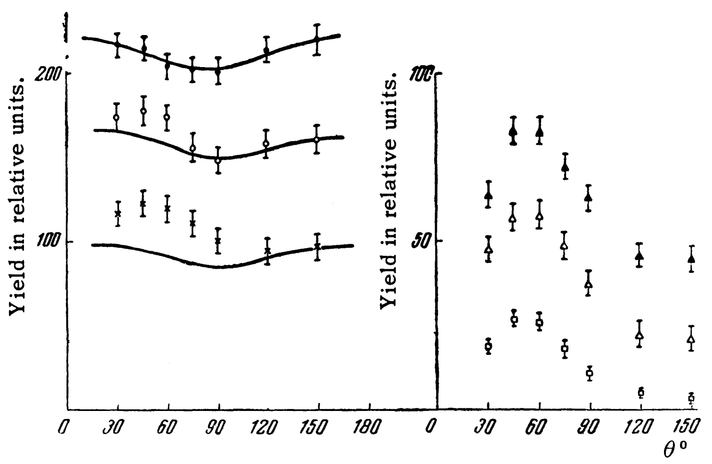


Fig. 1. Angular distributions of proton groups from photodisintegration of $Be^9$ by $\gamma$ quanta with $E_{\gamma max}$ = 44 Mev. The solid curves show the angular distributions calculated from the intermediate nucleus model, with transition to the ground $2^+$ state of $Li^8$. ● – $E_p$ = 4–5 Mev, ○ – $E_p$ = 5–6 Mev, × – $E_p$ = 6–9 Mev, ▲ – $E_p$ = 9–12 Mev, △ – $E_p$ = 12–15 Mev, □ – $E_p \geq$ 15 Mev.

| $l = 0$ | | | $l = 2$ | | |
|---|---|---|---|---|---|
| s | I | Angular Distribution | s | I | Angular Distribution |
| | | $Li^8$ left in $2^+$ ground state | | | |
| 3/2 | 5/2 | const | 3/2 | 5/2 | $4 + \sin^2\theta$ |
| 3/2 | 3/2 | const | 3/2 | 3/2 | const |
| 3/2 | 1/2 | const | 3/2 | 1/2 | const |
| 5/2 | 5/2 | const | 5/2 | 5/2 | $13 + 3\cos^2\theta$ |
| 5/2 | 3/2 | const | 5/2 | 3/2 | $2 + \cos^2\theta$ |
| 5/2 | 1/2 | const | 5/2 | 1/2 | const |
| | | $Li^8$ left in $3^+$ first excited state | | | |
| 5/2 | 5/2 | const | 5/2 | 5/2 | $13 + 3\cos^2\theta$ |
| 5/2 | 3/2 | const | 5/2 | 3/2 | $2 + \cos^2\theta$ |
| 5/2 | 1/2 | const | 5/2 | 1/2 | const |
| 7/2 | 5/2 | const | 7/2 | 5/2 | $1.7 + \cos^2\theta$ |
| 7/2 | 3/2 | const | 7/2 | 3/2 | $6 + 7\cos^2\theta$ |
| 7/2 | 1/2 | const | 7/2 | 1/2 | const |

$l$ is the relative orbital angular momentum in the final state, s is the total spin of the reaction products, I is the total angular momentum of the photon-target system.

It is not possible at present to evaluate the statistical weights of transitions with different s and I. Figure 1 shows the comparison of the computed angular distributions for photoproton groups with energies 4 — 5, 5 — 6 and 6 — 9 Mev with the experimental data, on the assumption that the statistical weights of all the transitions to the $2^+$ state are the same. If these protons are produced by $\gamma$ quanta absorbed by the nucleus in the region of the dipole resonance, then the assumption that the most probable transition is that to the ground state is valid. However, even if for some reason the intensity of transitions to the first excited state is comparable to the intensity of the ground state transitions, the table shows that the shape of the computed angular distribution should hardly change.

The angular distributions of the higher energy proton groups differ from those expected on the resonance theory of the compound nucleus. These deviations begin to appear even for the 5 — 6 Mev proton group, and increase with increasing proton energy. Starting with the 6 — 9 Mev proton group and higher, the experimental angular distributions have their maximum at an angle of 50°, i.e., the angular distributions are highly asymmetric around 90°, with preferential emission of the protons forward, in the direction of motion of the $\gamma$ quanta. The isotropic part of the distribution decreases with increasing energy of the photoprotons, and is only one-seventh of the anisotropic part for protons with energies greater than 15 Mev. At the same time, as we see from Fig. 2, the angular distribution of the protons from $Be^9$ which have energies above 12 Mev is in good agreement with the angular distribution of protons from photodisintegration of the deuteron by 42 Mev $\gamma$ quanta.[4] This shows that already at excitation energies of the order of 40 Mev the production of photoprotons from $Be^9$ occurs via a two-nucleon mechanism. Apparently the fixed position of the maximum, which is shifted markedly toward smaller angles (45° — 55°), in the angular distributions of other proton groups, shows the presence of the two-nucleon mechanism for absorption of $\gamma$ quanta by $Be^9$ down to proton energies of 6 — 9 Mev. The complete energy spectrum of the $Be^9$ photoprotons is given in Fig. 3. The analysis of its high energy part is also in favor of the quasideuteron model. In the spectrum of the photoprotons with energies above 12 Mev, which is shown in Fig. 4, there is a characteristic kink whose position is in qualitative agreement with the computed kink in the spectrum of protons from photodisintegration of the deuteron. The quantitative relation between the cross sections per effective quantum for the 12 — 15 Mev proton group from the $Be^9$ photodisintegration and the corresponding proton group from deuteron photodisintegration is

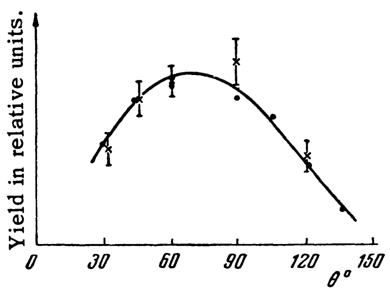


Fig. 2. Comparison of angular distribution of photoprotons from $Be^9$, assuming a two-nucleon interaction mechanism, with the angular distribution of the proton group of the same energy from photodisintegration of the deuteron. The data for the deuteron are shown by the solid curve. $E_{\gamma max}$ = 44 Mev, $h\nu$ = 42 Mev.

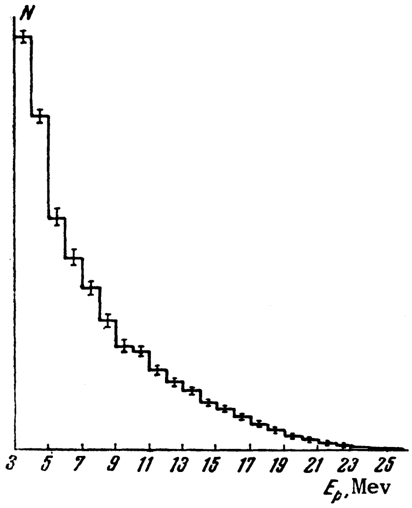


Fig. 3. Complete energy spectrum of protons from photodisintegration of $Be^9$; $E_{\gamma max}$ = 44 Mev.

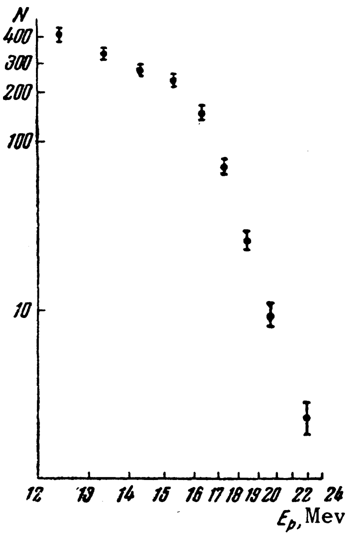


Fig. 4. Energy spectrum of protons with energies ≥ 12 Mev from photodisintegration of $Be^9$ (on a log-log scale); $E_{\gamma max}$ = 44 Mev.

$\sigma_{Be^9}$ = $(1.0 \pm 0.2) A\sigma_d$. It is clear that within the limits of error the proportionality coefficient is the same as that for higher energy proton groups.[1] This is also in accord with the assumptions made above concerning the mechanism of formation of photoprotons from $Be^9$ at these energies.

The angular distributions of protons from photodisintegration of $C^{12}$ by bremsstrahlung with $E_{\gamma max}$ = 30 Mev and $E_{\gamma max}$ = 44 Mev are the same (Fig. 5). Since in the first case the protons are formed only in the $C^{12}(\gamma, p)B^{11}$ reaction, the coincidence of the angular distributions is apparently related to the fact that the $C^{12}(\gamma, pn)B^{10}$ contributes little in this range of excitation energy. This is indicated also by the great similarity of the photoproton energy spectra, which are shown in Figs. 6 and 7. It is true that the maximum in the energy distribution of the protons from irradiation of $C^{12}$ by bremsstrahlung with $E_{\gamma max}$ = 44 Mev is shifted somewhat toward lower energies compared to the energy spectrum from irradiation of $C^{12}$ by $\gamma$ quanta with $E_{\gamma max}$ = 30 Mev.

For the low energy protons (4 — 7 Mev), which are apparently produced when $\gamma$ quanta are absorbed by the $C^{12}$ nucleus in the region of the giant resonance (since the energy distribution of the protons within this energy range reproduces the shape of the cross section curve for the $C^{12}(\gamma, p)B^{11}$ reaction and the maxima of the curves also coincide), the angular distributions are in good agreement with those expected on the model of a direct photoeffect, as well as with the distribution from the resonance theory of the compound nucleus. The identity of the conclusions from both models is caused by the fact that the final $B^{11}$ nucleus is left in either the $3/2^-$ ground state or in the $1/2^-$ first excited state. However, the experimentally observed angular distributions from $C^{12}$ for higher energy protons (which, like those for

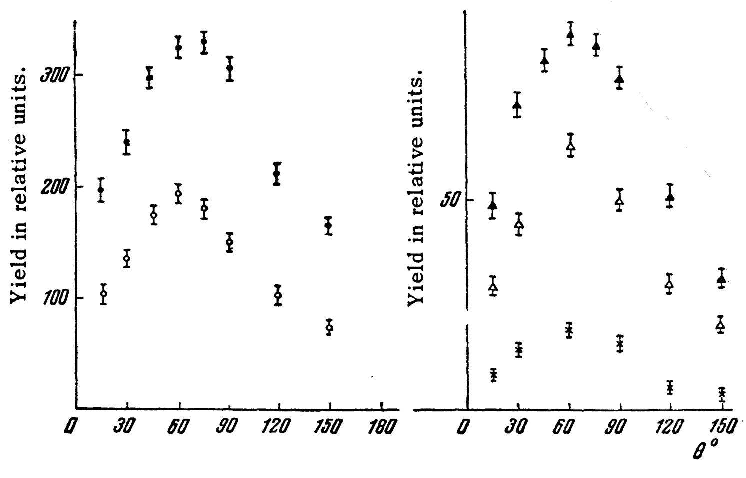


Fig. 5. Angular distributions of proton groups from photodisintegration of $C^{12}$ by $\gamma$ quanta with $E_{\gamma max}$ = 44 Mev: ● – $E_p$ = 5–7 Mev, ○ – $E_p$ = 7–10 Mev, ▲ – $E_p$ = 10–13 Mev, △ – $E_p$ = 13–16 Mev, × – $E_p$ ≥ 16 Mev.

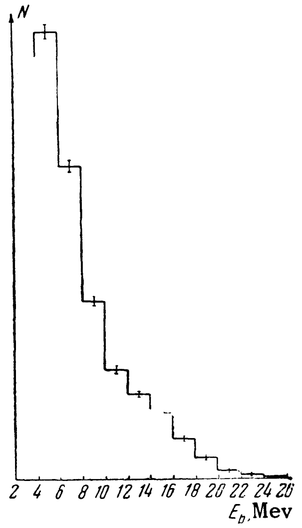


Fig. 6. Complete energy spectrum of protons from photodisintegration of C$^{12}$ by radiation with $E_{\gamma max}$ = 44 Mev.

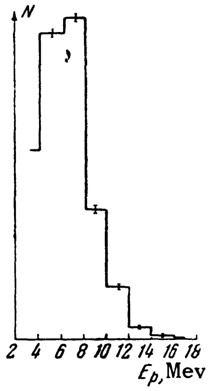


Fig. 7. Complete energy spectrum of protons from photodisintegration of C$^{12}$ by radiation with $E_{\gamma max}$ = 30 Mev.

Be$^9$, deviate from the resonance model) are essentially different from what would be expected from either of these models. The difference is characterized by a rapid decrease in the isotropic part of the distribution. An explanation for this is to be sought in the fact that, with increasing energy of the $\gamma$ quanta, the mechanism of absorption of the $\gamma$ quanta by individual substructures begins to be important. For carbon such structures are apparently quasi $\alpha$ particles. The angular distribution of the protons from photodisintegration of these structures has no isotropic part. Apparently the smallness of the isotropic part of the angular distributions of the high energy protons is also explained in this way.

It is of interest to note the appreciable contribution of the two-nucleon mechanism for absorption of low energy $\gamma$ quanta to the photodisintegration of Be$^9$. This may be related to the presence of a weakly bound neutron in the Be$^9$ nucleus. On the other hand, in the photodisintegration of carbon, because of the high neutron binding energy (17 Mev), the two-nucleon interaction mechanism does not appear. It also does not appear at higher energies. This is shown by the angular distributions and energy spectra of photoprotons with energies above 18 Mev which are obtained from photodisintegration of C$^{12}$ by $\gamma$ quanta from bremsstrahlung with $E_{\gamma max}$ = 64 Mev. In explaining this fact it should be remembered that the isotopic spin selection rule may play an important role for the interaction of $\gamma$ quanta with C$^{12}$ nuclei. In the case of the two-nucleon mechanism for absorption of $\gamma$ quanta, it forbids emission of a proton and a neutron with parallel spins.

So although the analysis of the results on photodisintegration of C$^{12}$ does not enable us to make a unique choice, the whole aggregate of experimental data on the photodisintegration of Be$^9$ and C$^{12}$ are in favor of the statement that the photodisintegration of light nuclei with absorption of $\gamma$ quanta in the region of the giant resonance occurs via formation of a compound nucleus. In the decay of the compound nucleus, the final nucleus is left preferentially in its ground state. With increasing energy of the $\gamma$ radiation, processes begin to be important in the photodisintegration of light nuclei which owe their occurrence to absorption of the $\gamma$ radiation by substructures within the nuclei. The two-nucleon mechanism for absorption of $\gamma$ quanta by nuclei is already the dominant process at energies of the order of 80 Mev.

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