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Abstract

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PHYSICS

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LOW-ENERGY CHARGED PARTICLES IN THE PHOTODISINTEGRATION OF THE Be^9 NUCLEUS

The energy spectra and yields of charged particles produced upon irradiation of Be^9 with bremsstrahlung with $E_{\gamma\,\max} = 35$ MeV were investigated. A beryllium target 4.7 mg/cm^2 thick was irradiated in a vacuum chamber with photographic plates, located in a uniform magnetic field ($H = 13\,500$ oersted), approximately perpendicular to the direction of particle emission ([1]). The particle ranges R and the orientations of their tracks in the emulsion were measured. The latter made it possible to determine the radii of curvature ρ of the trajectories in the magnetic field and, by comparison with calculated dependences $\rho(R)$ for a given H, to identify the particles. The scatter of the ρ measurements was taken into account by constructing the corresponding "error corridors." The irradiation doses were measured with a quantometer ([2]). In the proton region the total background for the two photographic plates examined was 38%, and in the α-particle region 23%. All measured background particles had ranges $\leq 50\,\mu$.

In Fig. 1 the calculated dependences $\rho(R)$ are shown by solid curves. The points represent the results of measurements after subtraction of the background. The triton region practically coincides with the region for α-particles; therefore it is not shown in the figure.

Figure 2 presents the energy distribution of 252 protons. The maximum of the energy distribution is not at $1.5 \div 2.5$ MeV, as obtained in ([3]), but at $E_p \simeq 4$ MeV. The intense maximum in the low-energy region of the proton spectrum obtained in ([3]), where particle discrimination was not carried out, is most probably due to a large contribution from α-particles.

Figure 3 shows the excitation function of the reaction $Be^9(\gamma, p)Li^8$, calculated under the assumption that all identified protons are due to this reaction, that the angular distribution of the photoprotons is isotropic, and that the recoil nucleus Li^8 is in all reaction cases formed in the ground state. Judging from the position of the maximum of the curve (at $E_\gamma \simeq 22$ MeV), its half-width, and the magnitude of the integral cross section measured from $E_\gamma = 18$ MeV to $E_\gamma = 26$ MeV, the excitation function constructed by us agrees well with the excitation functions of the (γ, p)-reaction measured in ([4,5]) from the characteristic β^--activity of the recoil nucleus Li^8. In accordance with Fig. 3,

$$\int_{18}^{26} \sigma_{\gamma p}(E_\gamma)\, dE_\gamma = (12 \pm 1.8)\ \text{mb} \cdot \text{MeV}.$$

The bremsstrahlung-spectrum-weighted cross section of the (γ, p)-reaction on Be^9,

$$\int \frac{\sigma_{\gamma p}(E_\gamma)}{E_\gamma}\, dE_\gamma,$$

according to calculations, should be 1.06 mb ([6]). It was shown in ([5]) that the integral cross section of the (γ, p)-reaction increases with increasing γ-quantum energy up to $E_\gamma \simeq 57$ MeV. If the excitation function obtained by us is smoothly continued from $E_\gamma = 18$ MeV to the threshold ($Q = 16.9$ MeV) and from $E_\gamma = 31$ MeV to $E_\gamma = 35$ MeV, then

$$\int_{16.9}^{35} \frac{\sigma_{\gamma p}(E_\gamma)}{E_\gamma}\, dE_\gamma \simeq 0.73\ \text{mb}.$$

In accordance with the data of ([5]),

$$\int_{35}^{57} \frac{\sigma_{\gamma p}(E_\gamma)}{E_\gamma}\, dE_\gamma \simeq 0.32\ \text{mb}.$$

Altogether,

$$\int_{16.9}^{57} \frac{\sigma_{\gamma p}(E_\gamma)}{E_\gamma}\, dE_\gamma \simeq 1.05\ \text{mb},$$

which

Fig. 1. Distributions of photoparticles from Be^9 by radii of curvature of the trajectories in a magnetic field and by ranges in the emulsion: **a** –for a photographic plate with $\varphi_0 = 35^\circ$, **b** –for a photographic plate with $\varphi_0 = 65^\circ$ (φ_0 is the angle between the line connecting the centers of the target and the photographic plate and the direction of the γ-quantum beam). **1** –particle zone; **2** –deuteron zone; **3** –proton zone.

Figure 1. Distributions of photoparticles from Be-9 by radii of curvature of the trajectories in a magnetic field and by ranges in the emulsion: a –for a photographic plate with $\varphi_0 = 35^\circ$, b –for a photographic plate with $\varphi_0 = 65^\circ$ (φ_0 is the angle between the line connecting the centers of the target and the photographic plate and the direction of the γ-quantum beam). 1 –particle zone; 2 –deuteron zone; 3 –proton zone.

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Fig. 2. Energy distribution of photoprotons from Be^9

Figure 2: Fig. 2. Energy distribution of photoprotons from Be^9

is in good agreement with the theoretical value of this quantity given above (1.06 mb).

The angular distribution of photoprotons with $E_p \geqslant 2.6$ MeV has the form of a function increasing with increasing θ from 40 to 90°. This is not in contradiction with the form of the angular distributions of nucleons in direct photoemission for $1p \to 1d$ and $1p \to 2s$ transitions ([7]).

Fig. 2. Energy distribution of photoprotons from Be^9

From the analysis of the data it also follows that, for $E_\gamma < 35$ MeV, the reactions $Be^9(\gamma, p)Li^{8*}(n)Li^7$ and $Be^9(\gamma, p)Be^{8*}(p)Li^7$ are improbable. It is difficult to suppose that these reactions occur with the emission of protons only with energies of 1 MeV, which were not recorded in the present work.

A rather high value was established for the ratio of the deuteron yield to the proton yield. For particles with energies $3.7 \div 14.2$ MeV, $Y_d/Y_p = 0.20 \pm 0.10$. On the whole, about 90 of the particles recorded in the experiment should have been identified as deuterons. The cross section of photoreactions accompanied by deuteron emission amounts to $6 \div 7\%$ of the total absorption cross section of γ-quanta with energies from 16.7 to 35 MeV. From a comparison of our data with the data of work ([6]) it may be concluded that not less than half of the particles assigned by us to deuterons are apparently due not to many-particle decays of the beryllium nucleus, but to the reaction $Be^9(\gamma, d)Li^7$.

Fig. 3. Excitation function of the reaction $Be^9(\gamma, p)Li^8$

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The energy spectra of α-particles are shown in Fig. 4. The spectra were constructed taking into account the contribution of only deuterons in the region for α-particles. In the photodisintegration of Be^9, α-particles may arise in (γ, n) and (γ, α)-reactions. From a comparison of the integral cross sections calculated in accordance with ([8,9]), it follows that the form of the obtained energy spectrum of α-particles is determined mainly by the reaction
$Be^9(\gamma, n)Be^{8*} \to 2\alpha$. Cases of the (γ, n)-reaction in which Be^8 is formed in the ground or in the first excited state were not recorded by us. As follows from the figure, at E_α near 6 and 10 MeV there are two broad peaks. According to the kinematics of the (γ, n)-process, the position of any group of α-particles in the experimental spectrum at a given energy of the "primary" neutrons is characterized by the dependence

$$\overline{E}_\alpha = E_\alpha^0 + E_n/16. \tag{1}$$

Here, $E_\alpha^0 = (E^*_{Be^8} + 0.094)/2$ is the kinetic energy of an α-particle in the center-of-mass system of the Be^8 nucleus having excitation energy $E^*_{Be^8}$; $E_n = \frac{8}{9}(E_\gamma - Q)$ is the energy of the "primary" neutron emitted from Be^9; $Q = 1.66 + E^*_{Be^8}$.

Taking into account the data of work ([6]), the addition $E_n/16$ in (1) has a value $\lesssim$ 0.5 MeV; consequently, the positions of the different groups of α-particles are determined mainly by the value E_α^0. In Fig. 4 the arrows at energies 5.7; 8.1; 8.4; 8.8; 10.0 and 11.3 MeV indicate the values of E_α^0 corresponding to the decay of Be^8 in known excited states at 11.4; 16.08; 16.7; 17.6; 19.9 and 22.6 MeV ([10,11]). It is seen that the broad maximum in the region E_α about

6 MeV can be identified with the decay of Be^8 only in the excited state at 11.4 MeV. The second group of α-particles, with an average energy of about 10 MeV, is explained by the formation and subsequent decay of Be^8 in states with $E^*_{Be^8}$ from 16.08 to 22.6 MeV.

Taking into account the results of the present work and the data given in ([5,8,12,13]), the absorption cross section of γ-quanta by the Be^9 nucleus, weighted over the bremsstrahlung spectrum, is

$$\sigma_{-1} = \int_{1.7}^{150} \frac{\sigma(E_\gamma)}{E_\gamma}\, dE_\gamma \simeq (6 \pm 1) \text{ mb}.$$

In the shell model with a harmonic-oscillator potential, $\sigma_{-1} = 0.36\, A^{4/3}$ mb ([13]). For Be^9 one obtains $\sigma_{-1} = 6.7$ mb, which agrees with the experimental value given above. σ_{-1} is related to the mean-square radius of the charge distribution in the nucleus ([14–16]):

Fig. 4. Energy spectrum of alpha particles arising in the photodisintegration of Be^9 (histogram). The smooth curve shows the spectrum obtained by viewing the photographic plate at $\varphi_0 = 35°$.

Figure 4: Fig. 4. Energy spectrum of alpha particles arising in the photodisintegration of Be^9 (histogram). The smooth curve shows the spectrum obtained by viewing the photographic plate at $\varphi_0 = 35°$.

$$\sigma_{-1} = \frac{4\pi^2}{3}\frac{e^2}{\hbar c}\frac{NZ}{A-1}(1-\Lambda)(\overline{R_c^2} - \overline{R_p^2}). \tag{2}$$

$\Lambda = 0.84(1+22A)^{-1}$, $\overline{R_p^2}$ is the mean square radius of the proton charge distribution. If $\sigma_{-1} = 6$ mb is adopted, then for Be^9 we obtain $\overline{R_c} \simeq 2.0 \cdot 10^{-13}$ cm. This agrees with the value $\overline{R_c} = (2.2 \pm 0.2) \cdot 10^{-13}$ cm obtained by Hofstadter ([17]).

According to our data and those cited in ([5,8,12,18]), for Be^9 the quantity

$$\sigma_{-2} = \int_{1.7}^{150} \frac{\sigma(E_\gamma)}{E_\gamma^2}\, dE_j \simeq$$

$$\simeq 395\ \mu\text{b} \cdot \text{MeV}^{-1}.$$

Migdal showed that σ_{-2} is proportional to the polarizability of the nucleus under the action of an electromagnetic field ([19]). In accordance with the results of his calculations, $\sigma_{-2} = 2.25\, A^{5/3}\ \mu\text{b} \cdot \text{MeV}^{-1}$ ([18]). For Be^9 this dependence gives 87 μb · MeV, which is 4.5 times smaller than the experimental value.

Fig. 4. Energy spectrum of α-particles arising in the photodisintegration of Be^9 (histogram). The smooth curve shows the spectrum obtained by viewing the photographic plate at $\varphi_0 = 35°$.

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Note: Figure translations are in progress. See original paper for figures.