HIGH ENERGY PHOTODISINTEGRATION OF Be^9 *AND* C^{12} *NUCLEI*

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Photo-absorption by Be^9 and C^{12} nuclei accompanied by the emission of protons is investigated on the basis of the α-particle model of these nuclei. The results are compared with the experimental results.

RECENTLY, a number of experimental and theoretical works[1-4] have indicated the possibility of the existence of clusters of nucleons in light nuclei. Moreover, the analysis of experimental data on photodisintegration of light nuclei leads to the conclusion that these clusters play an important role in radiative transitions. In particular, the characteristics (threshold and energy corresponding to the giant resonances) of the cross sections for the $C^{12}(\gamma, n)$ and $O^{16}(\gamma, n)$ reactions are close to the characteristics of the $He^4(\gamma, n)$ reaction cross section, and in addition to the first maximum (apparently corresponding to the unpaired neutron) of the cross section curve for the $Be^9(\gamma, n)$ and $C^{13}(\gamma, n)$ reactions, one also observes other maxima which lie close to the energy corresponding to the giant resonance in the $He^4(\gamma, n)$ reaction.

These facts indicate that in the above-mentioned light nuclei the photoabsorption occurs primarily in substructures similar to α particles. If clusters of nucleons actually exist in light nuclei, then their role should be especially important at high energies above the giant resonances and lead to considerable yields of high-momentum nucleons. Since the photon carries a small momentum into the nucleus, then such nucleons should already have a high momentum in the initial state, and the nucleons possessing high momenta in the nucleus should be strongly correlated with a less-than-average distance between them, so that they interact and form separate substructures.

1. The experimental data[5] on photoprotons emitted from the Be^9 and C^{12} nuclei by γ quanta of maximum energy 84 Mev show that these nuclei have very similar properties. For example, the angular distributions of photoprotons from Be^9 and C^{12} nuclei are the same within the limits of experimental error. They have a large asymmetry with respect to 90° with a maximum at 50° and a strongly diminished isotropic part. The total cross sections for the reaction at high energies in both cases drop exponentially with the γ-quantum energy and have a value of the order 10^{-28} cm^2 at an energy $\hbar\omega = 80$ Mev. If we compare these experimental results with the data on the photodisintegration of α particles,[6] then we readily note that there is a strong similarity between the properties of the Be^9 and C^{12} nuclei on the one hand and α particles on the other, which they display in interactions with γ quanta.

The foregoing discussion gives a basis for the suggestion that the photoreactions occur in Be^9 and C^{12} nuclei mainly through the interaction of γ quanta with individual quasi-α particles which are apparently formed by the clustering of nucleons in these light nuclei.

The present article is devoted to the study of the photodisintegration of the Be^9 and C^{12} nuclei on the basis of the mechanism of the absorption of γ quanta by α particles.

2. Under the assumption that the photonucleon is emitted from a bound quasi-α particle and the remaining nucleons are not disturbed by the radiation, we can write the wave function for the initial and final states as follows:

$$\Psi_i = \Phi\Psi_c(\alpha)\varphi_i, \qquad \Psi_f = \Phi\Psi_c(H^3)\varphi_f,$$

where Φ describes the motion of the undisturbed nucleons, $\Psi_c(\alpha)$ is the motion of the center-of-mass of the quasi-α particle in the field of the undisturbed nucleons of the nucleus, φ_i is the internal state of the quasi-α particle, $\Psi_c(H^3)$ is the motion of the center of mass of H^3 (or He^3), φ_f is the motion of the emitted nucleon relative to the residual nucleus.

To describe the internal motion of the quasi-α particle we employ a model which was used earlier[7] to describe the $He^4(\gamma, p)$ and $He^3(\gamma, n)$ reactions.

We assume that the interaction potential of γ quanta with the quasi-α particle contains all multipoles, both electric and magnetic. The motion of the center of mass of the quasi-α particle and the triton (or He^3) is described by Gaussian-type wave functions, and the motion of the emitted nucleon by a plane wave. Using the mechanism of the $He^4(\gamma, N)$ reaction (cf. [7]), we obtain for the differential cross section of the photodisintegration of α nuclei

$$\frac{d\sigma}{d\Omega} = B_0 n \frac{A-1}{A} \frac{k^3}{\omega} \sin^2\theta \exp[-2\alpha_0 k'^2 + 2\beta_0 kk'\cos\theta - 2\gamma_0 k^2]\{\delta' - \eta B_1 \exp[\alpha_1 k'^2 - \beta_1 kk'\cos\theta] - \eta B_2 \exp[-(\alpha_2-\alpha_0)k'^2 - (\beta_0-\beta_2)kk'\cos\theta - (\gamma_2-\gamma_0)k^2]\}^2 + \frac{1}{2} B_0 n \frac{A-1}{A} \frac{\mu_{n,p}^2}{c^2} \omega k \exp[-2\alpha_0 k'^2 + 2\beta_0 kk'\cos\theta - 2\gamma_0 k^2]\{1 - \exp[\alpha_1 k'^2 - \beta_1 kk'\cos\theta]\}^2, \quad (1)$$

where ω and $\mathbf{k}'$ are the frequency and wave vector of the incident quantum, $\mathbf{k}$ is the wave vector of the emitted nucleon, n is the number of quasi-α particles in the nucleus, A is the mass number of the initial nucleus, $\mu_{n,p}$ is the magnetic moment of the neutron or proton in nuclear magnetons, $\delta' = 1$ or 0 and $\eta = 1$ or 2, depending on whether a proton or neutron is emitted. The constants occurring in formula (1) are

$$B_0 = \frac{2^{13}\pi^{1/2}\gamma^3\beta^3\delta^3 l^2}{p^3 Mc}, \quad B_1 = \frac{3p - \beta^2 q}{3(A-1)p}, \quad B_2 = \frac{s\beta^2}{3(A-1)p},$$

$$\alpha_0 = \frac{p + (3\delta^2 + 4\beta^2)^2}{4p(\delta^2+\beta^2)}, \quad \beta_0 = \frac{(A-4)p + (3\delta^2 + 4\beta^2)q}{2(A-1)p(\delta^2+\beta^2)},$$

$$\gamma_0 = \frac{(A-4)^2 p + q^2}{4(A-1)p(\delta^2+\beta^2)}, \quad \alpha_1 = \frac{2(\delta^2 + 2\beta^2)}{p},$$

$$\beta_1 = \frac{2q}{(A-1)p}, \quad \alpha_2 = \frac{p + 64\gamma^4}{4pl}, \quad \beta_2 = \frac{16\gamma^2 s - 6Ap}{4(A-1)pl},$$

$$\gamma_2 = \frac{s^2 + 9A^2 p}{4(A-1)pl},$$

where M is the nucleon mass, c is the velocity of light,

$$p = 8\gamma^2(\delta^2+\beta^2) + \delta^2\beta^2, \qquad q = 4(A-1)\beta^2 + 3A\delta^2,$$
$$l = 8\gamma^2 + \beta^2, \qquad s = 8(A-4)\gamma^2 + 4(A-1)\beta^2.$$

In these formulas δ and β the parameters of the wave functions describing the motion of the center of mass of the quasi-α particle and center of mass of the triton (or He^3), respectively. The parameter γ corresponds to the internal state of the quasi-α particle.

Integrating expression (1) over the angular variable, we readily obtain the total cross section for the process. Thus

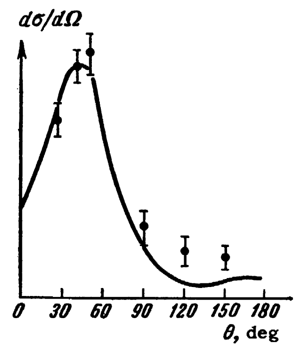

FIG. 1. Angular distribution of photoprotons in the $Be^9(\gamma, p)$ reaction for 80-Mev γ quanta.

$$\sigma = 8\pi B_0 n \frac{A-1}{A}\frac{k^3}{\omega}\exp(-\varphi_1)\{\delta'\Phi_1[\xi_1] + \eta^2 B_1^2 \exp(\varphi_2)\Phi_1[\xi_2] + \eta^2 B_2^2 \exp(\varphi_3)\Phi_1[\xi_3] - 2\delta'\eta B_1 \exp(\varphi_2/2)\Phi_1[\xi_4] - 2\delta'\eta B_2\exp(\varphi_3/2)\Phi_1[\xi_5] + 2\eta^2 B_1 B_2 \exp(\varphi_4)\Phi_1[\xi_6]\} + 2\pi B_0 n \frac{A-1}{A}\frac{\mu_{n,p}^2}{c^2}\omega k \exp(-\varphi_1)\{\Phi_2[\xi_1] + \exp(\varphi_2)\Phi_2[\xi_2] - 2\exp(\varphi_2/2)\Phi_2[\xi_4]\}, \quad (2)^*$$

where

$$\varphi_1 = 2\alpha_0 k'^2 + 2\gamma_0 k^2, \quad \varphi_2 = 2\alpha_1 k'^2,$$
$$\varphi_3 = 2(\alpha_0 - \alpha_2)k'^2 + 2(\gamma_0 - \gamma_2)k^2,$$
$$\varphi_4 = (\alpha_0 - \alpha_2 + \alpha_1)k'^2 + (\gamma_0 - \gamma_2)k^2,$$
$$\xi_1 = 2\beta_0 kk', \quad \xi_2 = 2(\beta_0 - \beta_1)kk', \quad \xi_3 = 2\beta_2 kk',$$
$$\xi_4 = (2\beta_0 - \beta_1)kk', \quad \xi_5 = (\beta_0 + \beta_2)kk',$$
$$\xi_6 = (\beta_0 + \beta_2 - \beta_1)kk', \quad \Phi_1[\xi] = \frac{1}{\xi^2}\left(\operatorname{ch}\xi - \frac{\operatorname{sh}\xi}{\xi}\right),$$
$$\Phi_2[\xi] = \frac{\operatorname{sh}\xi}{\xi}.$$

3. The numerical calculation of the angular distribution of the photoprotons was carried out for the $Be^9(\gamma, p)$ reaction for an incident γ-quantum energy $\hbar\omega = 80$ Mev. The result is shown in Fig. 1. Also shown are the experimental points obtained by Chuvilo and Shevchenko.[5] The curve for the total cross section calculated on the basis of formula (2) is shown in Fig. 2.

The parameters of the wave functions describing the motion of the center of mass of the quasi-α particle and of the center of mass of the triton were determined with the use of the electromagnetic radius of the nucleus, while the value of the parameter γ was taken from [7] ($\gamma = 8 \times 10^{12}$ cm^{-1}, $\beta = 4.20 \times 10^{12}$ cm^{-1}, $\delta = 4.17 \times 10^{12}$ cm^{-1}).

The data of [5] on Be^9 concerns the bremsstrahlung spectrum. To determine from these data the dependence of the $Be^9(\gamma, p)$ reaction cross section on the incident γ-quantum energy, we used the relation obtained by Chuvilo and Shevchenko

*sh = sinh, ch = cosh.

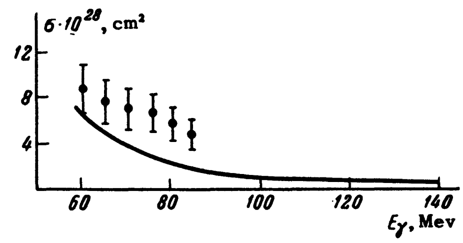

FIG. 2. Total cross section of the $Be^9(\gamma, p)$ reaction as a function of the incident γ-quantum energy.

$$\int_{\omega_{min}}^{\omega_{max}} \sigma_{Be^9}(\omega) I(\omega) d\omega = (1.0 \pm 0.2) A \int_{\omega_{min}}^{\omega_{max}} \sigma_d(\omega) I(\omega) d\omega,$$

where $I(\omega)$ is the bremsstrahlung intensity, $\sigma_d(\omega)$ is the photodisintegration cross section of the deuteron. According to [5], this relation does not depend, within the limits of experimental error, on the value of the maximum energy of the radiation ω_{max} (in the 50 — 85 Mev interval). This permits us to write

$$\sigma_{Be^9}(\omega) = (1.0 \pm 0.2) A\sigma_d(\omega).$$

The experimental points for σ_{Be^9} determined in this way are shown in Fig. 2, where the values of $\sigma_d(\omega)$ were determined from the curve given by Hulthén and Sugawara.[9]

As regards the $C^{12}(\gamma, p)$ reaction, the calculation [see (1)] shows that the character of the angular distribution is similar to the $Be^9(\gamma, p)$ reaction, which is in agreement with the experimental data.[10]

As seen from Figs. 1 and 2, the shape of the angular distribution is in good agreement with the theoretical curve, and the curve of the total cross section runs only slightly below the experimental points. These results allow us to conclude that in the energy interval under consideration the quasi-α particle absorption of γ quanta plays the basic role in the photodisintegration of the Be^9 and the C^{12} nuclei (~ 70%). Along with this, there are apparently other absorption mechanisms whose contributions to the photoabsorption cross section are evidently small.

Let us consider, for example, the photodisintegration of α nuclei from the viewpoint of the shell model. It is known (see, for example, Wilkinson[11]) that, according to this model, the angular distribution of the photoprotons strongly depends on initial angular momentum of the proton in the nucleus. Therefore, if the reaction takes place in accordance with the independent-particle model, one should observe a distinct difference in the angular distribution of the protons from the Be^9 and C^{12} nuclei, since the ratio of the number of protons in the p state to the number in the s state is 2:1 for carbon and 1:1 for beryllium. Feld et al[10] have drawn attention to this. Actually, the experimental angular distribution of the protons from the Be^9 and the C^{12} nuclei are almost identical.[5]

We note that on the basis of the α-particle absorption model one should expect the existence of the photonuclear reaction with the simultaneous emission of the proton and triton. Such a reaction has actually been observed by Maĭkov[12] in the case of the C^{12} nucleus in the energy interval 30 — 150 Mev, but no detailed investigation was made in view of the poor statistical accuracy. It is therefore best to defer the theoretical consideration of this reaction, which can be made in analogy with the theory developed above, until reliable experimental data have been accumulated.

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