INVESTIGATION OF THE $He^4(\gamma, np)D^2$ *PHOTONUCLEAR REACTION*

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The $He^4(\gamma, np)D^2$ reaction is treated in the nucleon-pair correlation model. The dependence of the total reaction cross section on the photon energy and the distribution of relative neutron and proton energies are derived. The results are compared with experimental data.

1. The photodisintegration of the He^4 nuclei accompanied by the emission of a neutron and a proton has been studied experimentally [1,2] for γ-ray energies from the reaction threshold up to 150 MeV. From a qualitative analysis of the obtained results, the authors have concluded that the main mechanism of the $He^4(\gamma, np)D^2$ reaction is the two-particle photon absorption, both in the low-energy range and for energies ≥ 75 MeV.

The direct application of the quasideuteron model of Levinger to the He^4 nucleus in order to obtain quantitative results in the energy range of interest is not correct. This is due first to the fact that the Levinger model, as is well known, gives satisfactory results only for photon energies greater than 150 MeV, and second, whereas for heavy nuclei the motion of the center of mass of the correlated pair can be described by a plane wave and the state of the relative motion can be considered as belonging to the continuous spectrum (as is assumed in the Levinger model), for very light nuclei like the He^4 nucleus bound states should correspond to both motions. On the other hand, the expression of such a wave function was obtained in [3]. This wave function takes the repulsive core of the nucleon-nucleon interaction at small distances into account, and gives best values for the binding energy and the dimensions of the He^4 nucleus.

In the present investigation we have studied the $He^4(\gamma, np)D^2$ reaction theoretically, assuming a direct interaction of γ rays with all nucleons of the He^4 nucleus, and using the wave function obtained in [3].

2. The total wave function of the He^4 nucleus, taking the correlations into account, can be written in the form

$$\Psi_t = \frac{1}{\sqrt{24}} \sum P\alpha(1)\alpha(2)\beta(3)\beta(4)\gamma(1)\delta(2)\gamma(3)\delta(4)\psi(1234), \quad (1)$$

where $\alpha(i)$, $\beta(i)$ and $\gamma(i)$, $\delta(i)$ are the spin and isospin nucleon wave functions respectively, and the coordinate part of the wave function $\psi(1234)$ is given by the equation [3]

$$\psi(1234) = \Omega(12)\Omega(13)\Omega(14)\Omega(23)\Omega(24)\Omega(34)\varphi(1)\varphi(2)\varphi(3)\varphi(4) \approx \psi(12)\psi(13)\psi(14)\psi(23)\psi(24)\psi(34)/\varphi^2(1)\varphi^2(2)\varphi^2(3)\varphi^2(4). \quad (2)$$

Here $\Omega(ij)$ is the correlation operator, $\psi(ij)$ is the wave function of the pair (ij) taking correlations into account, and $\varphi(i)$ is the single-particle nucleon wave function. The explicit expressions for those functions are given in [3]. To be definite, we shall ascribe the numbers 1 and 3 to protons and the numbers 2 and 4 to neutrons.

We assume that direct interaction of the γ ray with all nucleons of the nucleus causes emission of a neutron-proton pair which is spatially correlated at the moment of interaction with the radiation, while the other correlated pair forms the deuteron at the end of the reaction. Thus, it is assumed that the He^4 nucleon consists of two correlated pairs. In this approximation, we have to substitute in the expression for the wave function $\psi(1234)$ the function $\varphi(i)\varphi(j)$ for the wave functions $\psi(ij)$ of all pairs, with the exception of the two under consideration. (It should be noted that similar approximations have also been made in [3].)

As can be seen from Eq. (2), the wave function $\psi(1234)$ then reduces to the product of the wave functions of two pairs. From the mechanism of the process under consideration, we should, in our case, take only the first two functions out of the three possible functions $\psi(12)\psi(34)$, $\psi(32)\psi(14)$, and $\psi(13)\psi(24)$. We shall carry out the calculation using the first of these possibilities for the function $\psi(1234)$. Moreover, we have to multiply the final expression for the cross section by a constant g, which gives the effective weight of the configuration considered. If the configurations (12)(34) and (32)(14) contributed independently to the cross section, then the constant would be equal to $2/3$. In general, it will be of the order of $2/3$.

In view of the above, the wave function of the initial state of the system can be written in the form

$$\Psi_i = \psi(12)\,\psi(34)\,[Y_{00}(\tau_1\tau_2)\,Y_{00}(\tau_3\tau_4)\,Y^0_{011}(\sigma_1\sigma_2;\ \sigma_3\sigma_4) - Y_{00}(\sigma_1\sigma_2)\,Y_{00}(\sigma_3\sigma_4)\,Y^0_{011}(\tau_1\tau_2;\ \tau_3\tau_4)]/\sqrt{2}, \quad (3)$$

where $Y_{lm}(\sigma_i\sigma_j)$ and $Y_{lm}(\tau_i\tau_j)$ are the spin and isospin functions of the pair ij, and $Y^M_{Jl_1l_2}(\sigma_1\sigma_2;\ \sigma_3\sigma_4)$ and $Y^M_{Jl_1l_2}(\tau_1\tau_2;\ \tau_3\tau_4)$ are the spin and isospin functions of the four particles obtained from the spin and isospin functions of the pairs.

In the calculations, we take only the electrical term for the interaction of the radiation with the nucleus, neglecting the interaction of the radiation with the magnetic moment of the nucleons. At the same time, we have taken the delay effect into account. As is well known, the contribution of the magnetic interactions to the total cross section of photonuclear reactions at low and medium γ-ray energies is relatively small, and for $E_\gamma \sim 100$ MeV it amounts to a few per cent of the total cross section, as was shown by Matsumoto.[4] There are, therefore, sufficient reasons for neglecting the magnetic interaction.

We should take for the wave function of the final state a function that includes the interaction of the reaction products. However, as has been shown by a number of authors,[5,6] in photonuclear reactions involving very light nuclei the interaction of the photonucleons with the recoil nuclei influences the total cross section very little, and can thus be neglected. As far as the interaction between the emitted neutron and proton is concerned, we can state the following: the neutron-proton interaction can be appreciable only near the reaction threshold, for only there is this pair emitted with a low relative energy, as shown by the experiments of Gorbunov and Spiridonov[1,2] and confirmed by our calculations. At the same time, the total cross section as a function of the γ-ray energy has a maximum far from the threshold, and since we are interested in the features of the process and the correlation functions at high energies, we can neglect the neutron-proton interaction in the final state.

It is furthermore clear that the He^4 nucleus described by the wave function Ψ_1 can disintegrate as a result of interaction with radiation, emitting any one of the pairs (12) and (34). It is evident that the probability of both processes is the same, and we shall therefore limit ourselves to the calculation of the photodisintegration cross section involving the emission of the nucleons 1 and 2, and multiply the results obtained by two.

In view of the above, we can write the wave function of the final state of the system in the form

$$\Psi_f = \Phi(\mathbf{r}_{34})\exp(i\mathbf{k}_d\mathbf{R}_{34})\,Y_{1m'}(\sigma_3\sigma_4)\,Y_{00}(\tau_3\tau_4)\exp(i\mathbf{K}\mathbf{R}_{12}) \times [Y_{10}(\tau_1\tau_2)\,\psi_{-\mathbf{k}} + Y_{00}(\tau_1\tau_2)\,\psi_{\mathbf{k}}]\,Y_{1m}(\sigma_1\sigma_2)/\sqrt{2}, \quad (4)$$

where

$$\psi_{\pm\mathbf{k}} = \{\exp(i\mathbf{k}\mathbf{r}_{12}) \pm \exp(-i\mathbf{k}\mathbf{r}_{12})\}/\sqrt{2},$$

$$\mathbf{r}_{ij} = \mathbf{r}_i - \mathbf{r}_j,\quad \mathbf{R}_{ij} = (\mathbf{r}_i + \mathbf{r}_j)/2,\quad \mathbf{k} = (\mathbf{k}_1 - \mathbf{k}_2)/2,\quad \mathbf{K} = \mathbf{k}_1 + \mathbf{k}_2, \quad (5)$$

where $\mathbf{r}_i$ is the radius vector of the i-th particle, $\mathbf{k}_1$, $\mathbf{k}_2$, and $\mathbf{k}_d$ are the wave vectors of the proton, neutron, and deuteron respectively, and $\Phi(\mathbf{r}_{34})$ is the wave function of the deuteron. It should be noted that all values are calculated in the center-of-mass system of the reaction products.

The fact that the free pair (12) can be either in the isosinglet or the isotriplet state is taken into account in the expression of the wave function Ψ_f, and, therefore, the effect will likewise not vanish in the dipole approximation.

For the matrix element of the transition we obtain

$$H'_{if} = \frac{e\hbar}{Mc}\frac{M(m'm)}{2\sqrt{2}}D\{2a_2(\mathbf{K}_-)[(\mathbf{ke} - \mathbf{Ke})\,a_1(\mathbf{q}_+) + \mathbf{ke}a_1(\mathbf{q}_-)] + \mathbf{Ke}a_2(\mathbf{K}_+)\,a_1(\mathbf{k})\}, \quad (6)$$

where

$$D = \int \Phi(\mathbf{r}_{34})\,\varphi_1(\mathbf{r}_{34})\,d\mathbf{r}_{34},\quad a_1(\mathbf{q}) = \int \varphi_1(\mathbf{r}_{12})\exp(i\mathbf{q}\mathbf{r}_{12})\,d\mathbf{r}_{12},$$

$$a_2(\mathbf{K}_\pm) = \int \varphi_2(\mathbf{R})\exp(i\mathbf{K}_\pm\mathbf{R})\,d\mathbf{R},$$

$$\mathbf{q}_\pm = \mathbf{k} \pm \mathbf{k}_\omega/2,\quad \mathbf{K}_\pm = \mathbf{K} \pm \mathbf{k}_\omega/2,$$

M(m′m) is the matrix element of the spin function and $\mathbf{e}$ is the polarization vector of the incident γ ray.

In deriving the expression for the matrix element, we have made use of the fact that the wave function $\psi(12)\psi(34)$ can be represented in the form

$$\psi(12)\,\psi(34) = \varphi_1(\mathbf{r}_{12})\,\varphi_1(\mathbf{r}_{34})\,\varphi_2(|\mathbf{R}_{12} - \mathbf{R}_{34}|), \quad (7)$$

where φ_1 describes the internal state of the pair and φ_2 the relative motion of the pair.

3. From the expression (6) for the matrix element, we have obtained the dependence of the total reaction cross section on the photon energy and the distribution of the relative energies of the neutron and of the proton.

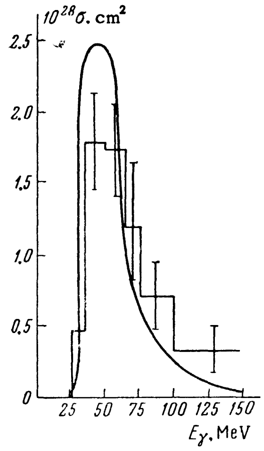

FIG. 1. Dependence of the total cross section of the $He^4(\gamma,np)D^2$ reaction on the γ-ray energy.

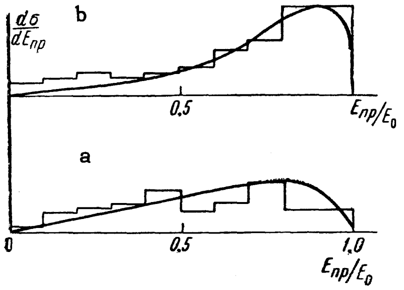

FIG. 2. Dependence of the cross section on the relative energy of the proton and the neutron in the c.m.s. for different γ-ray energies: a – E_γ=40 MeV, b – E_γ=70 MeV; E_{np} is the relative energy of the proton and the neutron, and E_0 is the energy imparted by the γ-ray to the nucleus.

The corresponding curves are shown in Figs. 1 and 2. The results shown in Fig. 1 are not multiplied by the factor g. Experimental results of [1] and [2] are also shown in the figures.

It can be seen from Fig. 1 that the theoretical curve gives, on the whole, a correct description both of the position of the maximum and of the energy dependence of the total cross section. Moreover, if we take into account that the cross section should be multiplied by the factor g, which is less than unity, we can conclude that, in the vicinity of the maximum, the theory is in good agreement with the experiment.

The curves in Fig. 2 show the existence of a correlation between the emitted neutron and proton. As should be expected, the most probable angle between the neutron and proton becomes close to 180°, with increasing energy, in agreement with the experimental data. [1,2]

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