Microscopic approach to direct cluster absorption of γ rays

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It is shown in the example of the reaction $^{16}O(\gamma, dd)^{12}C$ that the "quasi-alpha-particle" photodisintegration of light nuclei involves highly excited virtual clusters. It follows that the momentum distributions of the recoil nuclei should have the same form, $|\psi_{0S}(q)|^2$, for transitions to various levels of the final nucleus.

It was pointed out some time ago[1] that the deexcitation of virtual clusters in the course of their quasielastic ejection from a nucleus plays an important role in this ejection. In the present letter we work from the preliminary experiments of Ref. 2 to generalize this idea to the cluster photodisintegration of a nucleus in the case in which the corresponding fragments b_1 and b_2 emitted from the nucleus carry almost all the energy $E = E_\gamma - E_{\rm dis}$ and are detected by a coincidence arrangement.

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We consider intermediate energies, $E_\gamma \simeq 80$ MeV, and we start from the assumption that the nucleon which absorbs the γ ray is part of a virtual cluster B in the nucleus A. This cluster may be in one of many possible excited states in terms of its internal motion. As a result of the recoil to the other nucleons of the cluster B, the cluster disintegrates: $B \to b_1 + b_2$. The amplitude for the process is thus in principle the sum of many interfering terms.

We restrict the discussion to the simplest Hamiltonian for the interaction of γ rays with one-nucleon currents, $H = \Sigma H_j$:

$$H_j = -\frac{e}{M}\sqrt{\frac{2\pi n}{\omega}}\,[(e^{i\mathbf{q}\mathbf{r}_j}(\mathbf{u}\cdot\mathbf{p}_j)\frac{1}{2}(1+t_{3j}) + \frac{i}{8}([\mathbf{u},\mathbf{q}]\,\vec{\sigma}_j)\,e^{i\mathbf{q}\mathbf{r}_j}\{(g_p+g_n)+(g_p-g_n)t_{3j}\}], \quad (1)$$

where n is the number of γ rays per unit volume, and the notation is otherwise obvious. Using the multicluster representation[3] of the nuclear wave function in the translationally invariant shell model,[1] we can write the following expression for the amplitude for the direct process (γ, b_1, b_2):

$$T_{fi} = \begin{pmatrix} A \\ b_1+b_2 \end{pmatrix}^{1/2} \begin{pmatrix} b_2+b_2 \\ b_1 \end{pmatrix}^{-1/2} (b_1+b_2)\,\Sigma \langle A\,|\,A-B, b_1, b_2;\ \nu\lambda(\mathbf{x})n\Lambda(\mathbf{y})\rangle$$
$$\times\ \mathrm{CGC}\left\{\begin{pmatrix} b_1+b_2-1 \\ b_1-1 \end{pmatrix} \langle e^{i\mathbf{Q}\mathbf{R}}\,\psi^{(-)}_{\mathbf{Q}_x,\mathbf{Q}_y}(\mathbf{x},\mathbf{y})b_1^*|H_1|\,\psi_{\nu\lambda M_\lambda}(\mathbf{x})\,\psi_{n\Lambda M_\Lambda}(\mathbf{y})\right.$$
$$\times\ b_1\rangle\,\delta(|b_2\rangle, |b_2^*\rangle) + \begin{pmatrix} b_1+b_2-1 \\ b_2-1 \end{pmatrix} \langle e^{i\mathbf{Q}\mathbf{R}}\,\psi^{(-)}_{\mathbf{Q}_x,\mathbf{Q}_y}(\mathbf{x},\mathbf{y})b_2^*|H_1|\,\psi_{\nu\lambda M_\lambda}(\mathbf{x})$$
$$\left.\times\ \psi_{n\Lambda M_\Lambda}(\mathbf{y})b_2\rangle\,\delta(|b_1\rangle, |b_1^*\rangle)\right\}, \quad (2)$$

Here $\mathbf{R}$ and $\mathbf{Q}$ are the coordinate and momentum of the center of mass of the entire system in the final state; $\mathbf{x}$ is the distance between b_1 and b_2; $\mathbf{y}$ is the distance between the remainder $A-B$ and the center of mass of b_1+b_2; $\langle A\,|A-B, b_1\ldots\rangle$ is the multicluster genealogical coefficient[3]; and $\psi^{(-)}$ is the distorted wave which describes the relative motion of the clusters emitted from the nucleus and the residual nucleus. The letters CGC in (2) mean the Clebsch-Gordan coefficients, with intermediate angular momenta introduced in the obvious way.

For the particular reaction considered here, $^{16}O(\gamma, dd)^{12}C$ (this reaction was observed in the experiments of Ref. 4), the combined virtual cluster $B = b_1 + b_2 = {}^4He^*$ of four p-nucleons with the Young's tableau $\{f\} = \{4\}$ has $\widetilde{N} = N_1 + N_2 + \nu$ internal-excitation quanta, where N_1 and N_2 quanta correspond to the internal coordinates of the virtual deuterons, and ν correspond to their relative motion. Under the assumption that the emission angles θ_1 and θ_2 are symmetric with respect to the beam, that the momenta p_1 and p_2 are equal, and that these momenta lie in a common plane, we are

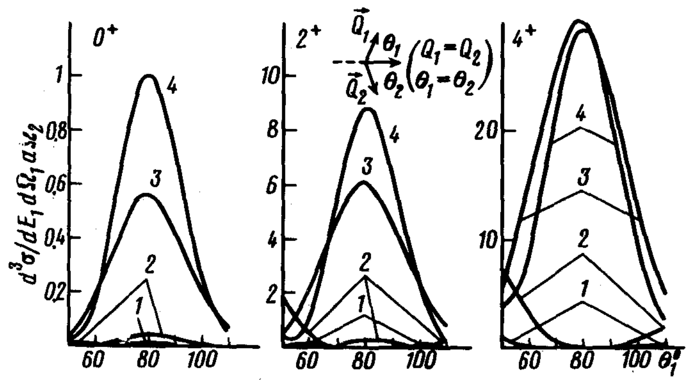

FIG. 1. Cross sections for the excitation of the three lowest levels of the ^{12}C nucleus with allowances for d-^{12}C interactions in the final state. 1—Only unexcited ^4He clusters are considered ($\tilde{N} = 0$); 2—doubly excited clusters ($\tilde{N} = 2$); 3—quadruply excited clusters ($\tilde{N} = 4$); 4—interference of all amplitudes. The unit here is $\sim 10^{-33}$ cm^2/(MeV·Sr^2).

dealing with a region of very small recoil momenta q at angles $\theta_1 = \theta_2 \simeq 81°–82°$. Here the momentum of the relative motion of the two final deuterons, Q_x, is large in comparison with the reciprocal nuclear radius, $Q_x \simeq 1.5$ fm^{-1}, while the amplitude $|\psi_{\nu\lambda}(Q_x)|$ increases rapidly with increasing ν in this region. The γ rays thus "catches" the highest-momentum component in terms of the relative motion ($\mathbf{x}$) of the liberated fragments ($\nu = \tilde{N} = \max = 4$). This predominance of the amplitudes with $\nu = N = 4$ over the amplitudes with $\nu = 0$ is intensified and reaches two orders of magnitude in the cross section if the final-state interaction[5] in each d-^{12}C pair is taken into account, since the local momentum Q'_x of the d-d relative motion in the interior of the nucleus is substantially larger than the asymptotic value of Q_x. However, the cross section is essentially no greater than that for the free α particle, since the momentum Q'_x corresponds to the remote periphery of the wave function, $\psi_{\nu\lambda}(Q_x)$, $|\psi_{\nu\lambda}(Q'_x)|^2 \ll |\psi_{\nu\lambda}(Q_x)|^2$. The observable consequence of importance here is that the momentum distributions of the recoil nuclei would be expected to be of the same type. In all three transitions, to the levels 0^+, 2^+, and 4^+ of the ^{12}C nucleus, we have essentially the same lowest possible wave function $\psi_{n\Lambda}(q)c$ $n = \Lambda = 0$ by virtue of the arguments above. Consequently, all three "momentum distributions" in Fig. 1, which shows the results of distorted-wave calculations, are described by essentially the same Fourier amplitude $|\psi_{n\Lambda}(q)|^2$ (in the distorted-wave basis) with $n = 0$ and $\Lambda = 0$. This is as it should be for various pairs of clusters and various nuclei. The difference in the absolute cross sections in Fig. 1 stems from the population factor[1] $\sim(2L + 1)$ and from the magnitudes of the matrix elements of the transition operators.

For the "quasi-alpha-particle mechanism" ($\tilde{N} = 0$), the three curves in Fig. 1 would literally correspond to the momentum distributions of α particles in the ^{16}O nucleus and would all be different [as in the (p, $2p$) process with $L = 0$, 2, and 4]. In particular, in the transition to the 0^+ state of the ^{12}C nucleus the width of the momentum distribution $|\psi_{n\Lambda}(q)|^2$ ($n = 4$, $\Lambda = 0$) would be 13.5°, rather than 24° as shown in Fig. 1.

By way of comparison, the role played by the $\widetilde{N}=2$ and 4 excitations in the quasielastic ejection of α clusters would be important but by no means as great.[1]

Experimentally, one can study the photoabsorption of any multi-polarity: The nature of the process is determined only by the value of E_γ. The $E1$ absorption is "more practical," however; the (γ, pt), (γ, dt), $(\gamma, t\,^3\mathrm{He})$ cross section is one or two orders of magnitude greater than in Fig. 1 (Ref. 4).

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