Anisotropy with respect to the Yang-Treiman angle in quasielastic knockout of clusters from atomic nuclei by hadrons

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A new experimentally observable consequence of the allowance for "de-excitation" of clusters, namely anisotropy with respect to the Yang-Treiman angle (YTA), is predicted on the basis of the dynamic approach of Golovanova *et al*. [JETP Lett, **20**, 310 (1974); **22**, 50 (1975), Sov. J. Nucl. Phys. **23**, 33 (1976), Nuclear Physics A262, 444 (1976)]. Certain conditions for the existence of the YTA are generalized. The degree of anisotropy depends on the range of values of the momentum p transferred to the cluster. Complete isotropy should always be observed in the region of maximum multiplicity of scattering of the hadrons by the cluster.

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Allowance for the possibility of "de-excitation" of the virtual cluster in the course of its quasielastic knockout from the nucleus by fast hadrons[1–3] has added much detail to the physical picture of such a process and has led to the prediction of a number of new effects. We point out in this paper a new experimentally observable consequence of the allowance for "de-excitation" of the clusters, namely, anisotropy with respect to the Yang-Treiman angle.[4] This anisotropy, which should be observed at small recoil momenta, q, is a consequence of the fact that the mechanism of the reaction does not correspond to the pole diagram if the indicated "de-excitation" is taken into account. Using the methods developed in[1-3] but taking all the scattering multiplicities into account, we obtain in the Glauber-Sitenko approximation the following expression for the matrix elment of the transition, for example, in the case of knock-out of a triton cluster,

$$
\begin{aligned}
M_{if}(q,p) = \frac{ip_0'}{2\pi} \sum_{\beta\mu\gamma} \langle A\alpha \mid A-3\beta;\mu;\gamma\rangle\, \phi_\mu(q) \int \Phi_t^*(R_1,R_2)
\\
\times\Bigg\{ \frac{2\pi}{ip_0} f(p) \left[e^{ip\frac{2}{3}\rho_{x_2}} + e^{ip(\frac{1}{2}\rho_{x_1}-\frac{1}{3}\rho_{x_2})} + e^{-ip(\frac{1}{2}\rho_{x_1}+\frac{1}{3}\rho_{x_2})} \right]
\\
-\left(\frac{2\pi}{ip_0}\right)^2 f^2\!\left(\frac{p}{2}\right) \Bigg[e^{\frac{1}{2}ip(-\frac{1}{2}\rho_{x_1}+\frac{1}{3}\rho_{x_2})}\, \delta^2(\tfrac{1}{2}\rho_{x_1}+\rho_{x_2}) + e^{i\frac{1}{2}p(\frac{1}{2}\rho_{x_1}+\frac{1}{3}\rho_{x_2})}
\\
\times \delta^2(\rho_{x_2}-\tfrac{1}{2}\rho_{x_1}) + e^{i\frac{1}{2}p\frac{2}{3}\rho_{x_2}}\, \delta^2(\rho_{x_1}) \Bigg] + \left(\frac{2\pi}{ip_0}\right)^2 f^3\!\left(\frac{p}{3}\right) \delta^2(\rho_{x_1})
\\
\times \delta^2(\rho_{x_2}) \Bigg\} \Phi_\gamma(R_1,R_2)\, d^3R_1\, d^3R_2. \qquad (1)
\end{aligned}
$$

The indices $\alpha=[f]LSTM_{LST}$ and $\beta=[f_1]L_1S_1T_1M_{L_1S_1T_1}$ characterize here the initial and final nucleus, respectively, $\gamma=[3]N_0L_0M_0S_0T_0M_{S_0T_0}$ and $\mu=n\Lambda m$ describe the internal state and the motion of the mass center of a virtual cluster, $p=p_0-p_0'$, $f(p)$ is the NN-scattering amplitude, $R_i=(\rho_i,Z_i)$ is the ith Jacobi coordinate ($i=1$ or 2), and Φ_γ and Φ_t are the wave functions of the virtual triton in the target and of the free triton, respectively.

From formula (1) we can draw a number of important conclusions:

1) In the region of scattering of maximum multiplicity (the term with $f^3(p/3)$, owing to scattering of a fast hadron by each nucleon of the cluster, there appear two-dimensional δ functions with respect to each Jacobi coordinate. The only possible value is therefore $M_0=0$, since the function in the potential well, at small ρ, has an asymptotic form ρ^{m_i} for each Jacobi coordinate. It is then perfectly possible to have $L_0\neq 0$. As a result, we can have in the indicated region only isotropy of the differential cross section with respect to the angle ϕ_q, although noticeable anisotropy with respect to θ_q is possible and is connected with the terms $L_0\neq 0$. Here ϕ_q (which is the Yang-Treiman angle at small q[4]) is the azimuthal angle of the recoil momentum q relative to the (p_0p_0') plane, while θ_q is the polar angle (the z axis is directed along the momentum p_0).

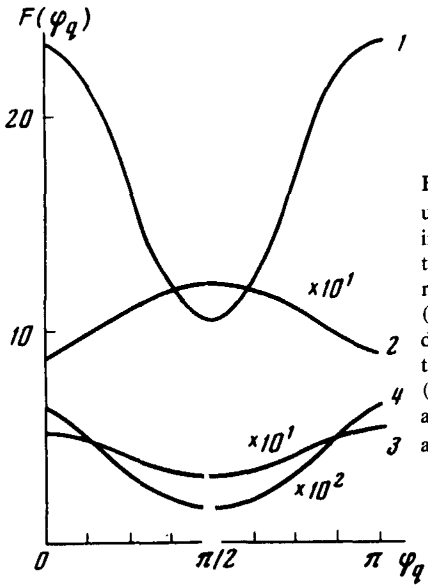

FIG. 1. Distribution with respect to the angle ϕ_q in relative units for the reaction $O^{16}(p,pt)N^{13}$. The N^{13} nucleus is produced in the ground state $^{22}P(J_1=1/2,E^*=0)$: curve 1 corresponds to the single-scattering region ($p^2=0.1$ (GeV/c)^2); curve 2—to the region of interference of single and double scattering ($p^2=0.1$ (GeV/c)^2); curve 3—to the region of interference of single and double scattering ($p^2=0.2$ (GeV/c)^2); curve 3 was calculated in the region of the maximum of double scattering ($p^2=0.40$ (GeV/c)^2); curve 4—in the region of interference of the double and triple scattering ($p^2=0.75$ (GeV/c)^2);for all curves $\theta_q=\pi/2$ and $q=100$ MeV/c.

2) If the scattering multiplicity is less than the maximum value, i.e., not every Jacobi coordinate involves a δ function, then we can have not only $L_0\neq 0$ but also $M_0\neq 0$. Thus, anisotropy is produced with respect to the Yang-Treiman angle (YTA) ϕ_q, as well as with respect to the angle θ_q. This makes the conditions for the existence of the YTA more general: the anisotropy can occur for any cluster, including an α particle, and for any target nucleus heavier than ^{6}Li, since it is connected not with the value of the total internal angular momentum J_x of the knock-out cluster, as a free particle, but with the value of the orbital angular momentum of the virtual cluster in the nucleus, which varies in the course of collision (a certain value $L_0\neq 0$ at the start and zero at the end).

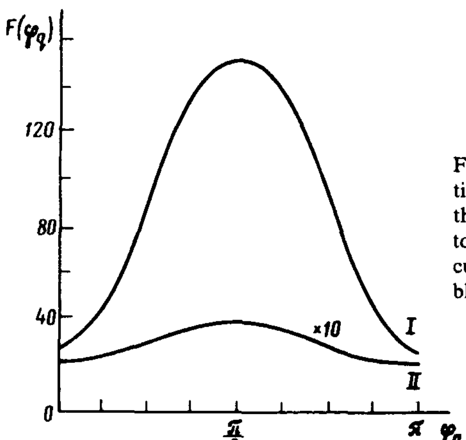

FIG. 2. The same distributions as in Fig. 1 for the reaction $O^{16}(p,pd)N^{14}$, when the nucleus N^{14} is produced in the ground state $^{13}D(J_1=1,E^*=0)$; curve 1 corresponds to the region of single scattering ($p^2=0.05$ (GeV/c)^2); curve 2 corresponds to the interference of single and double scattering ($p^2=0.35$ (GeV/c)^2).

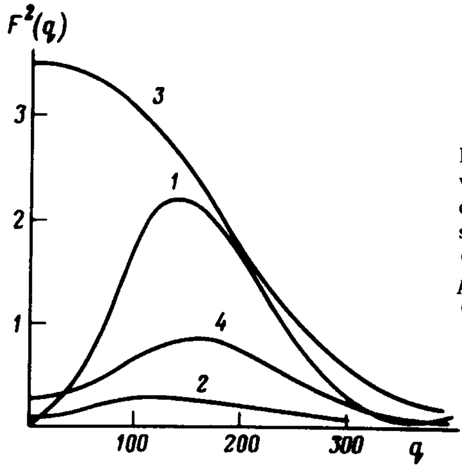

FIG. 3. Form factor $F^2(p,q)$ for the reaction $O^{16}(p,pt)N^{13}$, with transition to the ground state of the N^{13} nucleus: curves 1, 2, 3, and 4 correspond to the regions of single scattering $p^2=0.1$ $(\mathrm{GeV}/c)^2$, double scattering $p^2=0.40$ $(\mathrm{GeV}/c)^2$, interference of the double and triple scattering $p^2=0.75$ $(\mathrm{GeV}/c)^2$, and triple scattering $p^2=1.15$ $(\mathrm{GeV}/c)^2$, respectively. q is given in MeV/c.

Changing over from the amplitudes (1) to cross sections with the aid of vector algebra, we have calculated the YTA for two reactions (Figs. 1 and 2). Analytically, in the case of knockout of a triton cluster, the anisotropy is described by the expression

$$F^2(p,\ q) = \alpha(p)\cos 2\phi_q + \beta(p)\sin\phi_q + \gamma(p) \tag{2}$$

and, as shown by Figs. 1 and 2, can be appreciable.

3) From formula (1) follows also the important conclusion that the effective "momentum distributions" (form factors)

$$F^2(p,\ q) = [(d\sigma/d\Omega)_{\mathrm{fr}}]^{-1}(2J+1)^{-1}\int \overline{|M_{if}(p,\ q)|^2} d\Omega_q \tag{3}$$

depend on the value of p, i.e., on the scattering multiplicity. Figure 3 shows the form factors for the knockout of a triton from the nucleus ^{16}O at different values of p, and we see how strong the p-dependence can be.

We note in conclusion that the process of quasielastic knockout of clusters, as shown by the investigations in[1-3,5] and the present study, represent the complete physical realization of the entire list of formally possible nontrivial properties of the amplitudes of direct processes at high energies,[4] namely, anisotropy with respect to $\cos\theta_q$,[1,3] anisotropy with respect to the Yang-Treiman angle, and a dependence of the form factors $\overline{|F_{if}(p,q)|^2}$ (generalized momentum distributions of the clusters in the nucleus) on the momentum p.[2,3,5]

We have here therefore a very wide scope for experimental research, ,which will make it possible in conjunction with the foregoing, to explain the dynamics of the formation of virtual clusters in atomic nuclei.

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