Angular dependence of model-independent characteristics of inelastic $^{12}C(\alpha,\alpha')^{12}C_{4,43}$ scattering from measurements of angular α-γ correlations

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For the first time, an experimental study of angular correlations has yielded a complete set of independent spin tensors of the final-state density matrix. The angular dependence of the nine spin tensors of the density matrix of the 2^+ state of the ^{12}C nucleus has been determined for the reaction $^{12}C(\alpha,\alpha\gamma_{4,43})^{12}C$ in the angular interval θ_α (c.m.) = 26–168.5° at E_α = 25 MeV. The populations of substates of this state have also been determined.

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Measurements of the angular correlation between particles produced in nuclear reactions and the γ rays emitted by the even-even final excited nuclei in several γ-emission planes can yield all possible model-independent characteristics of the reactions (the irreducible spin tensors of the density matrix).[1] For the $2^+ \to 0^+$ transition, accompanied by the emission of an $E2$ γ ray, the irreducible spin tensors have nine components. All can be determined experimentally if the angular correlation functions are measured in at least three γ-emission planes.

For the reaction $^{12}C(\alpha, \alpha\gamma_{4,43})^{12}C$ the angular correlation function $W(\theta_\alpha; \theta_\gamma, \phi_\gamma)$ is expressed in terms of the components of the irreducible spin tensors $A_{k\kappa}(\theta_\alpha)$ as follows[1]:

$$W(\theta_\alpha; \theta_\gamma, \phi_\gamma) = \frac{1}{4\pi} \sum_{\substack{k=0,2,4 \\ -k\leqslant\kappa\leqslant k}} A_{k\kappa}(\theta_\alpha)\sqrt{\frac{2}{2k+1}}\,\bar{P}_k^\kappa(\cos\theta_\gamma)\cos\kappa\phi_\gamma, \quad (1)$$

where $\bar{P}_k^\kappa(\cos\theta_\gamma)$ are the normalized associated Legendre polynomials, and $A_{00}(\theta_\alpha) \equiv d\sigma/d\Omega(\theta_\alpha)$ Expression (1) is written in a coordinate system with z axis along the direction of the bombarding particle beam; the reaction plane is the (x, z) plane. The polar angle θ_γ and the azimuthal angle ϕ_γ specify the direction in which the γ ray is emitted; the angle θ_α specifies the direction in which the scattered α particle is emitted. In this coordinate system, all the $A_{k\kappa}(\theta_\alpha)$ are real, and we have $A_{k\kappa}(\theta_\alpha) = (-1)^\kappa A_{k-\kappa}(\theta_\alpha)$.

Angular correlations in $^{12}C(\alpha, \alpha\gamma_{4,43})^{12}C$ reactions have been studied elsewhere (see Ref. 2 and 3 and the other papers cited in Ref. 2). In most cases, however, measurements were taken exclusively in the plane of the reaction. Only in Ref. 3 were measurements taken both in the reaction plane and in the plane perpendicular to it, at

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$E_\alpha = 32$ MeV. Imposing some additional restrictions on the properties of the reaction amplitude, Burdzik and Heymann[3] reconstructed the polarization tensor of the final state of ^{12}C. Feofilov *et al.*[4] worked from measurements of the angular correlations of recoil ^{12}C nuclei and α particles from a reaction to determine the population of one substate of the 2^+ state of the ^{12}C nucleus at $E_\alpha = 24$ MeV.

In this paper we report a study of the inelastic scattering $^{12}C(\alpha, \alpha\gamma_{4,43})^{12}C$ at $E_\alpha = 24.8$ MeV. The experiment was carried out on a 120-cm cyclotron. The silicon detectors which detected the α particles were arranged along a special arced support at four different angles θ_α inside the scattering chamber. This support could be rotated around the beam axis over the angular interval from 0 to 90° with respect to the horizontal plane. The angle ϕ_γ was varied, while the angles θ_α and θ_γ were left constant. The scintillation detector with a NaI(Tl) crystal with dimensions of 60×60 mm used to detect the γ rays lay outside the scattering chamber and could be rotated in the horizontal plane.

The θ_γ dependence of the double differential cross sections was measured over

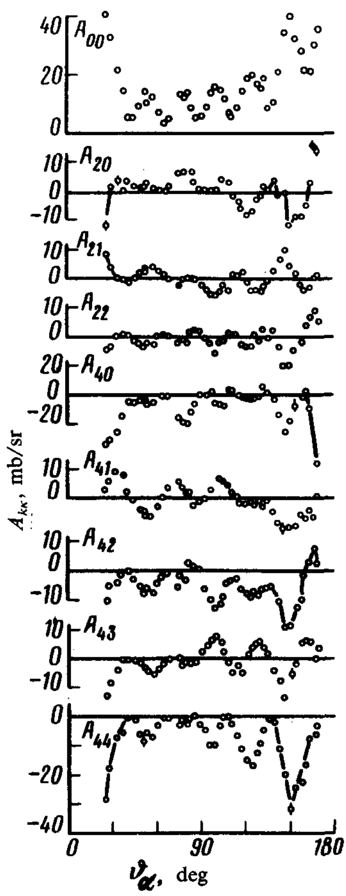

FIG. 1. The angular dependence $A_{k\kappa}(\theta_\alpha)$.

the interval from 27° to 149° in three planes ϕ_γ with respect to the reaction plane (0°, 45°, and 90°)[1)] for 43 values of θ_α. It was found that the experimental angular correlation functions for the different values of ϕ_γ are very different in form. The spin-tensor components $A_{k\kappa}(\theta_\alpha)$ were found by solving system (1) by the method of least squares, with corrections for the finite dimensions of the γ detector.

The values found for $A_{k\kappa}(\theta_\alpha)$ from the experimental data are shown in Fig. 1 in units of millibarns per steradian. Within the statistical error, the $A_{00}(\theta_\alpha)$ dependence is the same as the angular distribution of the differential cross section for inelastic scattering, as it should be according to Ref. 1. We see from this figure that each angular dependence $A_{k\kappa}(\theta_\alpha)$—not simply $A_{00}(\theta_\alpha)$—is oscillatory, but the behavior is not a reproduction of the angular dependence of the differential cross section. The components $A_{k\kappa}$ depend strongly on the angle θ_α, varying in sign as well as magnitude in most cases. We also see that all the components of the spin tensors are nonzero and are comparable in magnitude.

The set of $A_{k\kappa}(\theta_\alpha)$ which we found is a complete set of model-independent quantities, which can be used to find all the characteristics of this reaction. For example, we can calculate the populations $P_m^{J=2}$ of the substates of the final state of the nucleus, $J=2^+$, with various spin projections m (Ref. 1). The results of these calculations for $P_m^{J=2}(\theta_\alpha)$ are shown in Fig. 2. The values found for $P_{\pm 2}^{J=2}$ here are approximately the same as those reported in Ref. 4 for $\theta_\alpha \geqslant 120°$.

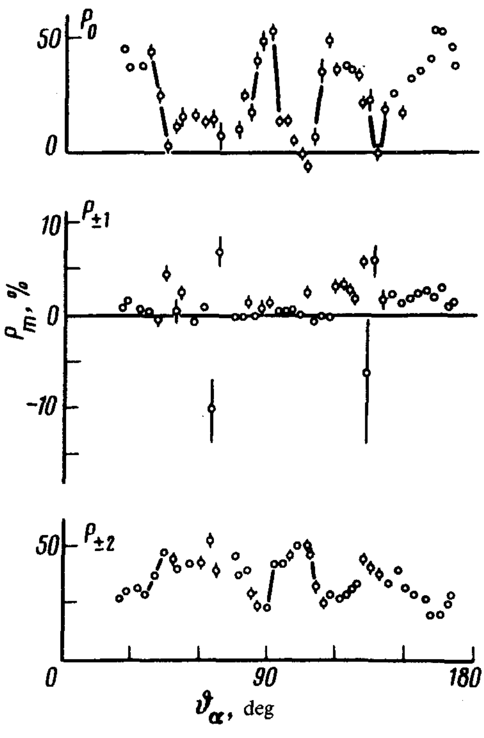

FIG. 2. Angular dependence of the various components of the $P_m^{J=2}$ population.

The experimental angular dependences of all nine $A_{k\kappa}(\theta_\alpha)$ contain much more information than the angular distributions, i.e., $A_{00}(\theta_\alpha)$. A quantitive analysis of the results is a complicated matter and as yet has not been carried out for any reaction mechanism. Nevertheless, certain conclusions regarding the reaction mechanism can be drawn from a relatively simple qualitative analysis of the $A_{k\kappa}$. It was shown in Ref. 1 that if the reaction amplitude is Hermitian, i.e., if the processes involving a retardation in the interaction—a two-step process,[5] for example—are of minor importance in the reaction mechanism, then the following relations should hold:

$$
\begin{aligned}
R_1 &= A_{00} + A_{20} - \sqrt{6}A_{22} + A_{40} + \sqrt{2.5}A_{42} = 0,\\
R_2 &= -4A_{00} + 8A_{20} + A_{40} - \sqrt{70}A_{44} = 0,\\
R_3 &= 4\sqrt{6}A_{00} + \sqrt{5}A_{41} + \sqrt{35}A_{43} = 0.
\end{aligned}
\tag{3}
$$

Calculations of R_i for all angles θ_α for which measurements were taken show that the R_i are approximately zero (when the statistical error is taken into account). The reason why the R_i are slightly different from zero might be either some small systematic errors which have not been taken into account or a small contribution from multiple-step reaction mechanisms. If conditions (3) hold, then the components $P^{J=2}_{\pm 1}$ should be zero. It follows from Fig. 2 that $P^{J=2}_{\pm 1}$ is in fact small, less than 5%.

In summary, a complete set of model-independent reaction characteristics has been obtained from measurements of α-γ angular correlations in various γ emission planes with respect to the reaction plane. This is the first case in which this possibility has been realized. All nine components of the spin tensors of the density matrix of the 2^+ state of the ^{12}C nucleus have been determined for the reaction $^{12}C(\alpha, \alpha\gamma_{4,43})^{12}C$. A qualitative analysis of the results suggests that single-step processes are dominant in the reaction mechanism.

[1)]In the coordinate system used in Ref. 1, these angles correspond to $\phi_\gamma = 180°$, 225°, and 270°.

[1]N. S. Zelenskaya and I. B. Teplov, Izv. Akad. Nauk SSSR, Fiz. **44**, 960 (1980); Nucl. Phys. **A406**, 306 (1983).
[2]E. M. Burymov *et al.*, Izv. Akad. Nauk SSSR, Ser. Fiz. **45**, 746 (1981).
[3]G. F. Burdzik and G. Heymann, Nucl. Phys. **A185**, 509 (1972).
[4]G. A. Feofilov *et al.*, Tez. dokl. XXIX Soveshch. po yad. spektroskopii i str. atomnogo yadra (Proceedings of the Twenty-Ninth Conference on Nuclear Spectroscopy and Nuclear Structure), Riga, 1979, p. 338.
[5]N. S. Zelenskaya, Yad. Fiz. **25**, 514 (1977) [Sov. J. Nucl. Phys. **25**, 276 (1977)].

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