Dependence of the mechanism of inelastic dissociation of a relativistic carbon nucleus into three α particles on its excitation energy

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A characteristic nonmonotonic dependence of the degree of collinearity of the transverse momenta of α particles in the azimuthal plane of the reaction $^{12}C \rightarrow 3\alpha$ at 4.2 GeV/c per nucleon on the excitation energy of the carbon nucleus has been observed. The data are consistent with a change from the mechanism of successive binary disintegrations ($^{12}C \rightarrow {}^{8}Be + \alpha \rightarrow 3\alpha$) to direct multifragmentation and a subsequent increase in the angular momentum of the fragmenting system with increasing "temperature" of the system. © *1995 American Institute of Physics.*

The multifragmentation of nuclei, whose excitation energies are comparatively low, is one of the main processes which yield direct information about the structure of the nuclei and the form of the equation of state of nuclear matter. Different theoretical approaches are used to describe the dynamics of this process. Two viewpoints, which are to a certain extent extreme, concerning the fragmentation mechanism can, however, be singled out: a time-dilated series of successive binary decompositions and "instantaneous" direct decay into a system of observed final fragments.

In some studies (see, for example, Refs. 1–3) it was found that the mechanism of the decay reactions of the nuclei depends on the excitation energy of the nuclei (or the "temperature" of the decay): At low energies ($kT \leqslant 3$ MeV/nucleon) successive binary decays predominate and at higher energies direct multifragmentation predominates. On the other hand, in some studies (see, for example, Ref. 4) no such transition was observed.

In the present letter we use a new method to analyze the excitation energy dependence of the mechanism for decay of excited nuclei for one of the simplest exclusive fragmentation channels. We shall investigate reactions in which relativistic carbon-12 nuclei decay into three α particles

$$^{12}C \rightarrow 3\alpha. \qquad (1)$$

These reactions were selected in an experiment with a two-meter propane bubble chamber at the High-Energy Laboratory (HEL) of the Joint Institute for Nuclear Research (JINR). We selected the dissociation reactions (1) from about 40 000 inelastic interactions of ^{12}C nuclei with the working material C_3H_8 of the bubble chamber, exposed in a beam of ^{12}C ions with a primary momentum of 4.2 GeV/c per nucleon in the heavy-particle synchrotron at the HEL. The experimental procedure for studying nuclear-nuclear

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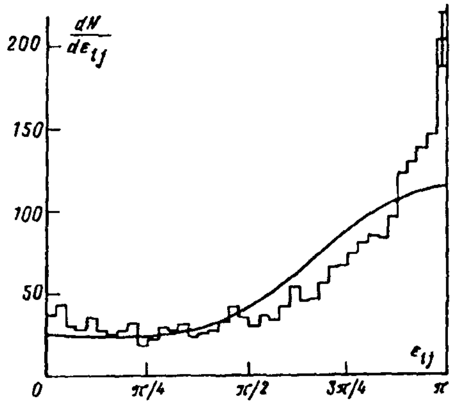

FIG. 1. Collinearity coefficient in the distribution $dn/d\varepsilon_{ij}$ versus the average transverse momentum $\langle p_T \rangle$ of α particles from the reactions (1) or versus the excitation energy of the ^{12}C nucleus, as estimated from Eq. (8).

interactions in the two-meter propane bubble chamber was described in detail in the early papers.[5] From the final DST, which contained approximately 40 000 events of the type $C-C_3H_8$, we selected 741 events with three fragments with $z=2$ in the final state (which, in what follows, are assumed to be α particles). These selected events consisted of the following:

a) 121 "pure" 3α events, which do not exhibit any visible indications of excitation or decomposition of the target nucleus and other secondary charged particles; these events are consistent with a coherent character of the given reaction on a carbon nucleus (diffraction or Coulomb reaction);

b) 51 3α events with a single proton-recoil track with $\theta<\pi/2$, in which $\mathbf{p}_T$(recoil proton) $= -\Sigma_{i=1}^{3}\mathbf{p}_{Ti}$; these events are consistent with a diffraction splitting $^{12}C \to 3\alpha$ on the free hydrogen of the propane;

c) 569 events of the type 3α with two or more additional (charged and neutral) particles; these are the incoherent decays $^{12}C \to 3\alpha$ on the target nuclei.

We studied the general characteristics of these 741 reactions in Ref. 6.

The exclusive character of the reaction which we investigated, i.e., the assumption that no other (neutral) spectator fragments from the projectile nucleus are present, makes it possible to switch easily to the center-of-mass system of the 3α particles (i.e., the rest system of the fragmenting nucleus). In what follows we shall study the momentum and correlation characteristics in this system.

Figure 1 shows the inclusive distribution over the pair azimuthal angle

$$\varepsilon_{ij}=\cos^{-1}(\mathbf{p}_{Ti}\mathbf{p}_{Tj}/p_{Ti}p_{Tj}) \qquad (2)$$

between the transverse momentum vectors $\mathbf{p}_{Ti}$ and $\mathbf{p}_{T_j}$ of the ith and jth α particles from one dissociation event (1) for all 741 events [the distributions for the groups a, b, and c (see above) are identical within the limits of error]. In the case of a direct random decay into 3α particles this distribution should be described by the formula

$$f(\varepsilon)=\pi^{-1}(1+c_1\cos\varepsilon+c_2\cos 2\varepsilon), \tag{3}$$

where $c_1=-\frac{\pi}{2}A$ and $c_2=\frac{\pi}{2}B$, and, finally, A and B are, correspondingly, the azimuthal asymmetry and collinearity coefficients, defined as

$$A=\frac{N_{\varepsilon>\pi/2}-N_{\varepsilon\leqslant\pi/2}}{N_{0\leqslant\varepsilon\leqslant\pi}} \tag{4}$$

and

$$B=\frac{N_{\varepsilon\leqslant\pi/4}+N_{\varepsilon\geqslant 3\pi/4}-N_{\pi/4<\varepsilon<3\pi/4}}{N_{0\leqslant\varepsilon\leqslant\pi}}. \tag{5}$$

In the case of a random decay into 3α particles we have $A_0=(N_\alpha-1)^{-1}=0.5$ and $B_0=0.64(N_\alpha-1)^{-2}=0.16$, while the empirical values of A and B, calculated for the distribution in Fig. 1, are equal to 0.46 ± 0.02 and 0.31 ± 0.02, respectively. Therefore, the transverse momenta of the α particles tend to fly apart collinearly in the transverse collision plane in the rest system of the fragmenting nucleus.

We shall now consider the dependence of the collinearity coefficient in Eq. (5) on the excitation energy of the carbon nucleus which fragments into 3α particles. We shall accordingly employ the statistical theory of fast fragmentation,[7,8] according to which the "temperature" of the decay is

$$kT=\frac{A}{A-1}\frac{\sigma_N^2}{m_N}, \tag{6}$$

where $A\equiv A_c=12$, m_N is the nucleon mass, and σ_N^2 is the dispersion of the intranuclear momentum distribution of the nucleons. Using the so-called parabolic law[8]

$$\sigma_N^2=\sigma_\alpha^2(A-1)/A_\alpha(A-A_\alpha), \tag{7}$$

where $A_\alpha=4$ and $\sigma_\alpha^2=\langle p_T^2\rangle/\pi$, we obtain a simple relation between the desired excitation energy kT per nucleon and the average transverse momentum of an α particle $\langle p_T\rangle$ in the rest system of the carbon nucleus:

$$kT=\frac{A}{A_\alpha(A-A_\alpha)}\frac{2\langle p_T\rangle^2}{\pi m_N}. \tag{8}$$

Figure 2 shows the main result of our work — the discovery of a dependence of the collinearity coefficient B of the distribution $dn/d\varepsilon_i$ over the pair azimuthal angle between the transverse momenta of the α particles in the rest system of a carbon nucleus that decays in the channel (1) on the average transverse momentum of these particles or (on the basis of the statistical theory) on the excitation energy of the nucleus. This dependence is nonmonotonic. For $\langle p_T\rangle\leqslant 200$ MeV/c ($kT\leqslant 10$ MeV/c) B decreases with increasing $\langle p_T\rangle(kT)$, reaching in the region $\langle p_T\rangle\approx 200$ MeV/c ($kT\approx 10$ MeV) its minimum value, which is virtually identical to the value of B_0 required by energy and momentum conservation in the direct decay $^{12}C\rightarrow 3\alpha$. For $\langle p_T\rangle>200$ MeV/c ($kT>10$ MeV) the collinearity coefficient starts to increase with $\langle p_T\rangle(kT)$, again reaching a rather high value ($B\approx 0.5$) at $\langle p_T\rangle\approx 400$ MeV/c ($kT\approx 40$ MeV).

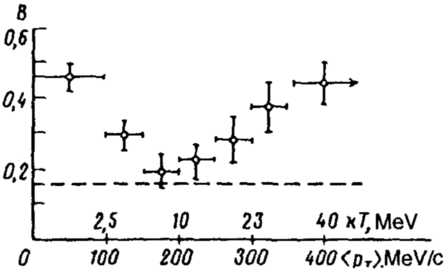

FIG. 2. Distribution over the pair azimuthal angle ε_{ij} in the center-of-mass system of the reaction $^{12}C \rightarrow 3\alpha$. The curve was calculated according to the phase-volume model for the given decay.

In conclusion, we shall discuss the interpretation of the observed effect. The decrease of the degree of collinearity of $\mathbf{p}_T$ of the α particles in the reaction (1) to the value of B_0 corresponding to a direct decay in the region ($kT \leqslant 10$ MeV/c) corresponds to a transition from the cascade model of the decay $^{12}C \rightarrow {}^8Be + \alpha \rightarrow 3\alpha$ with the formation of an unstable intermediate ^8Be nucleus in the ground or first excited state to direct multifragmentation as kT increases. This result is confirmed by the data of Ref. 9, where two separated maxima were discovered in the distributions over the relative polar angles and over the effective masses of the pairs of α particles from the events of the reaction (1) with $p_0 = 4.5$ GeV/c per nucleon in a photoemulsion. These maxima were observed in events with $\langle p_T \rangle < 100$ MeV/c ($kT \leqslant 2.5$ MeV) and were absent for $\langle p_T \rangle > 100$ MeV/c ($kT > 2.5$ MeV). The increase in B in the second section of the function $B(kT)$ (Fig. 2) with increasing kT for $kT > 10$ MeV cannot be attributed to the reverse transition from domination by the first decay channel (1) to domination by the cascade channel. A much more logical assumption is that the angular momentum, which the fragmenting nucleus acquires in an inelastic collision, increases with the excitation energy of the nucleus. Of course, further investigations are required in order to draw definite conclusions about the mechanism of different multifragmentation reactions as a function of the excitation energies of the nuclei.

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