Azimuthal effects in the fragmentation of relativistic nuclei

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Effects of the transverse motion and angular momentum of the residual fragmenting relativistic projectile nuclei have been discovered. Their effect on the observed characteristics of the fragmentation products and the dynamics of the process are discussed.

PACS numbers: 25.70.Np

The fragmentation of projectile nuclei is one of the most interesting parts of the complex process by which relativistic nuclei collide. The most important result of the early research on the subject was the establishment of a universal (Gaussian) distribution of the momentum components in the rest frame of the fragmenting nucleus, with a parabolic dependence of the variances (or "temperatures") of the momentum components on the fragment mass. This result follows from the statistical theory of fragmentation with minimal correlations among the momenta of the nucleons in the nuclei.[1] A further result has been the important and by now generally accepted conclusion that direct information can be obtained on the momenta of nucleons and nucleon clusters inside a nucleus, since in this approach these momenta are proportional to the observable momenta of the corresponding fragments. We wish to emphasize that these arguments lean heavily on the so-called 0° experiments with light nuclei ($A \leqslant 16$; see Ref. 2, for example).

It was recently found (in Ref. 3 for α particles and in Ref. 4 for an arbitrary charge z) that in the fragmentation of fast ^{56}Fe nuclei the transverse momenta p_T of the "spectator" fragments are considerably higher than those of light nuclei. Determining the nature of this growth—i.e., whether it is kinematic (in the case of a transverse motion and/or "rotation" of the residual nuclei) or dynamic—is very important, so we have carried out a study of the correlations among the fragments in the transverse plane of the interaction. In this letter we report the basic results.

We studied inelastic collisions of ^{12}C nuclei (primary momentum $p_0 = 4.5 \cdot A$ GeV/c, 1717 events), ^{14}N nuclei ($p_0 = 2.9 \cdot A$ GeV/c, 1017 events), and ^{56}Fe nuclei ($p_0 = 2.5 \cdot A$ GeV/c, 935 events) with the nuclei of a photographic emulsion. The spectator fragments of the projectiles with $z \geqslant 2$, their charges, and their emission angles were identified and measured reliably, without discrimination of any sort, in a 4π geometry and under identical conditions.

Figure 1 shows the inclusive distributions in $\epsilon_{ij} = \arccos(\mathbf{p}_{Ti}\mathbf{p}_{Tj}/p_{Ti}p_{Tj})$, which is the angle between the transverse momenta of the ith and jth fragments with $z \geqslant 2$ from one event. [Here and below, we are restricting the discussion to fragments with $z \geqslant 2$, since the singly charged fragments can be distinguished unambiguously from the s-particles (with a $\sim 15\%$ impurity). All the conclusions which we draw remain in force
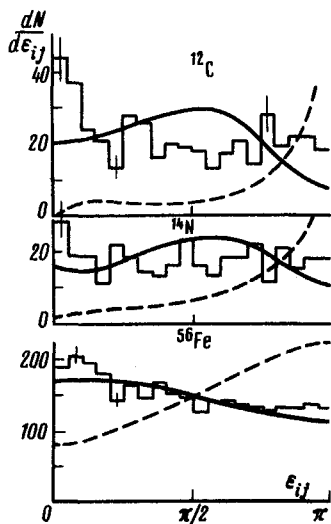
FIG.1 . Inclusive distributions in ϵ_{ij}, which is the angle between the spectator fragments of the projectile with $z \geqslant 2$. The curves are calculated from a model (discussed in the text proper) for the value $q_T = 0$ (dashed curves) and for the value of q_T which leads to the observed characteristics of the fragments (solid curves).

when the s-particles are incorporated.] Comparison with the distributions calculated for the fragmenting system of the projectile nucleons (dashed curves; the calculations are discussed below) reveals a pronounced azimuthal asymmetry in the emission of the fragments. This asymmetry means that the system has a transverse momentum $\mathbf{q}_T$.

What is the magnitude of q_T? To what extent does this momentum increase the actual values of p_T of the fragments (in the rest frame of the decaying system)? Is it responsible for the growth of $p_T(A)$ observed in Refs. 3 and 4? Finally, what are the "kinematically initial values" of the collinearity coefficient $k = (N_{\epsilon < \pi/4} + N_{\epsilon \geqslant 3\pi/4} - N_{\pi/4 < \epsilon < 3\pi/4})/N_{0 < \epsilon < \pi}$ when $q_T > 0$? This collinearity coefficient is a very simple characteristic of the ϵ_{ij} distribution and one which is sensitive to the angular momentum of the system.

To answer these questions we carried out Monte Carlo calculations from a simple fragmentation model. We adopted the following assumptions: (a) The residual nucleus decays in accordance with the cylindrical-phase-space model into n_1 singly charged, n_2 doubly charged, n_3 more highly charged $(z \geqslant 3)$, and n_0 neutral fragments [the empirical distributions in n_1, n_2, and n_3 are reproduced rigorously in all the ensembles, and the number n_0 is adopted as being equal, on the average, to the number of protons multiplied by $(A - Z)/Z$]. (b) The momenta p_T of the fragments are distributed in accordance with $f(p_T) \sim p_T \exp(-p_T^2/2\sigma^2)$, with $\sigma^2(z)$ as follows from the parabolic law[1] $[\sigma^2(z = 1) \equiv \sigma_N^2 = \langle p_{TN}^2 \rangle/2$ in the rest frame of the nucleus serves as an adjustable parameter]. (c) The residual nucleus "acquires" a transverse momentum $\mathbf{q}_T$ (q_T is a second adjustable parameter). For the case of ^{56}Fe, we also considered the case in which the momenta p_T of the fragments were equal to the corresponding values in the fragmentation of light nuclei.
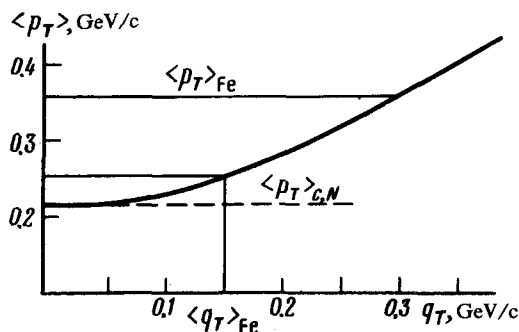
FIG. 2. Calculated dependence of $\langle p_T \rangle$ for α particles from ^{56}Fe-Em collisions on the value of q_T of the residual ^{56}Fe nucleus. It is assumed that the actual values of $\langle p_T \rangle$ are equal to the observed values in the fragmentation of ^{12}C and ^{14}N.

Analyzing the results, we draw the following conclusions.

1. The values of q_T of the residual projectile nuclei from inelastic collisions with ^{12}C, ^{14}N, and ^{56}Fe are comparable in magnitude (0.18, 0.17, and 0.15 GeV/c, respectively, with errors ~ 0.01 GeV/c). These values of q_T lead to both the azimuthal asymmetry (Fig. 1) and the expectation values $\langle p_T \rangle$.

2. The transverse motion of the nuclei substantially increases the values of $\langle p_T \rangle$ of the fragments. For example, the observed and actual values of $\langle p_T \rangle$ for the spectator α particles from ^{12}C-*Em* events are 0.25 and 0.18 GeV/c, respectively (the difference is $\sim 30\%$).

3. The transverse motion of the fragmenting nuclei has essentially no effect on the curves of $p_T(A)$. Figure 2 illustrates this important assertion: When the transverse motion of the ^{56}Fe nuclei is taken into account, even the strong (and wrong) assumption that the values observed for p_T of the fragments during the fragmentation of the light nuclei (^{12}C and ^{14}N) are "intrinsic" values leads to the result that the increase in the values of $\langle p_T \rangle$ of the α particles from ^{56}Fe-*Em* collisions (an increase in comparison with the values from ^{12}C-*Em* and ^{14}N-*Em* collisions) is only a fourth of that actually observed.[4] The increase is thus of a dynamic nature.

4. There is a tendency toward a collinear expansion in the transverse plane, as can be seen simply from Fig. 1, which shows the excess of angles ϵ_{ij} in comparison with the calculations for $\epsilon \to 0$ and $\epsilon \to \pi$. Figure 3, which shows the resulting increase in the empirical collinearity coefficients above the calculated values at the actual values of q_T and for a zero angular momentum, illustrates this conclusion particularly clearly. The fragmenting systems of nucleons thus have an angular momentum which also distorts the momentum characteristics of the fragments, as is easily shown.

By distorting the actual characteristics of the spectator fragments (in the rest frame), the effects of the transverse motion and rotation of the relativistic residual projectile nuclei observed in this study refute the suggestion of a correspondence between the observable and intranuclear momenta of nucleons and nucleon clusters. A second general conclusion—the proof that the increase in $\langle p_T(A) \rangle$ is of a dynamic nature[3,4]—makes the situation even bleaker, refuting the very concept of "spectators"
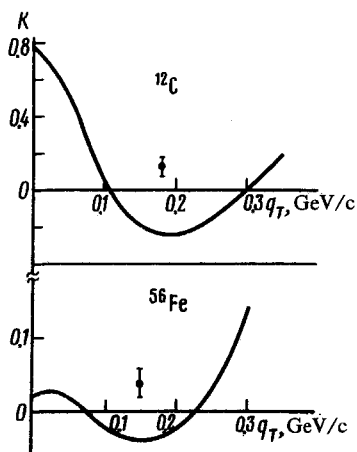
FIG. 3. Some representative empirical values of k and curves of k vs q_T.

and "participants" (the basic geometric "content" of most models for high-energy nucleus-nucleus collisions). There can be no doubt that the observed characteristics of the fragments are determined not only by the structure of the nuclei involved in the inelastic collisions but also (and probably to a greater extent) by the dynamics of these collisions). Consequently, correct information about the intranuclear characteristics of nucleons and nucleon subsystems can apparently be obtained only by taking the dynamics of these collisions into account (i.e., through a model) and/or deliberately singling out some extremely peripheral channels (diffractive or Coulomb dissociation, for example).

We thank our colleagues H. H. Heckman and I. Otterlund for furnishing the emulsions bombarded with ^{12}C, ^{14}N, and ^{56}Fe ions.

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