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COHERENT MULTIFRAGMENTATION OF RELATIVISTIC NUCLEI

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Reactions of coherent multifragmentation have been predicted and observed for relativistic projectile nuclei. At the first stage of studying such reactions, we considered the coherent break-up of $^{12}C \to 3\alpha$ and $^{16}O \to 4\alpha$ at 4.5*A* GeV/c. Their study points to the most favourable conditions for the investigation of nuclear structure and the search for various quasinuclear resonances.

The investigation has been performed at the Laboratory of High Energies, JINR.

Когерентная мультифрагментация релятивистских ядер

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Были предсказаны и наблюдались реакции когерентной мультифрагментации релятивистских ядер-снарядов. На первой стадии изучения реакций этого типа рассматривалась когерентная диссоциация $^{12}C \to 3\alpha$ и $^{16}O \to 4\alpha$ при 4,5*A* ГэВ/с.Изучение подобных реакций указывает на наиболее благоприятные условия для исследования ядерной структуры и поиска квазиядерных резонансов.

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1. Introduction

As early as 1953, a new type of high-energy hadron-nucleus interaction — the reactions of the coherent generation of particles in strong or Coulomb fields of nuclei — has been predicted by Pomeranchuk and Feinberg [1]. Coherently influencing the bombarding object, the target nucleus is proved to be a single, structureless whole in these reactions and remains, as a rule, in the ground state. The coherence condition, $1/q \geq R$ (R is the radius of target nucleus, q is the transferred momentum), leads to very small values of momentum transfer and to high values of the energy thresholds of such reactions. The first of them, $\pi^- + A \to \pi^-\pi^-\pi^+ + A$, was experimentally observed in 1961, and since that time, this class of inelastic interactions with nuclei has become an object of intensive study in many laboratories.

Recently [2], this idea has been spread to the multifragmentation reactions of relativistic projectile nuclei. The events of coherent multifragmentation (Fig.1)

$$A + B \rightarrow B + \sum_i F_i, \tag{1}$$

as well as their analogues in the case of hadron-nucleus collisions, are characterized by very small energy-momentum transfers, which are the consequences of the coherence conditions, and by the high values of the energy thresholds. The considerable interest in such reactions is for a number of objective reasons, among which are the relative simplicity of their theoretical description, the presence of very favourable conditions for the search for and study of various quasi-nuclear resonances, the possibility of studying the interactions between these resonances and intranuclear matter, etc.

2. Some Kinematics

Figure 1 presents the simplest diagrams for the diffractive and the Coulomb mechanisms of the projectile nucleus coherent decay. Assuming, for instance, the diffractive mechanism of dissociation, we can formulate its global features as follows:

(i) The angular distribution of the summary momentum $\sum_i \mathbf{p}_i$ of fragments F_i is the same as for elastic diffractive scattering;

(ii) The so-called intrinsic quantum numbers of the fragment system are the same as for the projectile nucleus;

(iii) The momentum transfer (to the target nucleus) is very small:

$$1/q \geq R_B. \tag{2}$$

From the energy-momentum conservation law one can easily find

$$q_L = \frac{M^{*2} - M_A^2}{2p_A} + \frac{E_A + M_B}{2M_B\, p_A} q^2 \approx \frac{M^{*2} - M_A^2}{2p_A} \tag{3}$$

(the approximation is correct at very high energies). So, the longitudinal (q_L) and transverse (q_T) momentum transfers are approximately independent and q_L depends only on M^*.

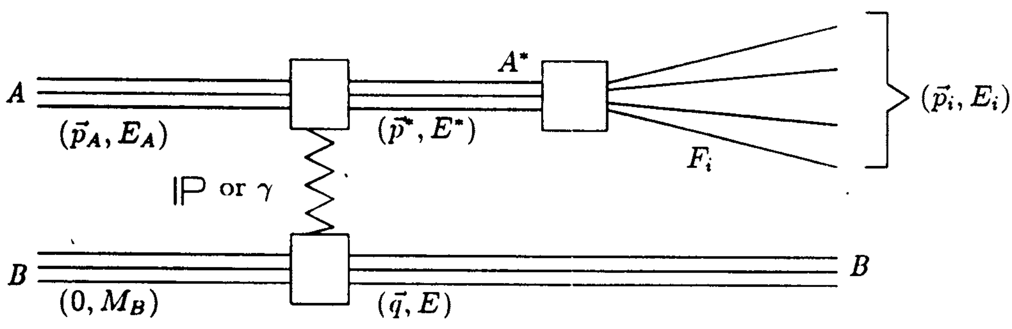

Fig.1. The simplest diagrams for nuclear coherent dissociation

The four-momentum transfer is

$$d\sigma/dt' \sim \exp(-a|t'|), \qquad |t'| = |t - t^{\min}(\sum_i m_i)| \cong q_T^2, \tag{4}$$

where $a = (R_A + R_B)^2/4$. Therefore, the distribution on q_T has a Rayleigh form

$$d\sigma/dq_T^2 \sim \exp(-aq_T^2), \qquad \langle q_T \rangle \cong (\pi/4a)^{1/2}. \tag{5}$$

The minimum value of q_L is realized at $M^*_{\min} = \sum_i m_i$ and $q_T = 0$, i.e.,

$$q_L^{\min} \cong \frac{(\sum_i m_i)^2 - M_A^2}{2p_A} \cong \frac{M_A}{p_A}\Delta, \tag{6}$$

where Δ is the «mass detect» of the channel under consideration,

$$\Delta = \sum_{i=1}^{n} m_i - M_A \tag{7}$$

(m_i is the mass of i-th fragment). It is clear that $|t|^{\min} = (q_L^{\min})^2$ and

$$(M^{*2})^{\max} \cong M_A^2 + 2p_A\,\mu B^{-1/3}. \tag{8}$$

Rough estimates of upper limits for q_L and q_T are given [1] by

$$q_L \leq \mu/B^{1/3}, \qquad q_T \leq \mu, \tag{9}$$

where μ is the pion mass and B is the target mass number. Finally, Eqs.(3) nad (9) immediately give an estimation of the coherent reaction threshold

$$p_A^{\min} \cong \frac{M^{*2} - M_A^2}{2\mu} B^{1/3} \cong \frac{M_0 B^{1/3}}{\mu}\Delta. \tag{10}$$

For instance, for the reaction $^{16}\mathrm{O} \to 4\alpha$ (see below) on a target with mass number $B \approx 100$, the threshold takes up about ~ 0.5 GeV/c per nucleon.

3. Some Experimental Results

The variety of exclusive channels for coherent reactions at high energies is very great. For example, the coherent emission of protons: $^{A}X_Z \to {}^{A-m}Y_{Z-m} + mp$ (m = 1, 2,...), neutrons: $^{A}X_Z \to {}^{A-m}Y_Z + mn$, α-particles: $^{A}X_Z \to {}^{A-4m}Y_{Z-2m} + m\alpha$, etc., by the projectile nucleus can be considered.

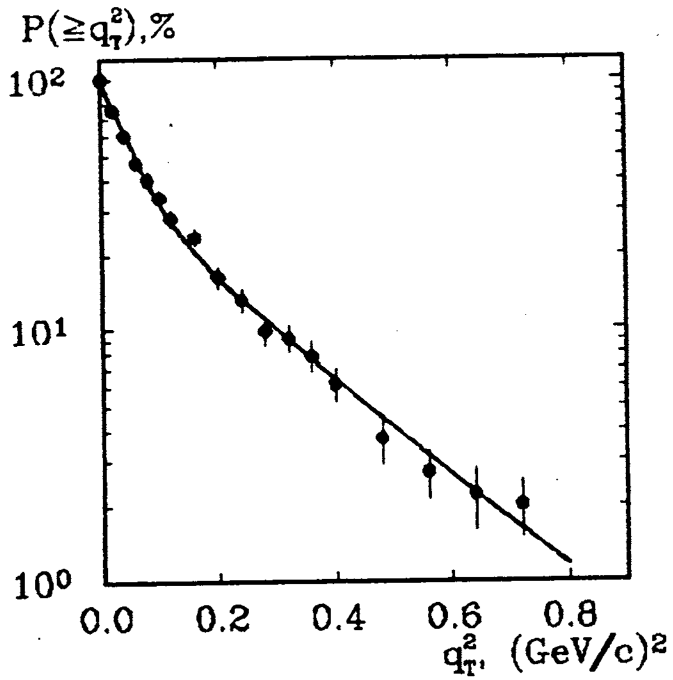

Fig.2. Integral distribution on q_T^2 for reaction (12) at 4.5*A* GeV/c. The curve is a fit by the sum of two Rayleigh distributions

The first experimental data, which confirmed the existence of coherent nuclear fragmentation reactions, have been obtained for channels

$$^{12}C \to 3\alpha, \tag{11}$$

using the usual nuclear photoemulsions, emulsions enriched by Pb and the 2m propane bubble chamber of LHE (JINR), and

$$^{16}O \to 4\alpha, \tag{12}$$

using the usual nuclear emulsion at $p_0 = (4.2-4.5)A$ GeV/c. For details for these experiments see Refs.[3,4, 5,6,7]; here we present only a short review.

The distributions of the four-momentum transfer (4) for the investigated channels (11), (12) have a typical form, reducing to the sum of two exponents corresponding to dissociation on a nucleon and on a nucleus as a whole. An example of such distribution is given in Fig.2.

Comparison of the data on various target nuclei also permits one to conclude that the diffraction mechanism probably dominates for the light nuclei; and the Coulomb one, for heavy targets. The mean free path for the coherent $^{12}C \to 3\alpha$ events in the emulsion enriched by Pb was found to be twice as large as in the usual emulsion, although the averaged target mass numbers in both of the mentioned stacks were approximately the same [6].

The statistical theory of fragmentation [8] allows one to estimate the «temperature» kT (or the average excitation energy per nucleon) of the fragmentating nucleus,

$$kT = \frac{A}{A-1} (\sigma_N^2 / m_N), \qquad (13)$$

where m_N is the nucleon mass, σ_N^2 is the dispersion of the intrinsic momentum distribution of nucleons that can be calculated using the so-called «parabolic law»,

$$\sigma_\alpha^2 = \sigma_N^2 A_\alpha (A - A_\alpha) / (A - 1). \qquad (14)$$

Here A is the mass number of the projectile nucleus, $A_\alpha = 4$ is the same for α and $\sigma_\alpha^2 = \langle p_T^2 \rangle / 2$, where $\langle p_T^2 \rangle$ can be experimentally measured in the rest system of fragmentating nuclei. We obtain $kT \cong (3 - 3.5)$ MeV for coherent reactions (11), (12) which is considerably (several times!) less than in the reactions of usual multifragmentation at relativistic energies measured in inclusive experiments.

In Figs.3, 4 we show examples of distributions on p_T^2 and $\varepsilon_{ij} = \arccos (\mathbf{p}_{T_i} \mathbf{p}_{T_j} / p_{T_i} p_{T_j})$ for the secondary α in the c.m.s. of fragmentating nuclei. Neither of these distributions can be described using the statistical theory of prompt decay. The remarkable features of these spectra are the high-momentum «tail» in p_T and the considerable trend to the coplanarity of $\mathbf{p}_T$ in the transverse plane of the reactions.

Further, it was found that the coplanarity of $\mathbf{p}_T$ depends on the excitation energy of the dissociated nuclei. In Fig.5 we show the dependence of the coplanarity coefficient,

$$C = (N_{\varepsilon_{ij} \le \pi/4} + N_{\varepsilon_{ij} \ge 3\pi/4} - N_{\pi/4 < \varepsilon_{ij} < 3\pi/4}) / N_{0 \le \varepsilon_{ij} \le \pi} \qquad (15)$$

on kT for reaction (11) at 4.2A GeV/c measured in the 2m propane bubble chamber. The coherent channel of (11) only takes place at $kT \le 10$ MeV. In this region, the coplanarity of the transverse momenta of α decreases with increasing kT. Then, it reaches its minimum value $C_0 = 0.16$, which corresponds to the case of prompt decay of ^{12}C into three alphas, and begins to increase with increasing kT in the incoherent region of high temperatures.

At the same time, the distributions on the relative angles and effective masses of α pairs in reactions (11), (12) display two peaks which can be associated with the decay of the short-lived intermediate states of the ^8Be nucleus in the ground (0^+) and first excited (2^+) states. The relative probabilities of prompt and cascade decay modes also depend on the temperature of the fragmentating nucleus (see an example in Fig.6). The character of the dependencies of the momentum and correlation characteristics of α-particles on the nuclear excitation energy agrees with the picture of the transition from the mechanism of

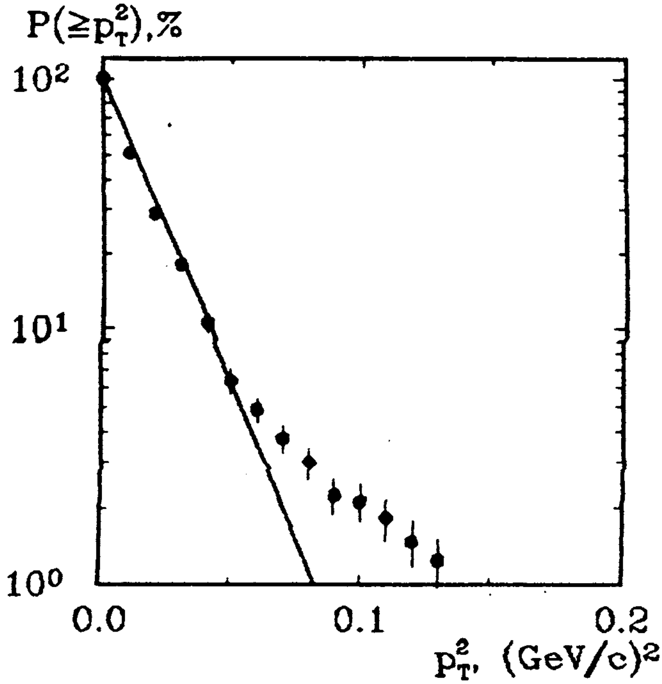

Fig.3. Integral distribution on p_T^2 for α from reaction (12). The line is a single Rayleigh distribution with $\langle p_T^2 \rangle = \langle p_T^2 \rangle_{exp}$

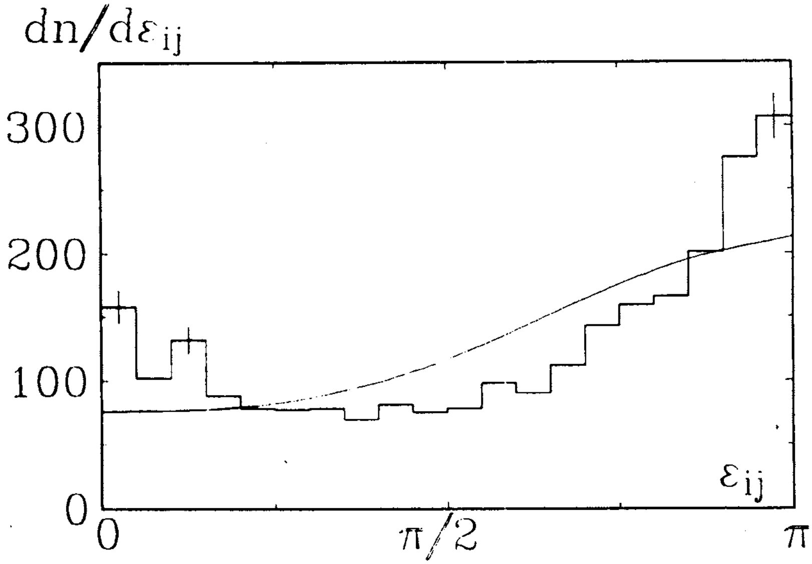

Fig.4. Experimental and calculated (see text) distributions on ε_{ij} for reaction (12)

sequential binary fission to prompt multifragmentation with a further growth of angular momenta acquired by the fragmentating system during collision with increasing nuclear «temperature».

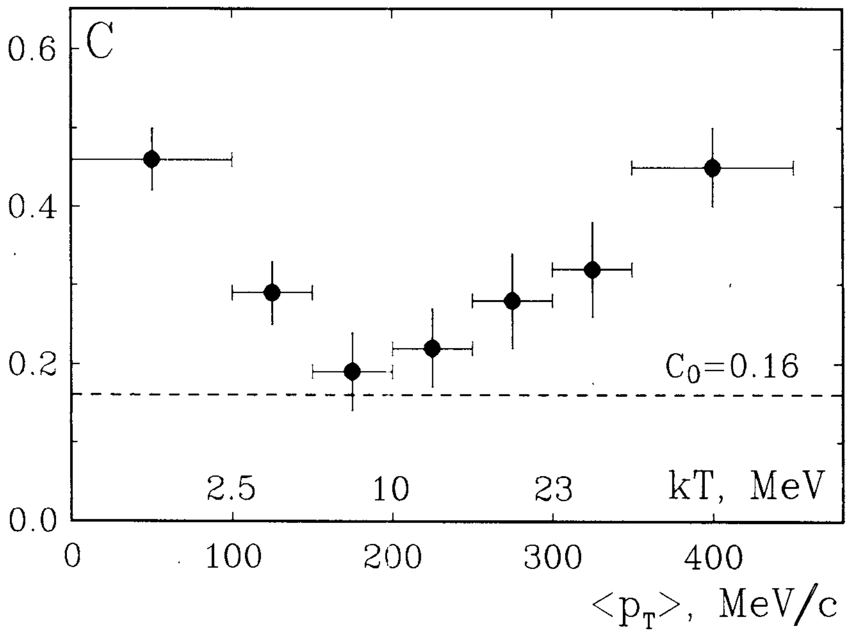

Fig.5. The coplanarity coefficient *vs.* *kT* for reaction (11) at 4.2*A* GeV/c

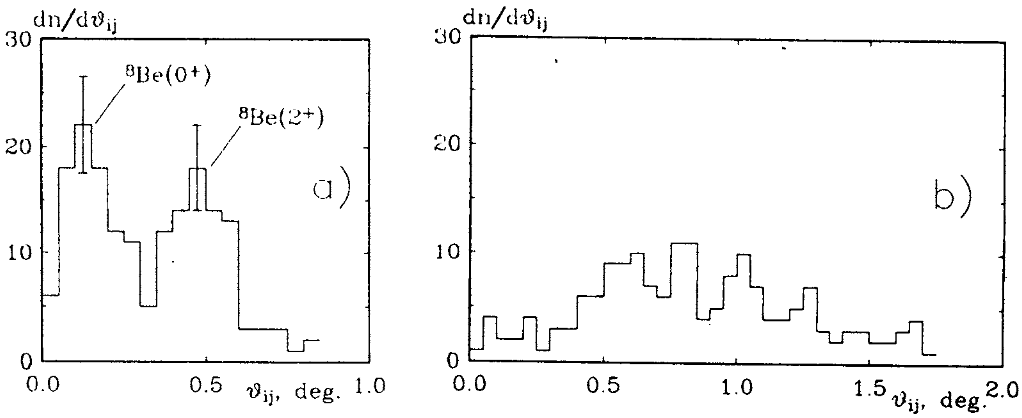

Fig.6. The relative angle distributions for events of coherent reaction (11) with *kT* < 2.5 MeV (a) and *kT* > 2.5 MeV (b)

The whole complex of results of the study of coherent reactions (11) and (12) points to the most favourable conditions for realizing the reactions of coherent multifragmentation of relativistic nuclei for the investigation of nuclear structure and the shape of the nuclear equation of state at small excitation energies, and the study of quasi-nuclear resonances and their interactions with nucleons and nuclei.

The obvious extension of this work is to a directed search for and study of various resonance-like peculiarities in the spectra of relative angles and/or effective masses of fragments — *pp, pd, pt, dd, dt, pα, dα*, etc. — the spectator products of relativistic projectile nuclei. The abundant formation of such «nuclear resonances» in coherent multifragmentation reactions at very small excitation energies augurs well for the future.

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