THE PROJECTILE FRAGMENTS IN NUCLEAR EMULSION

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1. The fragmentation of relativistic nuclei and critical phenomena

Our present understanding of the universe is based on the dogma that in the beginning there were the "quark - gluon plasma" (QGP). Density and temperature of the QGP decreased as the universe expanded with the time. Quarks and gluons began to "freeze", forming protons and neutrons. Beyond a certain critical point of density and temperature only one homogeneous equilibrium phase QGP can exist, and all changes of the parameters are continuous and smooth. Thus, the phase transition of the first - order took place about 13 billions years ago. Our universe has arisen from the QCD vacuum as the result of the phase transition. But then, according to the first principles, confirmed both thermodynamic and lattice QCD, we have hard believe that nuclear matter, under extreme conditions, can evolve into a new state of matter, a QGP.

The problem up to now consist in the question - whether the new deconfined phase of matter been produced at the CERN SPS energy ? To check it is true or not at CERN ' s SPS the beam of lead ions with energy 160 A GeV was created. One of the simple experiments with this beam is EMU01 experiment, which used nuclear emulsion as target and detector for produced particles and projectile fragments. The emulsion technique with its superior spatial resolution is very well suited for obtaining precise charges and angular measurements. The central events are easily found due to their high multiplicity.

It has common use to consider that production of the nuclear fragments may by subdivision into several stages. The formation of an intermediate highly excited nuclear system is proceed on the first stage. The idea about formation of the QGP is also based on the hypothesis about existing of the highly excited nuclear system.

Our investigation of the fragmentation of Pb at 160 A GeV in its central interactions with nuclei in emulsion is an attempt to answer the question - are there hard distinguishes between the fragmentation of light nuclei (Ne, Li) with energy about 4 GeV per nucleon and of Pb at 160 A GeV.

2. The main regularities of the fragmentation of light nuclei

Consider the main regularities in ^{22}Ne and ^{6}Li projectile fragment transverse momenta distributions respectively at 4.1 A GeV/c and 4.5 A GeV/c in photoemulsion.

A photoemulsion chamber which consists of 600 mkm thikness $10*20\ cm^2$ sheets of $BR-2$ emulsion was irradiated by the beam of ^{22}Ne ions with the momentum 4.1 GeV/c per nucleon from synchrophasotron in Dubna. 4309 events were used for analysis, all projectile fragments (6309) were recorded and the charges Z and emission angles were measured.

In accordance with the existing physical foundations, the fragment transverse momenta projection on the emulsion plane in experiment

$$P_Y = P_0 \cdot Sin\,\varphi \cdot A_{Fr} \cdot \sqrt{\frac{A-1}{A_{Fr} \cdot (A - A_{Fr})}}$$

should have the normal distribution with the mean value equal zero and dispersion

$$\sigma_0^2 = \frac{P_{Fermi}^2}{5}.$$

Here, A_{Fr} – the mass number of fragments ($A_{Fr} = 2Z_{Fr}$), produced in the fragmentation of relativistic nucleus with the mass number A; P_0 – projectile momentum per nucleon; φ – angle between projection of fragment transverse momentum on the emulsion plane and vector $\mathbf{P}_0$; P_{Fermi} – the nucleons Fermi momentum of projectile nucleus in the ground state known from electron scattering on nuclei; σ_0 is the standard deviation of the projectile nucleons momenta projection on a random direction in CMS of the fragmentation nuclei.

Our experiment [1,2] gives the mean value $< Py >= 0.15 \pm 2.5$ MeV/c and $\sigma_0 = 102.5 \pm 2.5$ MeV/c. This result agrees with known Fermi momentum of nucleons in ^{22}Ne nucleus ($\sigma_0 = 105.1\ MeV/c$). To verify the agreement of the experimental distribution with the normal one, the statistical parameter-free Kramers-Mizes criterion (ω^2-criterion) has been used.

Thus, experimental distributions of fragment transverse momenta projection on the emulsion plane are fully determined by the Fermi momentum for ^{22}Ne nucleus in the ground state.

In the fragmentation of relativistic nuclei the fragments observed experimetally can be the decay products of residual nuclei, i.e. pre-fragments. No experimental information is available practically on the properties of pre-fragments.

We propose new method for an estimate of the fragment transverse momenta in the c..m. frame of the pre-fragment on the basis of quantities observable experimentally [3]. It was demonstrated that the ratio $\eta = p_\perp(lab)/p^*_\perp(c.m.s.1 - 2)$ for the independent production of two fragments with equal masses must be equal to $\sqrt{2}$.

To test the relation η we selected 1004 events, containing only two fragments inelastic interactions of ^{22}Ne nuclei with emulsion nuclei. Experimentally ratio is $\eta = 1.32 \pm 0.01$. The Monte Carlo simulation yielded a value of $\eta = 1.461 \pm 0.003$. Consequently experimental value η is much smaller than both the prediction and the Monte Carlo estimation. It should be viewed as an indication that the pre-fragments in our experiment were exited.

A photoemulsion chamber which consists of 600 mkm thickness $10*20\ cm^2$ sheets of $BR-2$ emulsion was irradiated by the beam of ^6Li ions with the momentum 4.5 GeV/c per nucleon from synchrophasotron at JINR (Dubna). The 934 events have been analyzed [4] to determine: the fragment charge Z; the angles φ and α between the fragment momentum projection onto the emulsion plane and the direction of P_0 in the XOY and XOZ planes, respectively; the quantity $p\beta c$ and its error $\Delta p\beta c$ obtained from the data on multiple scattering.

The distribution of the transverse momentum projection onto the emulsion plane for protons of ^6Li $P_\varphi = P_0 \cdot Sin\,\varphi$ obeys the normal distribution $N[0,\ \sigma_0^2]$ with $\sigma_0 = 57.7 \pm 3.6$ MeV/c. A value of Fermi momentum for ^6Li is 129 ± 8 MeV/c.

Experimental estimations of $\sigma_1(^3He) = 114 \pm 9.7$ MeV/c and $\sigma_2(^4He) = 120 \pm 9.6$ MeV/c for fragmentation of ^6Li show that they are a little above the expected value from Fermi momentum $\sigma_F = 102 MeV/c$. But distribution of projections onto the emulsion plane does not agree with the hypothesis of normal distributions. This experimental dstribution can be discribed by mixture of two normal distributions with parameters $\sigma_1 = 40.0$ and $\sigma_2 = 125.0\ MeV/c$, with a part of the first distribution $k = 0.257$.

About 1/4 of the two-charge fragments at the fragmentation of relativistic ^6Li is formed on the periphery of a nucleus, while the remaining fragments are formed in the central part, in the range of the order of 2 fm. Our experiment allowed us to estimate the quantitative characteristics of the emission zone of nuclear matter in ^6Li. High-momentum fraction in the transverse momentum distribution really exists here, but it is not related to some worming-up of fragmenting nucleus and the increase of its temperature. This effect is due to the nucleus structure in its ground state.

For all well identified pairs of fragments proton-proton, proton-$\alpha-$particle we did not observe the difference between the value η defined upper and $\sqrt{2}$. So, for all events η is 1.36 ± 0.05 in experiment, and η is 1.39 ± 0.02, obtained by Monte-Carlo method. Thus, there is no evidence for the existence of excited pre-fragments stage in the fragmentation of relativistic ^6Li nuclei: the observed fragments come directly from the ^6Li nucleus.

3. Some new methods of experiment

We have measured charges and angles in emulsion plane of the projectile fragments using our own methods. In [5] the new method of relativistic nuclei light fragment charges determination in emulsion has been proposed. The method is based on the blob sum length measurement procedure to estimate the fragment charges with high reliability. As is shown in [6], from the blob spectrum on the proton tracks with known range it is possible to estimate the ionization G of particle up to ten times larger than the minimal one for the single charged particle. In the case of relativistic fragments with small Z the problem of the charge estimations with blob spectrum is more simple compared with the problem of G estimation resolved in ref. [6]. It was resolved it in such a way that the reliability of fragment charge estimation was sufficiently high and known for every fragment.

So, utilization of this method has a number of advantages over previously used ones. It does not depend on operator and the fragment charge and the reliability of its estimate is already known during the measuring procedure.

The method was sampled for light fragment charges determination in the case of ^{22}Ne at 4.1 A Gev and lead at 160 A GeV projectiles.

The opportunity to measure angles between tracks of particles in nuclear emulsion had been considered as the important virtue of a photo method from the very beginning of its origin. But only from the experiments with protons at 200 GeV [7] it became clear that the angular measurements of produced particles provide the examinations of particles on rapidity as well as examinations of their transverse momenta with high precision.

The necessity of experimental examination of precision of angular measurements in zero value range became of especial importance for fragments of heavy relativistic projectiles (lead and gold). The first problem is caused by the angle values become of few microradians. The second difficulty is connected to the thickness of projectile tracks in emulsion.

For solving both of the problems in ref [8] the coordinates of 10 points of all tracks in event were measured at distances $10 - 20$ mm downstream the interaction point, moving across the beam with 1 mm intervals. The angle $\varphi_{i,j}$ between any two fragment track was obtained by the χ^2- method. In our experiment the grain noise is reduced in an order, because the reading of Y coordinate has been made using the group of grains in each of 10 points. The relative measurements of tracks closely- spaced to each other eliminate both layer distortion, spurious scattering and stage noise.

The second problem was solved in ref. [9]. Using the measured coordinates of n fragments in every event one can estimate the dispersion of fragment angle distribution with respect to unknown initial projectile momentum $\mathbf{p}_0$ in the whole sample of events with different number of fragments n.

To do this we used the empirical risk minimization method, which is as follows. The general idea is to determine the pair angles ε between all unreplicated pair tracks in the event ($n(n-1)/2$ pair angles). The empirical distribution function for all values ε in a complete set of experimental events $F(\varepsilon)$ depends on the distribution of this set on a number of fragments in the event n and single free parameter σ which characterizes normal distribution of true angle φ with respect to unknown direction of vector $\mathbf{p}_0$ of the initial nucleus. To estimate the parameter σ we are interested in it is necessary to find the minimum of a functional called the empirical risk

$$I(\sigma) = \int \{F(\varepsilon) - F_T(\sigma,\varepsilon)\}^2 f(\varepsilon) d\,\varepsilon,$$

where $f(\varepsilon) d\,\varepsilon = d\,F_T(\sigma,\varepsilon)$.

This procedure is correct because with the increase of a sample the empirical distribution function tends uniformly to a true distribution function with a probability equal to unity. So σ tends to its true value. The efficiency of this method was checked up by Monte Carlo method, it appeared to be rather good.

4. The main regularities of the fragmentation of lead 160 A GeV

All these methods permit us to measure the fragment angles of lead projectile at 160 A GeV and to get very interesting information about the distribution of their transverse momenta.

Within the EMU01 Collaboration, we dealt with a part of emulsion chamber (20 layers) exposed at CERN by lead projectiles at 160 A GeV. The search for events was carried out on the area and across the beam to detect the jets of secondary particles. Only the events with fragments with $Z < 9$ have been analyzed. The charges of 672 fragments with $2 < Z < 9$ where determined and all angles between fragments where measured. The constant of the normal distribution of fragment angles φ with respect to initial projectile momentum direction $\mathbf{p}_0$ is found to be $\sigma_\varphi = (0.37 \pm 0.02)$ mrad. It is correspond to the constant of nucleon momentum distribution for lead nucleus equal $\sigma_0 = 121 \pm 6$ MeV/c, thus being the value expected from Fermi momentum for lead nucleus.

Thus, we conclude that even in deep inelastic interactions of the lead nuclei with photoemulsion nuclei the angular distribution of light fragments is determined by Fermi momentum for projectile nucleus in its ground state.

The ^8Be nucleus decays into two α-particles during 10^{-16} sec without a visible track in the emulsion. We tried to prove the existence of $^8Be \to 2\alpha$ among the double-charged fragments of lead by observation of the angle between two particles. The average angle in emulsion plane between two $\alpha-$particles which is due to the decay of ^8Be must be about $0.01 - 003$ mrad. We observed maximum in that region in experimental distribution value of $\varphi_{i,j}$ (see ref.10).

5. Parton picture of the fragmentation of nuclei

We can see that all these experimental data are amenable to an interpretation based on the formation of highly excited nuclear system. The "temperature" of nuclei as ^{22}Ne at $\simeq 4$ A GeV and lead at 160 A GeV is the same and equal to $T = P^2_{Fermi}/5\,m_N$. The process of the fragmentation is sudden (fast) and rather "cold" then "hot". That is why we can use (on the qualitatively level) the theoretical approach for description of the fragmentation process and the multiparticle production in relativistic nucleus-nucleus interaction in the framework of the parton picture (see ref. [11]). According to this picture relativistic nucleus (like a hadron) even before its interaction with another nucleus (or hadron) represents a system of massles, pointlike particles or partons. That may be nucleons, its associations (fragments), mesons or quarks and gluons. Each parton can produce another parton with probability approximately equals to unity. The cascade of partons arises. All that ensemble of partons can collect into the first stage parton, particle or nucleus. However, if a parton (it is as usual parton with small rapidity) collides on its way with some "external" parton belonging to another nucleus, then this interaction destroys the coherence of both cascades. All partons of two relativistic nuclei begin to get the masses and to the end of this process become "real", observed particles, mesons, fragments.

It is very important that, due to the momentum conservation law, the momenta of "real" particles are the same as they are in the parton cascade before interaction. It is clear that we have the limiting fragmentation. Thus, now we can consider the "fragmentation" process as the the convertation of the virtual partons existing in nuclei (or hadrons) into real fragments (hadrons). That is phase transition of some part of QGP into real particles. Some part of the kinetic energy ΔE of the colliding nuclei in its CMS is converted to the rest mass of produced particles (or fragments). Then, according to Gibbs, the probability of such process must be proportional to $exp(-\Delta E/T)$. This permits us to calculate the relative probability to observe yields of some fragments. By this way we can explain the azimuthal correlations in reaction of fragmentation of $^{16}O \rightarrow 4\,\alpha$ [12]. We have developed the simple method of calculation of fragment yields in their multiparticle production, which is not connected with traditional conception about two stage mechanism of fragmentation and excitation of nucleus. In our opinion, the "equilibrium" which is necessary to use the Gibbs distribution, is achieved on the level of partons and vacuum before the interaction of two relativistic nuclei. The calculations in this scheme of $\alpha-$ particles and ^8Be isotope yields in nuclear fragmentation of carbon and oxygen agree with experiment.

6. Observation of the narrow jets of fragments [13]

Presumably new physical phenomena take place when projectile fragments are so closely-spaced to each other. One of them observed in the process of lead-nucleus fragmentation at 160 A GeV energy in nuclear emulsion is as follows. A narrow projectile fragment jet with a great number of secondary stars downstream the vertex has been observed in peripheral type of events, where projectile nucleus decays into fragments without any excitation of a target nucleus and without produced particles.

At CERN SPS, in the framework of the EMU01 Collaboration investigations, the part of emulsion chamber (15 layers of NIKFI BR-2) has been horizontally exposed by lead projectiles at 160 A GeV. The search for events has been carried out along the beam until its exit from the chamber and 1699 deep inelastic interactions have been found. We have selected, using the $N_h = 0$ criterion, 352 peripheral events with relativistic projectile nucleus transformed into narrow jet of relativistic fragments in the interaction point.

The same investigations have been carried out for the part of emulsion chamber (8 layers of NIKFI BR-2 emulsion) horizontally exposed at BNL by gold projectiles at 10.7 A GeV energy. The number of inelastic interactions has been found to be 499, 144 of them being peripheral events with narrow fragment jet. The event selection criterion was the same as for Pb+Em interactions.

For every analyzed event the number of interactions of lead (gold) fragments with the emulsion nuclei has been determined within 1.5 cm from the vertex of event in the corresponding fragmentation cones. The distance between the event vertex and every secondary star has been measured. The event with 7 secondary stars in the narrow jet of lead fragments is shown in the figure as an example.

The experimental results are as follows. In the sample of 352 peripheral Pb-Em interactions the numbers of events with 3, 4, 5, 6 and 7 secondary stars at 1.5 cm from the vertex are 54, 19, 6, 2 and 2 accordingly. But in the case of 144 alike Au-Em interactions none event with 3, 4, 5, 6 and 7 secondary stars has been observed.

In the sample of Pb+Em peripheral events there is a sub-sample of 29 events with the number of secondary interactions from 4 up to 7. The number of all charged projectile fragments has been determined after the last secondary observed star.

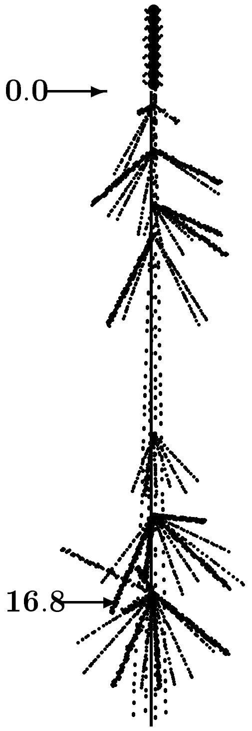

Fig. Cascade of the seven subsequent nuclear collisions in the narrow fragment jet of the lead projectile at 160 A GeV. Only 16.8 mm separate the first collisions from the last.

Assuming the whole number of secondary interactions in the narrow jet to be the superposition of independent interactions of k from n fragments with the emulsion nuclei, the total probability to observe such event with intervals $x_1, x_2, ...x_k$ between interactions has been estimated. The estimated probability at fragment mean free path λ=10 cm is $W = (10^{-6} - 10^{-5})$, while the experimental value is $W_{exp} = 2 \cdot 10^{-3}$. The interval correlation coefficient between neighbouring stars is equal to zero.

Therefor, the nonlinear effect, that is a great number of secondary stars near the event vertex, has been observed in the narrow jet of the 160 A GeV lead projectile fragments. This effect cannot be explained as a superposition of independent interactions of fragments with emulsion nuclei because this effect does not exist for alike Au+Em interactions at 10.7 A GeV.

Our interpretation of this effect is as follows. In the average the number of fragments and their transverse momenta are the same for both nuclei, nevertheless for high energy fragmentation of Pb (160 A GeV) the fragment density and density fluctuations in the jet are much greater than for Au at 10.7 A GeV. That is probably why the probability for few fragments in the narrow tube to interact with the same target nucleus increases.

Over the projectile energy range about few TeV per nucleon such effects should probably play a significant role. We hope our investigation should give rise to an interest towards this new physical phenomenon.

7. Conclusion

Up to now all attempts to get the proof of the existence of QGP were connected with the process of the multiparticle production by heavy nuclei under its interaction with heavy nuclei. But the fragmentation of the relativistic nuclei may be more useful for this. We did not observe in our experiment any signature of the compression of heavy nuclei at 160 A GeV which are need to create QGP.

On the other side we observe the new phenomenon - it is the narrow jets of relativistic fragments. When the energy of the A - A interaction will be more and more, the density of particles in this jets can be very high. The phase transition is the most typical and essential phenomenon in such system with high density of particles. The investigation of the fragmentation of the relativistic nuclei will be continued.

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R e f e r e n c e s

[1] F. G. Lepekhin, B. B. Simonov, Preprint PNPI 1885, St-Petersburg, 1993, 34p.
[2] F. G. Lepekhin, Reaserch Report 1990-1991, St-Petersburg, 1992, p.80.
[3] F. G. Lepekhin, B. B. Simonov, Pis'ma Zh. Eksp. Teor. Piz., **58,** 493(1993).
[4] F. G. Lepekhin, D. M. Seliverstov, B. B. Simonov, Eur. Phys. J., **A1,** 137(1998).
[5] F. G. Lepekhin, O. V. Levitskaya, Preprint PNPI 2172, Gatchina, 1997, 13p.
[6] L. M. Bogomolova, F. G. Lepekhin, B. B. Simonov,
Preprint A. F. Ioffe PTI 272, Leningrad, 1970,15p.
[7] F. G. Lepekhin, B. B. Simonov, Yad. Fiz., **27,** 175(1978).
[8] F. G. Lepekhin, O. V. Levitskaya, D. M. Seliverstov, B. B. Simonov,
Preprint PNPI 2252, Gatchina, 1998, 11p.
[9] F. G. Lepekhin, in *"Physics of a nucleus and elementary particles"*.
Materials of 34 Winter School PNPI, St-Petersburg, 2000, p.474.
[10] M. I. Adamovich,...F. G. Lepekhin, O. V. Levitskaya,... D. M. Seliverstov, B. B. Simonov,...,
at al., Eur. Phys. J., **A6,** 421(1999).
[11] F. G. Lepekhin, in *Physics of a nucleus and elementary particles"*.
Materials of 31 Winter School PNPI, St.-Petersburg, 1997, p.315.
[12] F. G. Lepekhin, O. V. Levitskaya, B. B. Simonov, Preprint PNPI 2313, Gatchina, 1999, 18p.
[13] F. G. Lepekhin, O. V. Levitskaya, V. V. Rusakova (JINR),
in *"International Simposium on Nuclear Physics"*, BARC, Mumbai (India), **43B**, 428(2000).