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COMPRESSED NUCLEAR MATTER ON THE NUCLOTRON

V. A. Karnaukhov, E. A. Strokovsky, S. P. Avdeyev

Joint Institute for Nuclear Research, Dubna

Study of compressed nuclear matter seems to be very interesting as it promises getting the new and very interesting information on the properties of nuclear matter in different regions of its phase diagram. It is important that the competitive ability of the Nuclotron-M in such studies is very high now and in the near future.

Изучение сжатого ядерного вещества представляется чрезвычайно интересным, так как обещает получение качественно новой информации о ядерной материи в различных областях фазовой диаграммы. Важно также то, что конкурентоспособность, которую имеет нуклотрон-М в таких работах, весьма высока сейчас и останется таковой в ближайшие годы.

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1. HOW TO MEASURE THE DENSITY OF HOT NUCLEI

In experimental study of the phase diagram for nuclear matter, the first question is how to measure relevant physical quantities (density, temperature, etc.). The problem of measuring the density of hot nuclei produced in nucleus–nucleus collision was carefully considered by W. Reisdorf and H. G. Ritter [1, 2]. The compression energy accumulated at the moment of collision is realized via the collective flow of the emitted particles. The created particles (pions and baryons) suffer the so-called «antiflow rescattering» in the expanding particle source [3]. Heavier ejectiles are free of this effect. The most *adequate* probe to study the radial flow is the *intermediate mass fragments* (IMF, $2 < Z < 20$). They are heavier than alpha particles but lighter than fission fragments. Intermediate mass fragments are produced in the relativistic nucleus–nucleus collisions by two mechanisms: the coalescence process in the fireball region and the nuclear multifragmentation of hot residual nucleus. Thus, there are three sources of composite particles: overlapping region, excited projectile spectator and excited target spectator. Figure 1, taken from the paper by S. Nagamiya [4], gives the schematic presentation of the collision of nuclei at relativistic energy.

The overlapping region is hot and compressed. It is expanding because of the extra pressure created in collisions: $P = P_T + P_c$. The pressure P has two components, P_T and P_c, which are related to the thermal (W_T) and compression (W_c) energies per nucleon. Therefore, the observed radial flow has two components, «compressional» and «thermal». The following equations are obtained for the subrelativistic and relativistic collisions:

$$P_c = \rho^2 \frac{dW_c}{d\rho}, \quad P_T = \alpha\rho W_T. \tag{1}$$

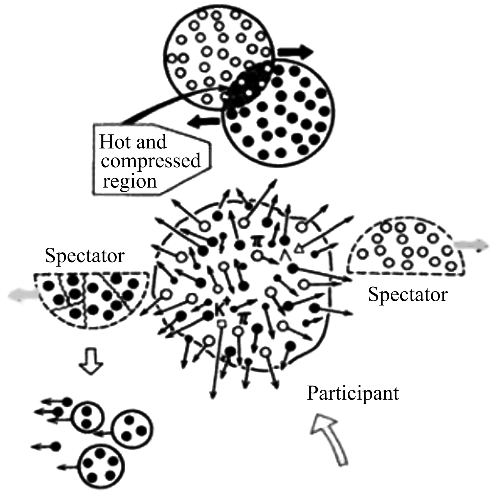

Fig. 1. Hot and compressed overlapping region is expanding with emission of different particles. Excited spectators disintegrate by multifragmentation. The participant region is also a source of fragments formed by the coalescence process

The compression energy is directly related to the excess of the density over the normal one ρ_0:

$$W_c = \frac{K}{18}\frac{\rho_0}{\rho}\left(\frac{\rho}{\rho_0} - 1\right)^2. \tag{2}$$

The parameter K, the nuclear matter compressibility, plays a crucial role. Two options for this parameter, $K = 200$ MeV (soft) and $K = 380$ MeV (hard) are frequently used [1]. Nobody knows exactly the K-value for the hot nuclear system. The central collisions are more suitable for the study of the nuclear dynamical compression. It is expected that compression effects should be larger for the central collisions, which can be selected by measuring the multiplicity of the charged particles created.

The thermal energy is determined by the temperature T of a system with the Fermi energy ε_F:

$$W_T = \frac{\pi^2}{4\varepsilon_F}T^2\left(\frac{\rho_0}{\rho}\right)^{2/3}. \tag{3}$$

Figure 2 shows the calculated pressure P_c as a function of ρ/ρ_0 in the range which is expected for nucleus–nucleus collisions at an energy of several hundred MeV per nucleon.

Figure 3 gives the calculated pressure P_T as a function of the temperature. Pressure of both types is expected to be comparable in real nucleus–nucleus collisions.

The calculated flow energies related to the compression and to the heating of the nuclear system are presented in Figs. 4 and 5.

Some procedure should be developed to disentangle both types of collective flow to get the value of W_c. In practice it can be done in the analysis of the kinetic energy spectra of nuclear fragments, their angular distributions and correlations.

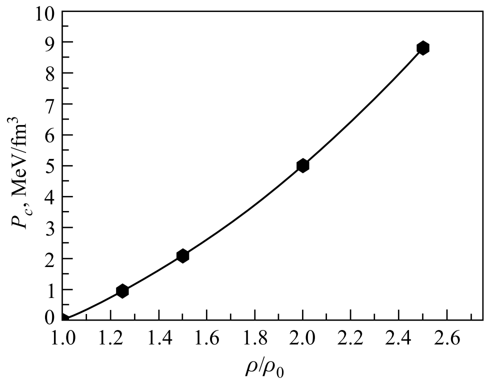

Fig. 2. Pressure inside of the compressed nucleus as a function of density

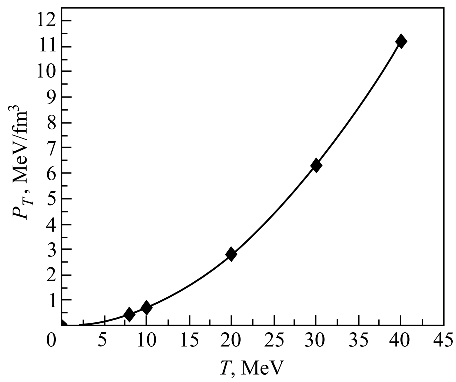

Fig. 3. Pressure inside of the hot nuclear system as a function of the temperature

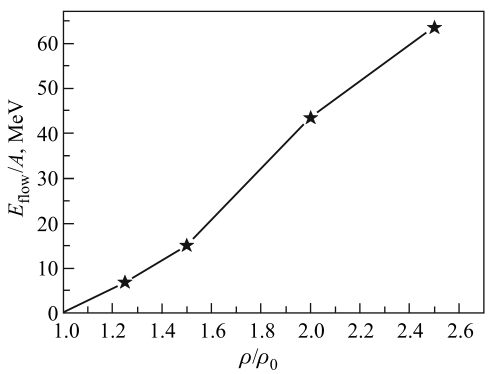

Fig. 4. Radial flow energy induced by the compression of the system

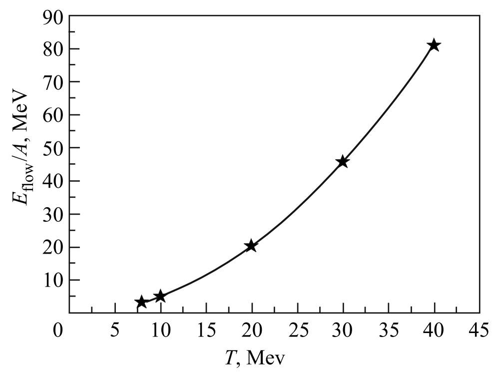

Fig. 5. Radial flow induced by the heating of the nuclear system up to temperature T

The fragment kinetic energy is composed of four terms:

$$E = E_{\rm th} + E_c + E_{\rm rot} + E_{\rm flow}. \tag{4}$$

The first term is the thermal energy, which is determined by the temperature of the source. The second term is caused by the acceleration of the fragment in the Coulomb field of the source. The rotation energy $E_{\rm rot}$ may be significant if the angular momentum of the source is high enough. It is negligible for the central collisions. The last term is the flow energy, which is originated from the extra pressure P inside the hot nucleus. For example, for the case of Au + Au collisions at 400 MeV/nucleon the collective energy is around 55 MeV per nucleon and this value accounts for 50–60% of the total kinetic energy of fragments [2]. According to the blast model [2], it corresponds to $\rho/\rho_0 \approx 2.5$: the system is rather compressed. Similar results may be obtained in collisions of lighter beams like ^{132}Xe.

Measuring the flow energy of IMF is the way to obtain experimental information on the compression energy W_c.

2. DYNAMICS OF COMPRESSION PROCESS

During the collision, the density in the overlapping region is changing as shown in Fig. 6 [4]. The temperature of the system is changing in a similar way. The only difference is the strating point: it is zero for the temperature and it is ρ_0 for the density. The density and the temperature reach their maxima at the time t_0 and fall down on the way to the final configuration after disintegration.

The challenge is to find the way to investigate the dynamics experimentally. It seems to be possible to measure the characteristic time for the compression–decompression process by the analysis of the IMF–IMF correlations as a function of the relative angle or velocity. Similar analysis has been done to obtain the emission time in the multifragmentation process [5].

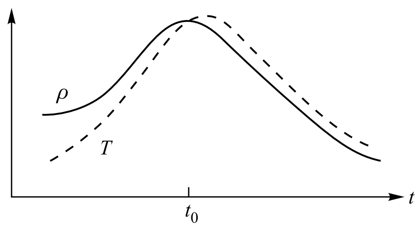

Fig. 6. Temporal change of the density and the temperature of the overlapping region in the relativistic nucleus–nucleus collisions

3. CLUSTER CONSISTING OF PIONS AND NEUTRONS

The collective flow in nucleus–nucleus collisions can increase the probability of formation of very exotic clusters consisting of pions and neutrons because of some kind of collimating effect. This problem has been discussed for many years [6–10]. These clusters are usually called *pineuts* or *deltons*. Several neutrons cannot form a bound state, but the self-energy of the system may be significantly changed by adding negative pions because of the strong attractive P_{33} interaction of π^- and the neutron resulting in formation of the Δ isobar. The situation is similar to that with ordinary nuclei when the strong optical potential of the proton in a piece of neutron matter causes a decrease in the self-energy of the system, which results in the nuclear bound state. It is believed that *heavy deltons are more promising for the search.* It was shown experimentally [11, 12] that the Δ excitations of nuclei have properties different from the free Δ excited in nucleon–nucleon collisions. A qualitative description of heavier deltons, $\Delta^{-Z}n^A$, was done by van Danzig [6].

For the systems containing more Δ^- and neutrons, the binding energy is expected to grow simply because of the increase of the number of the interacting pairs. It was assumed that the binding for Δ-nuclear clusters would scale up in the same way as for the normal nuclei: $\Delta^-n : \Delta^-n^2 : \Delta^{-2}n^2 \sim d : {}^3\mathrm{H} : {}^4\mathrm{He}$. Taking 30 MeV as the binding energy for the Δ^-–n system, one should get about 400 MeV for $\Delta^{-2}n^2$. So, this exotic alpha particle is expected to be stable so far as one needs approximately 300 MeV as binding energy to prevent the decay of the Δ particle. The lifetime of deltons is determined by the lifetime of pions, which *may be less* than the free pion lifetime. For free pion, the electron branch of decay is forbidden because of helicity conservation. This forbidding is canceled for the bound pion as the total spin value is 1.

Up to now the experimental search for the stable *single* and *twice* charged deltons has been unsuccessful [8, 9, 13]. The first work was done in 1985; the search of exotics was performed using breakup of relativistic α particle. The last work was done in 1995 using the Si beam with energy 14.6A GeV. Deltons were not observed at the level 10^{-6} of total inelastic cross section. This level is two orders of magnitude lower than the expected yield.

New searches for *heavier* deltons using very heavy beams are needed. Figure 7 shows the result of calculations of mean multiplicities (per collision) of deltons produced in Au + Au collisions at 2 GeV/nucleon. The coalescence mechanism for Δ^- and neutrons was used [10].

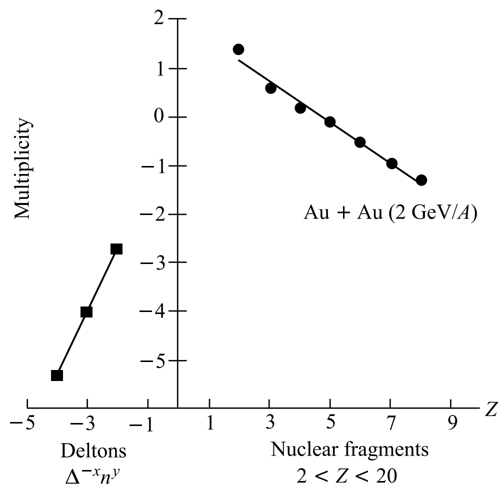

Fig. 7. The calculated multiplicity (in logarithmic scale) for deltons, and the measured multiplicity [2] for the intermediate mass fragments for collisions Au+Au at 2 GeV per nucleon

The expected multiplicities of deltons are shown together with the multiplicities of the intermediate mass fragments measured in [2]. The yield of deltons is decreasing with the charge much faster than the yield of fragments. Nevertheless, it is reasonable to search for exotic nuclei with the Z value larger than 2. The calculated differential cross section is presented in Fig. 8 for four angles of emission. The angular distribution of deltons is strongly forward peaked. Thus, electromagnetic separation of negative charged cluster seems to be favorable.

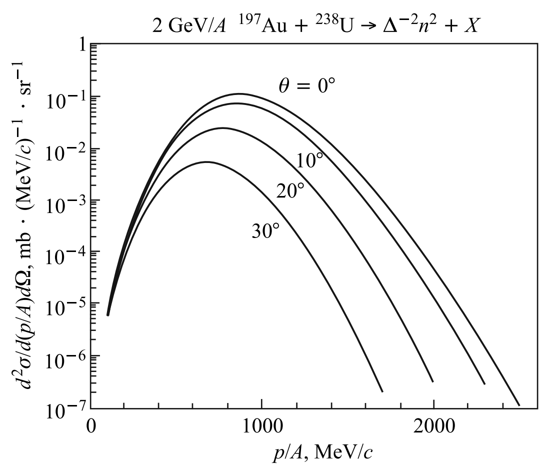

Fig. 8. The differential cross sections for production of $\Delta^{-2}n^2$ clusters in collisions of ^{197}Au with the ^{238}U target

CONCLUSION

New possibilities for experimental study of the compressed nuclear matter produced in nucleus–nucleus collisions at the Nuclotron-M are considered. It is suggested that the radial collective flow of the intermediate mass fragments is the most adequate tool for these studies. The collective flow has two components, one caused by the compression at the moment of the collision and the other related to the heating of the system. The dynamics of the compression process can be studied via the IMF–IMF correlations as a function of the relative angle or velocity.

The collective flow can increase the probability of formation of very exotic clusters consisting of the negative pions and neutrons because of some kind of collimating effect.

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