High Energy Physics and Nuclear Physics

Volume 21, Number 3

Energetic Protons and Cold Nuclear Multifragmentation Pattern

Zhang Fengshou[1], E. Suraud[2], and J.L. Laville[3]

[1](Institute of Modern Physics, The Chinese Academy of Sciences, Lanzhou, China)
[2](Laboratoire de Physique Quantique, Université Paul Sabatier, 118 Route de Narbonne, 31062 Toulouse Cedex, France)
[3](SUBATECH, Université de Nates/IN2P3/Ecole des Mines de Nantes, 44070 Nantes Cedex 03, France)

Multifragmentation is studied in correlation with energetic protons. A cold multifragmentation pattern is proposed based on the numerical simulation of the stochastic Boltzmann-Langevin model to describe the intermediate heavy ion collisions, i.e., a sizeable fraction of the available energy is released from the system by fast non-equilibrium proton emission, in which the explosion is caused by a violent but cold expansion of the system. Some typical examples simulated for $^{40}Ca+^{40}Ca$ central collisions at 90 MeV/u are presented. A possible experimental signature which could be detected using a 4π detector system is suggested.

Key words: cold nuclear multifragmentation pattern, energetic protons, stochastic transport theory.

In recent years, there has been an increasing interest in the study of the decay of highly excited nuclei via multifragmentation, namely the production of several intermediate mass fragments (IMFs) [1-7]. These studies are expected to be possibly linked to the properties of the equation of the state of nuclear matter and to its transport properties. The new generation of 4π detectors should facilitate progress in our understanding of multifragmentation [8-10]. It should however be noted that there are

---

Received on March 20, 1996. Supported by the Foundation of the Chinese Academy of Sciences and the Post-Doctor Function and the National Natural Science Foundation of China.

only very few observables that allow a clear understanding of the phenomenon. Therefore, any possibility offered to analyze the huge quantity of data obtained from experiments is welcome.

From the theoretical side, IMF production is related to the mechanically unstable spinodal region of the nuclear matter equation of state where density fluctuation should be enhanced. A possible scenario of IMF generation is therefore presented as follows. A highly excited (hot and compressed) composite is formed in the early stage of the collision, which subsequently undergoes a more or less violent expansion. Its density diminishes and reaches the value, at which nuclear matter becomes unstable with respect to small fluctuations (the spinodal region). These fluctuations may actually come from the early, most dissipative, phase of the collision, as expected from the fluctuation-dissipation theorem. During the expansion, fluctuations are propagated by the mean-field and damped by two-body collisions which in turn lead to a thermalization of the system. In that respect heavy-ion collisions lead to a complicated situation where both thermal and mechanical effects are intricately mixed.

In order to circumvent this difficulty to study multifragmentation, one may use the collisions of a very light ion against a heavy nucleus or alternatively heat the target nucleus by antiproton annihilation [11]. In both cases mechanical effects are small and the major excitation mechanism is of a thermal nature. Comparing this hot multifragmentation to the standard one from heavy-ion collisions, one notes that the latter one is more complicated because of the mixture of the mechanical and thermal effects. In turn it would be highly interesting to identify and alternate a cold multifragmentation mechanism, in which the excitation of the system would be dominantly of a mechanical nature. In this case the leading mechanism would be an expansion, dominated by mean-field effects, as two-body collisions would be suppressed to a large extent. This means that one might expect to see original fluctuations be propagated in a frozen way.

The purpose of this contribution is to propose a way to identify such cold multifragmentation patterns from standard multifragmentation events. The way to trigger this mechanism is to select events losing a sizeable fraction of the available energy through energetic protons. These events can however enter the mechanical unstable region during the stage of expansion and finally fragment into several IMFs. Our investigation is based on the simulations of stochastic transport theory [12-15]. We first discuss non-equilibrium proton production and then turn to cold events.

The Boltzmann-Langevin (BL) equation for the fluctuating single-particle density $\hat{f}(r, p, t)$ reads:

$$\left(\frac{\partial}{\partial t}-\frac{p}{m}\cdot\nabla_r-\nabla_r U(\hat{f})\cdot\nabla_r\right)\hat{f}(r,p,t) = K(\hat{f})+\delta K(r,p,t), \tag{1}$$

The left-hand side describes the Vlasov propagation determined in terms of the nuclear mean field $U(\hat{f})$ and the right-hand side contains the collision term $K(\hat{f})$ and its fluctuation $\delta K(r,p,t)$. For the Vlasov part of the equation, we work with a simplified three-parameter Skyrme-type interaction of soft potential $U(\rho) = A(\rho/\rho_0) + B(\rho/\rho_0)^\sigma$, which leads, for a saturation density ρ_0, to an incompressibility modulus of order $K \approx 200$ MeV. The collision term $K(\hat{f})$ is the same as one typical of the Boltzmann-Uehling-Uhlenbeck (BUU) form, but expressed in terms of the fluctuating density. The fluctuation $\delta K(r,p,t)$ arises from correlations not accounted for by the collision term and can be characterized by a correlation function $\langle\delta K(r_1,p_1,t_1)\delta K(r_2,p_2,t_2)\rangle = C(p_1,p_2)\delta(r_1-r_2)\delta(t_1-t_2)$. Brackets here denote a local average, performed over fluctuating densities generated during a short-time interval δt. The correlation function $\langle\delta K(r_1,p_1,t_1)\delta K(r_2,p_2,t_2)\rangle$ is assumed to be local in space and time, similarly to the Markovian treatment of the Boltzman collision term.

Numerical simulations of the BL could in principle be obtained the employment of standard methods to solve stochastic differential equations. However, to apply this method it is necessary to introduce a certain approximation, since the stochastic variable is a 6-D phase space distribution. We employ here the projection method to simulate the BL. Fluctuations are projected the local multipole moments of the momentum distribution. They are evaluated for the two non-vanishing terms of this expansion, namely, quadrupole and octupole moments. Fluctuations are finally injected back to the momentum distribution itself in a local way, which might be sufficient for describing density fluctuations. In this work, we compute each physical nucleon with 20 numerical test particles and the collision integral is evaluated by means of a standard full ensemble technique of 100 events. The usual BUU simulations, as those presented below, are recovered from the BL simulations by switching off the fluctuating collision integral.

As a first step we calculate non-equilibrium proton multiplicity. Non-equilibrium protons may be identified by suitable kinematic and geometric conditions during a relevant time interval preceding the completion of thermalization. We have chosen a time window corresponding to the decrease of the quadrupole moment of the momentum distribution from its original value to about 0. This is a typical quantity to represent the thermalization phase. In the case of central $^{40}Ca+^{40}Ca$ collisions at 90 MeV/u, this corresponds to a time window of about 20-40 fm/c starting at about 20 fm/c after contact. To identify a non-equilibrium particle we impose the following kinematic and geometric conditions: The i-th test particle (r_i,p_i) is required to fulfill four conditions at the same time: (i) $\|r_j\| \geq 1.4\sqrt[3]{A_{\mathrm{proj.}} + A_{\mathrm{targ.}}}$ fm (geometry), (ii) the local density $\rho_i \leq 0.02\ \mathrm{fm}^{-3}$ (geometry), (iii) its single particle energy $\varepsilon_i \geq 8$ MeV (energetic), and (iv) $r_i \cdot p_i > 0$ (kinematics).

To compare BUU to BL in Fig. 1, one notices that BUU is unable to produce the energetic protons. It is shown that between 40 fm/c and 60 fm/c, only low energy (<200 MeV) protons are produced, but there is no increase of high energy ones (>200 MeV). High energy protons are produced only during the early phase of the reaction and thus are dominantly non-equilibrium particles. This suggests the appealing possibility of triggering non-equilibrium particle by an energy cutoff, i.e., 200 MeV, for the present system.

Figure 2 is a correlation plot between the total proton energy loss and individual non-equilibrium particle energy for BUU and BL. This figure exhibits several interesting features. First, we see that as time evolves (between 40 and 60 fm/c) the average total energy loss increases by more than 2 factors both in BUU and BL, which reflects the continuous nature of the escaping proton flux. The

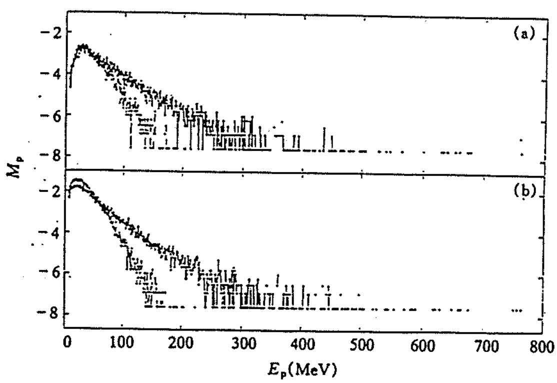

Fig. 1
The energy spectra of the multiplicity of emitted protons by BL (solid lines) and BUU (dashed lines) simulations at 40 fm/c (a) and 60 fm/c (b) for central $^{40}Ca+^{40}Ca$ collisions at 90 MeV/u. —— : BL; ----- : BUU.

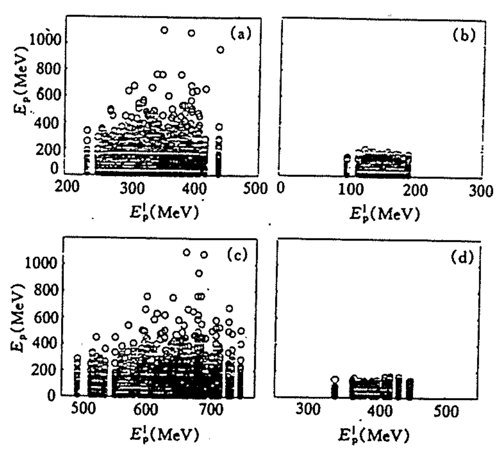

Fig. 2
The correlation between the energies of emitted protons and emitted total energy of protons by BL (a and c) and BUU (b and d) at 40 fm/c (a and b) and 60 fm/c (c and d) for central $^{40}Ca+^{40}Ca$ collisions at 90 MeV/u.

dispersion around this average value increases more slowly. However, the most interesting feature is the behavior of producing very energetic protons ($>$600 MeV) in the early stages of the collisions, which is in agreement with the finding of Fig. 1. Second, in a given event, the higher the maximum non-equilibrium proton energy, the higher the total energy loss. The latter behavior is quite interesting for experiments since it suggests that energetic non-equilibrium particle might provide a trigger to select a special class of cold event where a sizeable fraction of energy has been ejected in the early stages of the collisions through specially energetic protons. For these events one may expect, to some extent, the frozen propagation mentioned above. We also notice that the result of BUU calculations is completely different, which gives a flat, structureless, and uncorrelated picture.

This problem could be quantitatively understood in Fig. 3. One can see that, in consideration of the dynamic fluctuations, there is a broad distribution around Q_{20} = 60 fm^{-2} in BL calculations, which leads to some energetic nucleon emissions and the loss of the total energy of the non-equilibrium nucleons E^{l}_{n+p} is 3 times as large as the BUU calculations, but the multiplicity of emitted nucleons is almost the same in these two calculations. We can estimate the thermal excitation energy from the above calculations. The calculations by BL only produce a thermalized system with excitation energy of 4.68 MeV and the lowest deposit is 2.24 MeV. In the same simulation conditions, we obtain the excitation energy of 10.15 MeV, and the corresponding lowest energy deposit of 8.73 MeV in BUU calculation, which is 2 times larger than the case of BL simulation. After 40 fm/c, Q_{20} will approach to a constant value and there will be many nucleon emissions in the low energy range as shown in Figs. 1 and 2.

The question now is if this cold system can be subject to multifragmentation. We can study this question by tracing the square of the sound velocity v_s^2 in the region around the center of mass and compare it with the static Fermi gas model at different temperatures. The v_s^2 is proportional to the slope of the pressure-density isotherm. Using the soft potential of Eq.(2), v_s^2 reads:

$$v_s^2=\frac{1}{m}\left(\frac{10}{9}< E_k > +A\left(\frac{\rho}{\rho_0}\right)+B\sigma\left(\frac{\rho}{\rho_0}\right)^{\sigma}\right), \tag{2}$$

where $\langle E_k\rangle$ is the average kinetic energy. For the homogenous nucleon Fermi gas [16] at temperature T

$$v_s^2=\frac{1}{m}\left(\frac{10}{9}\,\frac{C_{3/2}(\mu)}{C_{1/2}(\mu)}T+A\left(\frac{\rho}{\rho_0}\right)+B\sigma\left(\frac{\rho}{\rho_0}\right)^{\sigma}\right), \tag{3}$$

where $C_v(\mu)$ is the Fermi-Dirac integral and $\mu = \mu(\rho,T)$ is the chemical potential of free nucleons, which can be numerically obtained from the conservation of the total nucleon number. One can see from Fig. 4 that the nucleon Fermi gas system enters the dynamical unstable region at densities 0.100, 0.070, and 0.065 fm^{-3} for temperatures 0, 4, and 8 MeV, respectively. At higher T, such as 12 MeV, the system is in a vaporization pattern and never approaches to this spinodal region. Based on BUU and BL simulations, for real heavy ion collision trajectories one can clearly say whether the system could enter this unstable spinodal region. During the first 30 fm/c there is no difference in the average observables from BL and BUU calculations. At 28 fm/c, both systems can reach the maximum compression and the maximum overlap density is about 1.5 times the saturation one. But one should notice the difference of the fluctuations of v_s^2. The dispersions of BL are several times larger than the one of BUU during 10-40 fm/c. These dynamical fluctuations will lead to many energetic nucleon emissions which is in agreement with the finding of Figs. 1 and 2. One should also notice that the

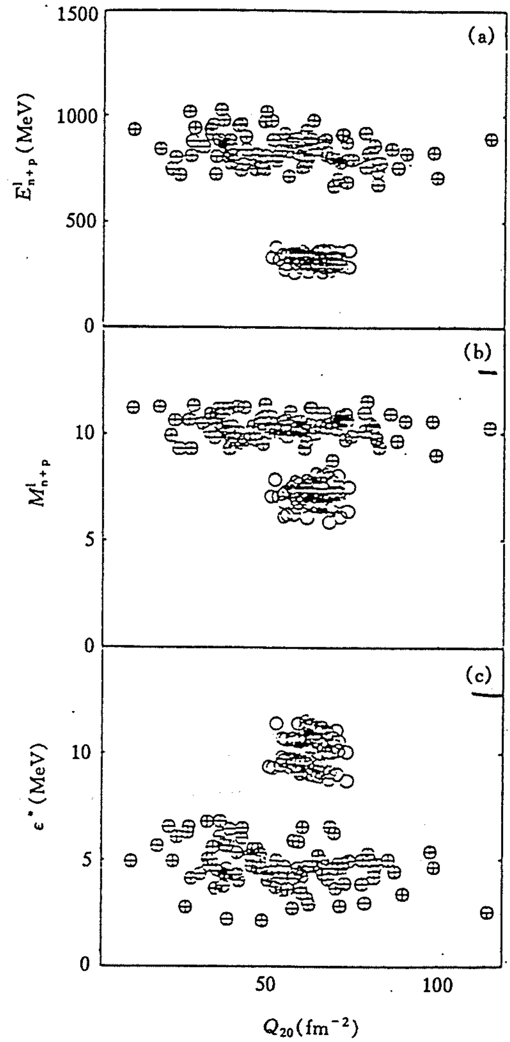

Fig. 3

The correlations between the emitted energies E^1_{n+p} (a), multiplicities M^1_{n+p} (b) by non-equilibrium nucleons, the thermal excitation energy per nucleon ε^* (c) and their corresponding Q_{20} by BL and BUU simulations at 40 fm/c for central $^{40}Ca+^{40}Ca$ collisions at 90 MeV/u. ⊕ : BL; ○ : BUU.

dynamical fluctuations can dramatically change the initial trajectories. The system can enter spinodal region at 50 fm/c with a density 0.082 fm^{-3} from BL simulation because the averaged $v_s^2 < 0$, while from BUU calculations it is possible to enter spinodal region only from some fluctuations in the late stage of collisions. In comparison of BL and BUU calculations with the Fermi gas, one finds the entering temperature is 4 MeV for BL simulations but 10 MeV for the BUU case. For BL calculations, some events are near $T = 0$ MeV temperature and one can get 7.8% of the events outside the "one standard deviation" for a normal distribution at the low side of the dispersion of v_s^2, which is just the probability of the cold multifragmentation pattern. Of course, it is not easy to compare directly between the static

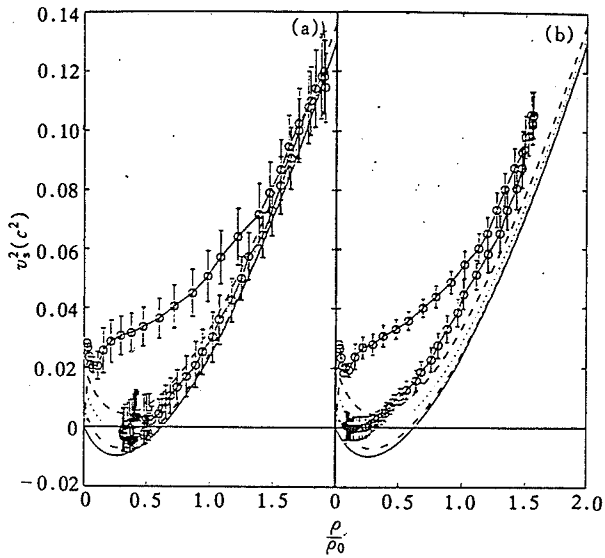

Fig. 4

The square of the sound velocity v_s^2 and its dispersion as a function of ρ/ρ_0 in a sphere surrounding the center of mass with a radius of 2.0 fm by BL (a) and BUU (b) for central $^{40}Ca+^{40}Ca$ at 90 MeV/u. The solid, dashed-dotted, dotted, and dashed lines are the results of homogeneous nucleon Fermi gas at temperatures of 0, 4, 8, and 12 MeV, respectively. —o—o— : BL; —— : $T=$ 0 MeV; —•— : $T=4$ MeV; • • • : $T=8$ MeV; ----- : $T=12$ MeV.

Fermi gas model and the BL equation, but there seems to be the cold multifragmentation pattern in both the static and BL simulations. Because a large part of energy of the system is taken by the emitted energetic non-equilibrium nucleons in the early stage of the collisions the thermal excitation is largely prevented. However, the collision system can also enter the mechanical unstable region in the mean field and finally multifragment at a very low thermal excitation energy.

In summary, based on the stochastic transport theory for describing intermediate energy heavy ion collisions and in correlation with the energetic emitted protons, we proposed a possible multifragmentation pattern, i.e., these protons take away a large fraction of energy and the system finally multifragments because of the violent but cold expansion. We hope to obtain the experimental signatures of this cold multifragmentation pattern in correlation measurement of the energetic non-equilibrium protons and multifragmentation events with the help of 4π detectors.

REFERENCES

[1] F.S. Zhang and E. Suraud, *Phys. Lett.*, **B319**(1993), p. 35.
[2] F.S. Zhang and E. Suraud, *Phys. Rev.*, **C51**(1995), p. 2301.
[3] G.F. Bertsch and S. Das Gupta, *Phys. Rep.*, **160**(1988), p. 189.
[4] J. Aichelin, *Phys. Rep.*, **202**(1991), p. 233.
[5] X. Campi, *Phys. Lett.*, **B208**(1988), p. 351.
[6] D.H.E. Gross and Sa-Ban Hao, *Nucl. Phys.*, **A437**(1985), p. 643.

[7] M. Ploszajczak and A. Tucholski, *Phys. Rev. Lett.*, **65**(1990), p. 1539.
[8] D.R. Bowman *et al.*, *Phys. Rev. Lett.*, **67**(1991), p. 1527.
[9] C.A. Ogilvie *et al.*, *Phys. Rev. Lett.*, **67**(1991), p. 1214.
[10] G. Bizard *et al.*, *Phys. Lett.*, **B302**(1993), p. 162.
[11] J. Hufner, *Phys. Rep.*, **125**(1985), p. 13.
[12] S. Ayik and C. Gregoire, *Nucl. Phys.*, **A513**(1990), p. 187.
[13] J. Randrup and B. Remaud, *Nucl. Phys.*, **A514**(1990), p. 339.
[14] P. Chomaz, G.F. Burgio, and J. Randrup, *Phys. Lett.*, **B254**(1991), p. 340.
[15] E. Suraud *et al.*, *Nucl. Phys.*, **A580**(1994), p. 332.
[16] Zhang Fengshou and Ge Lingxiao, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **16**(1992), p. 666.