Physics of Heavy-Ion Collisions at JHF

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Abstract

Expected characteristic features of heavy-ion collisions at JHF energies ($20 \sim 25A$ GeV) are discussed. At JHF energies, the baryon density during collisions would be as high as $\rho_B \sim 10\rho_0$, which may be enough to form baryon rich QGP. By using several probes, it would be possible to detect the phase transition from dense hadronic matter to baryon rich QGP. Combining these results with the JHF first stage achievements in strangeness nuclear physics, it becomes possible to discuss the rich properties of the highest baryon density matter, which may be realized in the neutron star core and at the very initial stage of supernova explosion based on the experimental data obtained in the laboratory.

1 What we can do with 50 GeV PS machine ?

After long discussions, construction of high intensity proton accelerator fascility has been proposed and approved as the JAERI-KEK Joint (JKJ) project. This project covers a wide range of science, from material science, nuclear engeneering, nuclear physics, to particle physics. Among the complex accelerators in this project, high intensity 50 GeV proton accelerator inherits the idea of Japan Hadron Project or Japan Hadron Fascility (JHF). In the first stage of the project, the main physics goal of JHF (or JKJ-50 GeV) fascility in nuclear physics is to elucidate the roles of strangeness in nuclei and nuclear matter. In the later stages of the project, we strongly expect that more beam lines and experimental halls would be constructed, and in addition to the proton beam, heavy-ion beams become available. With this extended form of the fascility, I think, and we find in the meeting that many researchers think, this project is suitable for studying the phase diagram of hadronic matter, especially of highly dense matter, which is one of the most attractive facets of nuclear, hadron, and quark physics.

In JKJ, variety of beams are available. The incident energy of proton beam covers 2 orders from 400 MeV to 50 GeV. In this energy range, the reaction mechanism of pp reaction evolves from elastic, resonance production, to string formation. Then we can produce various hadrons such as pion, kaon, muon, neutrino, and anti-proton, which are utilized as secondary beams. In addition, when heavy-ion beams are accelerated in the second stage of the project, the incident energy ($\sim 25A$ GeV) may be the best energy to produce the highest baryon density matter in the laboratory.

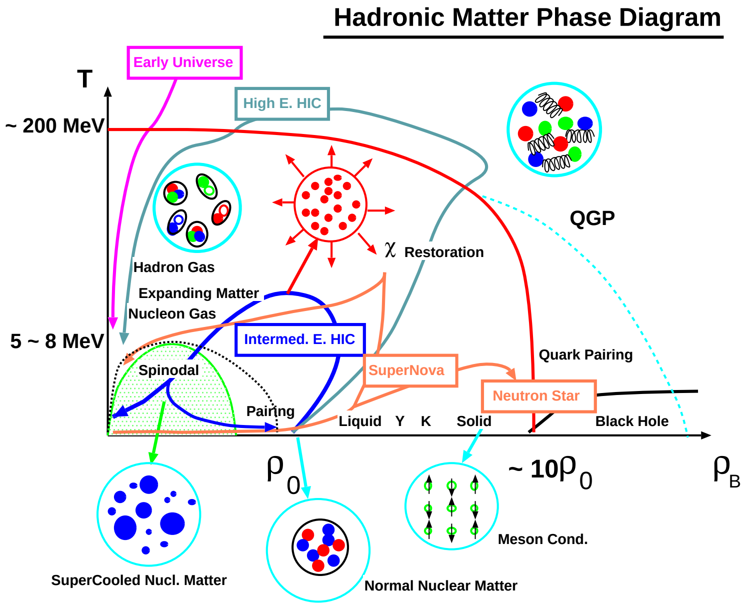

Figure 1: Hadronic matter phase diagram.

Many of recently constructed or planned big accelerator fascilities in the world aim at elucidating properties of nuclear matter under extreme conditions. RIKEN-RIBF tries to produce the most neutron-rich and/or most heaviest nuclei in the laboratory, which may be formed tentatively during the supernova explosion and play essential roles in synthesizing heavy elements. BNL-RHIC and CERN-LHC aim at producing the hottest matter, in which quarks and gluons are freely moving in the perturbative vacuum. This form of matter, QGP, existed at the very beginning of this universe, then the study of QGP formation and its decay or hadronization would give us insight on the picture of the early universe.

In JHF, it is possible to reveal the properties of nuclear matter at the highest baryon density. In this report, I would like to appeal how attractive high density matter is.

2 Towards the highest density matter formation

In the universe, nuclear matter at the highest baryon density appears in the central region of neutron stars. It may be formed tentatively during the supernova explosion, or just before the primodial neutron star collapses to a black hole, as shown in Fig. 1. Neutron stars have provided us with a lot of interesting subjects to physisists since the time before their discovery [1], as Prof. Tatsumi reported in this meeting [2]. Supernovae are the source of many elements, and in its first stage, the nuclear Equation of State (EoS) at high density plays an vital role. Thus the understanding of high baryon density matter is important to describe neutron stars (*"Where do we go ?"*) and supernovae (*"How are we (various elements) made ?"*).

In addition to the importance in understanding the universe, there are a lot of theoretical conjectures in high density matter. Anisotropic neutron superfluid ($^3P_2$) is already accepted as a standard in neutron star matter [3], and as the baryon density increasese, various phases are proposed to appear in neutron stars; pion condensation, hyperon admixture, kaon condensation, and the baryon-rich QGP. Also for the partial restoration of the chiral symmetry, the effects of baryon density would be stronger and more direct than those of temperature [4]. Recently, another new form of matter, color superconductivity [5], has been proposed and has attracted much attention. In spite of these many proposals, we do not have decisive answers yet. This is partly because realistic lattice QCD calculations are not available at present for finite baryon densities. Another aspect is that the problem of high density matter is essentially a problem of interaction, while the QCD phase transition at zero baryon density is a transition of the particle degrees of freedom; a naive estimate based on free pions and free quarks and gluons gives a comparable transition temperature to that in sophisticated lattice QCD calculations.

Since there is no first principle estimate, experimental data and theoretical model esitmates are vital. Among them, (1) interactions associated with strange hadrons, (2) EoS at high baryon densities, (3) medium modification of hadron properties, and (4) baryon-rich QGP formation, are of the highest priority.

2.1 Strangeness Nuclear Physics

Hyperons are expected to appear at $\rho_B = (2-4)\rho_0$ in neutron stars, and they soften the EoS at higher densities and help to cool neutron stars rapidly. These understandings are based only on theoretical esitmates and several observations of neutron star masses and radii. But the above density and EoS strongly depend on the YN and YY interactions, where $Y = \Lambda, \Sigma$, and Ξ. Since YN and YY interactions other than ΛN are not known well, these understanding can be very different after JHF provides a lot of data on ΣN, ΞN, and $\Lambda\Lambda$ interactions. For example, the discovery of one clear double hypernuclear formation ($^{6}_{\Lambda\Lambda}$He) has limited the strength of the $\Lambda\Lambda$ interaction, and the theoretical estimate based on this double hypernucleus shows that the critical temperature of the $\Lambda\Lambda(^1S_0)$ superconductivity would be smaller than the internal temperature of neutron stars [6]. Strangeness nuclear physics is the main research field in the JHF first starge, and other important aspects of the strangeness nuclear physics, such as the kaon-nucleon interactions, will be reported by Dr. Hiyama [7] and Prof. Nagae [8] in this volume.

2.2 Equation of State and Collective Flow

The nuclear (or non-strange) part of the EoS is, of course, also important in neutron star and supernova physics. First principle theoretical construction of EoS from realistic NN interactions is usually based on hole-line expansions (Brückner theory) or variational calculations, and it becomes less reliable at higher densities. Thus it is also necessary to invoke heavy-ion collision data in order to obtain phenomenologically verified EoS. In high energy heavy-ion collisions, nuclear matter is compressed and heated for a while, expands until the freeze-out density/temperature, and emit various hadrons and fragments. Since heavy-ion collisions are non-equilibrium dynamical processes of finite system, it is not straightforward to extract the information on EoS from data. However, through systematic studies of many observables, it would be possible to obtain, or at least limit, the EoS. For example, in a recent work, it is shown that it is possible to explain the incident energy dependence of hadronic transverse mass spectra, directed and elliptic flows simultaneously by using moderately stiff EoS ($K \sim 300$ MeV) in a transport model (RBUU) [9]. The interaction adopted in this work also reproduces the energy dependence of the real part of NA potential. (We have checked that softer or harder EoS does not reproduce some of the above observables.)

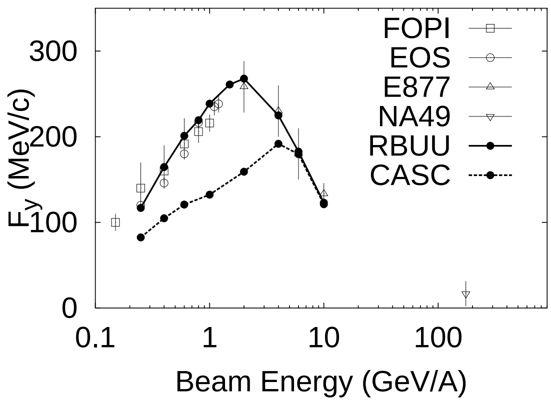

Figure 2: Energy dependence of transverse flow, $F_y = d < P_x > /d(y/y_{cm})$, from GSI to SPS energies. Taken from Ref. [9].

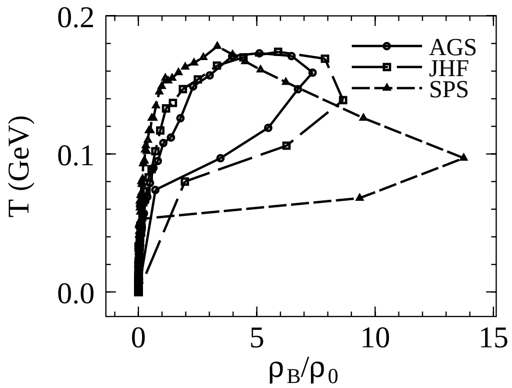

Figure 3: Thermal evolution of nuclear matter in heavy-ion collisions at AGS, JHF, and SPS energies. Taken from Ref. [10]

From this point of view, heavy-ion collisions at JHF energy would provide us with unique and important information; the available kinetic energy in each NN collision is in the middle of those at AGS and SPS energies ($\sqrt{s_{NN}} - 2m_N \sim 3, 5, 15$ GeV). In addition, the highest baryon density matter is expected to be formed at around JHF energies. In Fig. 3, I show the thermal evolution of hadronic matter formed during heavy-ion collisions at AGS, JHF and SPS energies calculated and analyzed by Nara [10]. Up to around JHF energies, this evolution is smooth; first matter is compressed, and through the frequent sequential collisions, it is heated up gradually. Above SPS energies, due to the large γ factor, the density seems to be very large,

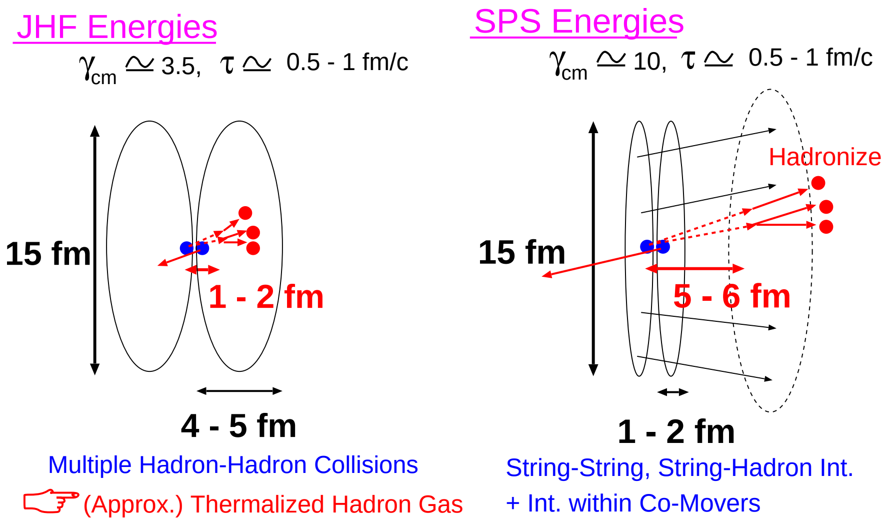

Figure 4: Primary and secondary hadron interaction points at JHF and SPS energies.

but it is just a mixture of heated matter and unheated matter. From the highest density point, it quickly goes to high T and low ρ_B, then it is not appropriate to discuss, for example, medium modification at high baryon density.

This difference may be intuitively understood by considering the formation time of hadrons, as illustrated in Fig. 4. After the primary NN collisions in heavy-ion collisions, many hadrons are produced, but they cannot interact for some time period, $\tau \sim 0.5 - 1.0 \mathrm{fm}/c$, because of the finite hadron size and finite interaction time. Fast hadrons move 1-2 fm (5-6 fm) at JHF (SPS) energies during this formation time before secondary interactions. As a result, we cannot expect frequent energetic secondary *hadron*-nucleon collisions at SPS energies, although *string*(or pre-hadronic) interactions would be important. At JHF, on the other hand, the γ factor is around $\gamma_{cm} \sim 3.5$, then the depth of the target nuclei ($\sim 4 - 5$ fm) is larger than the above formation length. Thus frequent energetic secondary hadron-nucleon collisions may take place at AGS and JHF energies. This nature of secondary interactions may be already seen in the hadron spectra at AGS and SPS energies. In Fig. 5, hadron rapidity (left) and transverse mass (left) spectra are shown [11]. Proton rapidity distributions show that baryons are well stopped at AGS showing one peak, but this baryon stopping power seems to be reduced at SPS showing a dip structure. In addition, proton transverse mass spectrum at AGS seems to be *stiffer* than that at SPS, in spite of the fact that the available kinetic energy ($\sqrt{s_{nn}} - 2m_n$) at SPS is much larger than that at AGS. Both of the these findings are consistent with the above consideration on the secondary interactions.

Unfortunately, these evidences of the "high baryon density" are indirect. We cannot extract the baryon density at the most compressed point from experimental data directly. In addition, collective flows (radial, directed, and elliptic flows) are affected not only by the EoS (baryon densities, nuclear interactions, and particle degrees of freedom) but also by the time-scale of the reactions. As shown in Fig. 2, the transverse flow becomes maximum at GSI-SIS energies ($\sim 2A$ GeV). Above GSI-SIS energies, the maximum density goes higher, but the time of interaction between participants and spectators becomes short. This short participant-spectator interaction

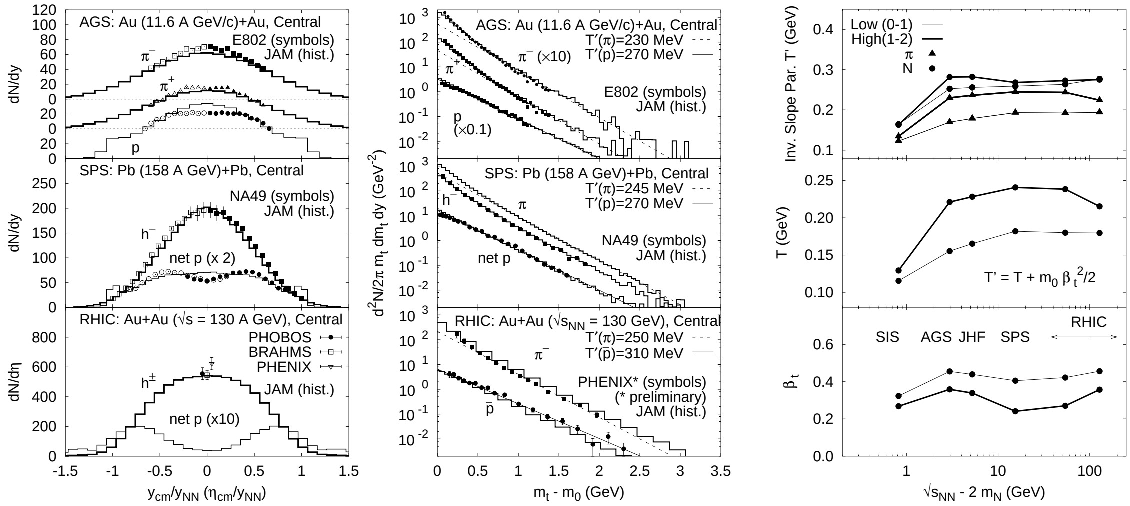

Figure 5: Left: Rapidity distribution (dN/dy) at the AGS and SPS energies, and pseudorapidity distribution ($dN/d\eta$) at the RHIC energy. Middle: Transverse mass (m_t) spectra of hadrons at the AGS, SPS and RHIC energies. Right: Inverse slope parameter of hadron m_t spectra, and its decomposition into T and β. Calculated results are compared with experimental data [12, 13, 14, 17, 15, 16]. Taken from Ref. [11].

time reduces the transverse flow ($F_y = d < p_x/A > /d(y/y_{cm})$), which is the forward-backward asymmetry in the emission from participants This also applies to elliptic flows. Above SPS energies, v_2 is considered to be a measure of thermalization degree and initial pressure gradient. For example, the large v_2 at mid-rapidity can be well explained by hydrodynamical models in heavy-ion collisions at RHIC [18], while v_2 in the fragmentation region is overestimated by hydrodynamics. This suggests that early thermalization is achived only in mid-rapidity region, and hadron dynamics (in which the thermalization time is longer than in QGP) may be more appropriate in the fragmentation region [19]. However, up to AGS energies, spectator nucleons block emitted particles from participants, and this supresses in-plane ($v_2 > 0$) emission.

JHF energy would be marginal in several senses. Hadron rescatterings generate large stopping power and baryon density becomes very high. Then radial as well as elliptic flow may show local maximum as a function of the incident energy. On the other hand, since the participant-spectator interaction is small but not negligible, transeverse flow (F_y) will be very small. These are important in understanding the properties of dense matter, but it would be more direct to measure other observables if we want to reveal the properties of the "highest baryon density matter".

2.3 Medium Modification of Hadrons

The above features of JHF energy — formation of the highest baryon density matter — may appear most clearly in the medium effects on hadron properties. For example, the baryon density effects on vector meson mass modification would be stronger than temperature effects [4].

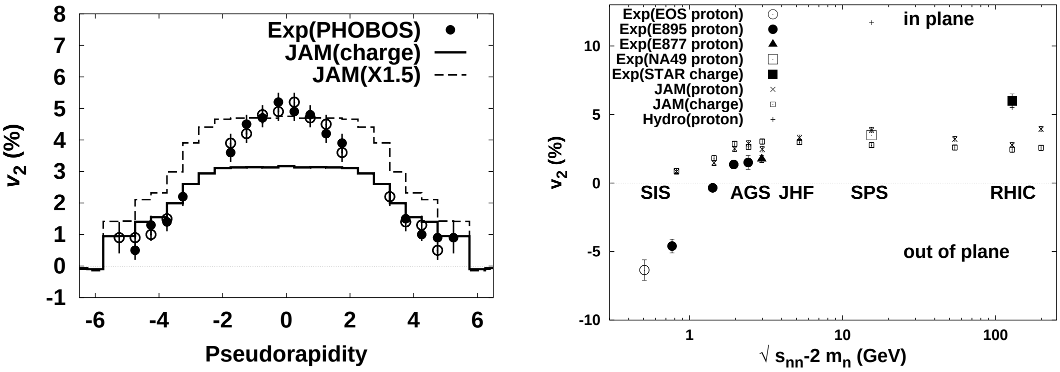

Figure 6: Left: Pseudo rapidity dependence of the elliptic flow (v_2) at RHIC energy, $\sqrt{s_{NN}} = 130$ GeV in comparison with RHIC data [20]. Right: Incident energy dependence of elliptic flow (v_2). Taken from Ref. [19].

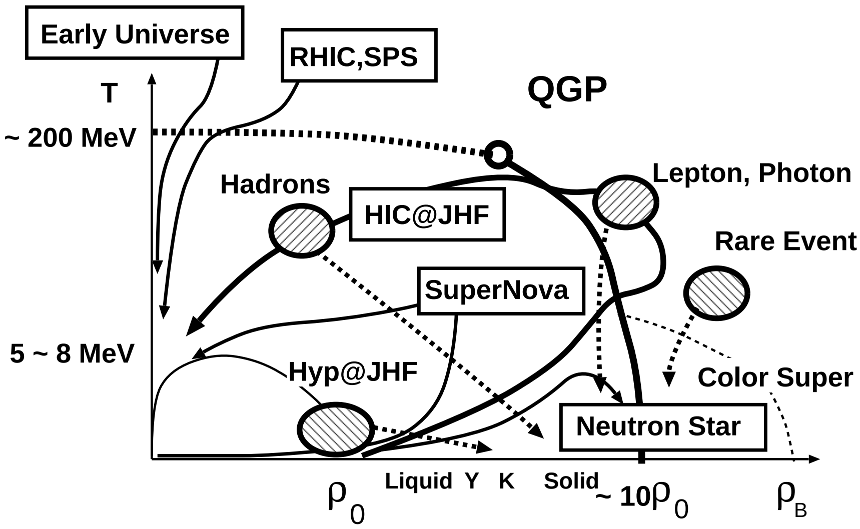

Figure 7: Three ways extapolation to investigate cold dense matter in JHF energy heavy-ion collision.

This may be the reason why we can observe the mass reduction of vector mesons in pA reactions at KEK [21] as well as in heavy-ion collisions at SPS energies [22]. Then what happens at $\rho_B \sim 10\rho_0$? Experimentally, the di-lepton invariant mass spectra have not been measured in heavy-ion collisions at energies around 10-30 A GeV, at which high baryon density matter is formed. In a theoretical side, it is a big challenge to estimate non-perturbative effects in ρ_B in a well-founded framework.

Anyway, provided that our present understanding is correct, di-lepton invariant mass spectra would be very different from those expected from the hadron cocktail; spectral function in the vector channel is widely spread, and at finite baryon density, σ and ω will mix strongly. Predictions and speculations are necessary; especially it is very important to have predictions on the difference of the spectra in the dense hadronic matter and in the baryon-rich QGP.

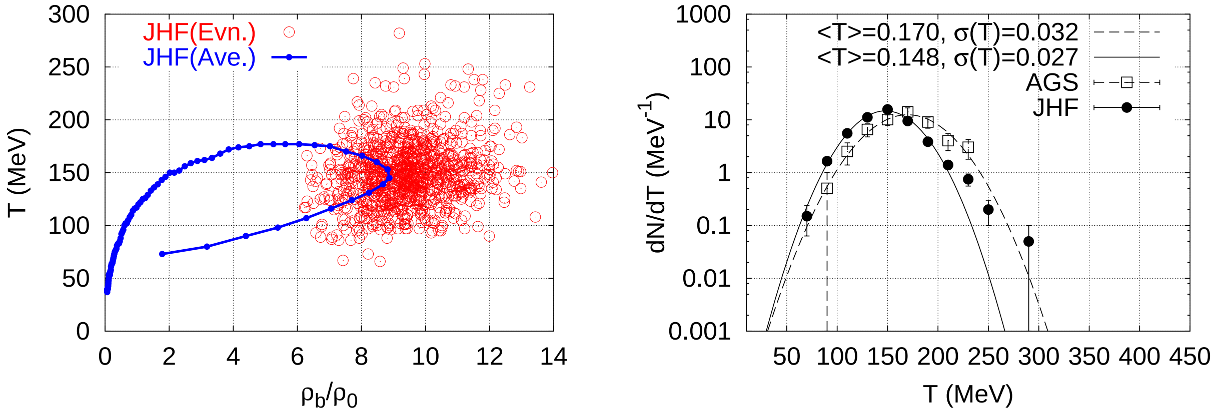

Figure 8: (ρ_B, T) distribution at the highest density point in AGS and JHF energy Au+Au collisions.

2.4 Baryon-Rich QGP Formation

In the preceeding subsections, two ways to probe baryon rich matter have been discussed. The freeze-out properties can be determined by observing hadrons, which should have informations of the initial dense stage. Penetrating probes such as leptons and photons are useful to extract the properties of initial dense matter directly. Then by combining these probes, the average evolution path in the phase diagram can be determined. As already shown in Fig. 3, the baryon density would reach 8-10 ρ_0 during the heavy-ion collision at JHF energies. In the central region, the density stays to be $\rho_B > 6\rho_0$ for around 3 fm/c. It should be discussed whether we can create baryon rich QGP with this density or not, but it is promising.

Although the temperature at the highest baryon density is calculated to be still high ($T \sim 150$ MeV) to create an ultimate form of matter in the laboratory — cold and dense neutron star matter or color superfluid —, some part of energy would be exhausted by the latent heat then the temperature may be reduced when the matter goes across the phase boundary. In addition, since the above mentioned density is the *event averaged* one and the system size is finite, we necessarily have fluctuations around the average path. On the one hand, this fluctuation generates uncertainty in understanding heavy-ion dynamics, especially in hydrodynamical interpretation of freeze-out observables and medium effects on hadron properties, where we usually use local (static) matter approximation. On the other hand, it is useful when we want to probe the region which is distant from the average path.

In Fig. 8, I show the calculated results of the highest baryon density point in 1000 events generated by using JAM [23]. Even without taking account of the phase transition, the temperature can be as low as 50 MeV in one event out of $10^3 \sim 10^4$ events. At this temperature, we can expect to observe some precursor signals of color superconductivity [24].

Another interesting topics about the event-by-event fluctuation in relation with the tricritical point will be reported by Hirano [25].

3 Summary

In this report, I discussed the expected features of heavy-ion collisions at JHF energies ($20 \sim 25A$ GeV). The thermal and/or chemical freeze-out point would be between those at AGS and SPS energy heavy-ion collisions, but I would like to emphasize that the evolution path can be very different. At JHF energies, the baryon density during collisions would be as high as $\rho_B \sim 10\rho_0$, which may be enough to form baryon rich QGP. Hadron yields and spectra contain the information of the evolution path, along which high baryon densities are probed; we expect strong radial and elliptic flows, and strong strangeness enhancement. By using penetrating probes such as leptons and photons, we can get more direct information on the high baryon density stage. Since hadron spectral functions are expected to be more sensitive to the baryon density rather than to the temperature, di-lepton spectra at JHF would be very different from those in hadron cocktail at vacuum. If strong intensity heavy-ion beams are available, it is worthwhile to search for exotic signals such as the precursor of color superconductivity [24].

By combining these observations and the achievements in strangeness nuclear physics, I hope we can elucidate the rich properties of the highest baryon density matter, and then it becomes possible to discuss the properties of neutron star core and the very initial stage of supernova explosion based on the experimental data obtained in the laboratory.

This report is based on the collaboration work with M. Isse, N. Otuka, P.K. Sahu, Y. Nara.

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