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TOWARDS HIGH-DENSITY MATTER WITH RELATIVISTIC HEAVY-ION COLLISIONS

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Abstract: Recent progress in nucleus-nucleus collisions at BNL and CERN suggests a hint that the formation of high-density nuclear matter could be possible with relativistic heavy-ion beams. What is the maximum density that can be achieved by heavy-ion collisions? Are there data which show evidence or hints on the formation of high density matter? Why is the research of high-density interesting? How about the future possibilities on this subject? These points are discussed.

1. INTRODUCTION

1.1 Can We Expect the Formation of High-Density Matter?

Nuclear collisions at high energies can be described as two clouds of individual nucleons colliding with each other. In the low-energy region, such as a few 100 A MeV, each colliding nucleon will escape easily after the first nucleon-nucleon (NN) collision because of the nature of isotropic angular distribution in NN collisions in that energy domain. This situation is illustrated in the upper graph of Fig. 1.

On the other hand, in the high-energy domain, such as the AGS energy domain, each nucleon will dive into the matter after the first NN collision, as shown in the lower graph of Fig. 1, and will experience sequential NN collisions. This is because the angular distribution in NN collisions in this case is sharply forward (and backward) peaked. If, however, the nucleus is thick enough to slow down incident nucleons within the nuclear matter thickness, then these nucleons will be confined within a Lorentz contracted volume, so that a formation of "baryon-rich high-density" matter would be expected. In this case the density will reach[1]

$$\rho = 2\gamma_{cm}\,\rho_0, \qquad (1)$$

where γ_{cm} is the γ-factor that is used for Lorentz transformation and ρ_0 is the density of normal nuclei. The factor 2 comes from the

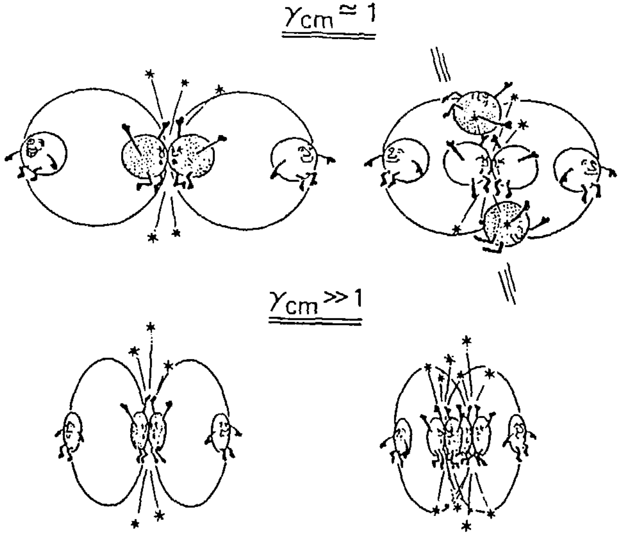

Fig. 1: Schematical illustration of nucleus-nucleus collisions.

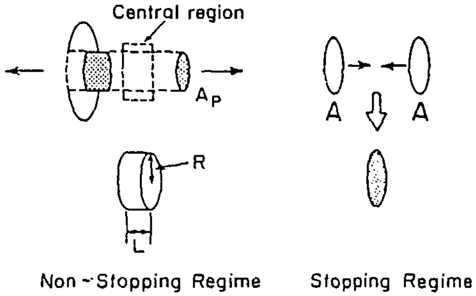

Fig. 2: Two extreme cases for nucleus-nucleus collisions.

overlap of two colliding nuclei and γ_{cm} from the Lorentz contraction of these nuclei. Now, the volume is given by

$$V = (A/\rho_0)/\gamma_{cm}, \tag{2}$$

and the energy accumulated into this volume is the nucleon number (2A) times the energy carried by each nucleon ($\gamma_{cm} mc^2$):

$$E = 2A\gamma_{cm}\, mc^2. \tag{3}$$

Therefore, we expect to have the following energy density ε:

$$\varepsilon = E/V = 2\gamma_{cm}^2\, mc^2 \rho_0 = 2\gamma_{cm}^2 \varepsilon_0 , \tag{4}$$

where $\varepsilon_0 = mc^2\rho_0$ ($\cong$ *0.15 GeV/fm*^{3}) is the *energy density of normal* nuclear matter.

If we apply the above formulae to the BNL-AGS energy domain ($\cong$ 15 A GeV), we have $\gamma_{cm} \cong 2.9$, $\rho \cong 6\rho_0$, and $\varepsilon \cong 2.5$ GeV/fm^3. Namely, the density on the order of six times the nuclear matter density may be achieved.

At much higher energies, the projectile and target would penetrate through each other, and the nucleus becomes transparent (see Fig. 2). Along their passages, however, a hot baryon-free region is likely to be created due to the formation of bunched gluon strings. This region, called the central region, is ideal *for the formation of a* "hot baryon-free" region. In this case, $\rho = 0$ but the energy density would reach[2]

$$\varepsilon = \frac{1}{\pi R^2 \tau_0}\frac{dE_T}{dy} \quad \text{(Bjorken formula)}, \tag{5}$$

where R is the radius of the colliding nucleus, τ_0 is a typical hadronic scale (1-2 fm) which is related to the length L in Fig. 2 by the relationship of $L = c\tau_0 dy$ (and dy = 1 is taken in this case), and dE_T/dy is the total energy accumulated per unit rapidity which is directly related to the experimental variable of transverse energy flow E_T. In the environment of Relativistic Heavy-Ion Collider (RHIC) at which U (or Au) beams at 100 A GeV are accelerated in a collider mode, it is expected that a *clear formation* of the central region is possible. The expected total event multiplicity in a Au + Au collision is about 5000 so that dN/dy(at $y \cong 0$) $\cong$ 1200 (which is equivalent to dE_T/dy = 800-900 GeV). Using a *typical value of* τ_0 = 1-2 fm/c and R = 6.5 fm, we have ε = (3-7) GeV/fm^3. This number is close to or larger than what is needed for the phase transition from hadronic gas to quark-gluon plasma. In other words, RHIC would be the accelerator which provides an ideal situation for the study of "baryon-free" quark-gluon plasma.

Although the above baryon-free domain is the major focus among the current theorists in the field, I would like to focus in this article on the subject of the baryon-rich high-density domain, where relatively little has been *known* in the past. Clearly, the best beam energy to study this subject is the highest energy at which the colliding nuclei can still stop each other. This question is discussed in Sec. 2.

1.2 Rapidity and Psuedo Rapidity

Before describing the data, a short comment is added on the variable called rapidity (y). Rapidity is a Lorentz-invariant longitudinal "velocity" (an additive quantity under Lorentz transformation), defined by

$$y = \frac{1}{2}\ln\frac{E + p_L}{E - p_L} = \tanh^{-1}(p_L/E), \tag{6}$$

where p_L is the *longitudinal momentum parallel to the beam.* In the case of transverse momentum $p_T = 0$ and $p_L/E = \beta \ll 1$, $y \cong \beta$ (particle velocity). On the other hand, in the limit when the particle mass can be neglected, ($p, p_T \gg mc$), which *is a good approximation for pion* emission at BNL and CERN domains, the rapidity is related to the emission angle of a particle,

$$y \cong \frac{1}{2}\ln\frac{1 + \cos\theta}{1 - \cos\theta} = \ln(\tan\theta/2) \cong \eta , \tag{7}$$

since $p_L/E \cong p_L/p = \cos\theta$. Here the variable η is called the pseudo rapidity. The c.m. 90° (in the NN collision) at 14.5 A GeV/c (BNL) corresponds to $\theta_{lab} \cong 20^\circ$ and that at 200 A GeV/c (CERN) to $\theta_{lab} \cong 5.5^\circ$. *Particles are sharply peaked at both energies in particular at* CERN.

2. NUCLEAR TRANSPARENCY AND THE FORMATION OF HIGH-DENSITY MATTER

2.1 Data of Transverse and Forward Energy Flows

First, I show the data of transverse energy *flow* (E_T) *and forward* energy *flow* (E_F) measured by calorimeters at BNL and CERN. Fig. 3 shows typical data of E_T. The upper figure[3-5] is from BNL measured with 14.6 A GeV/c ^{28}Si beams on Al, Cu, Ag and Au targets and the lower

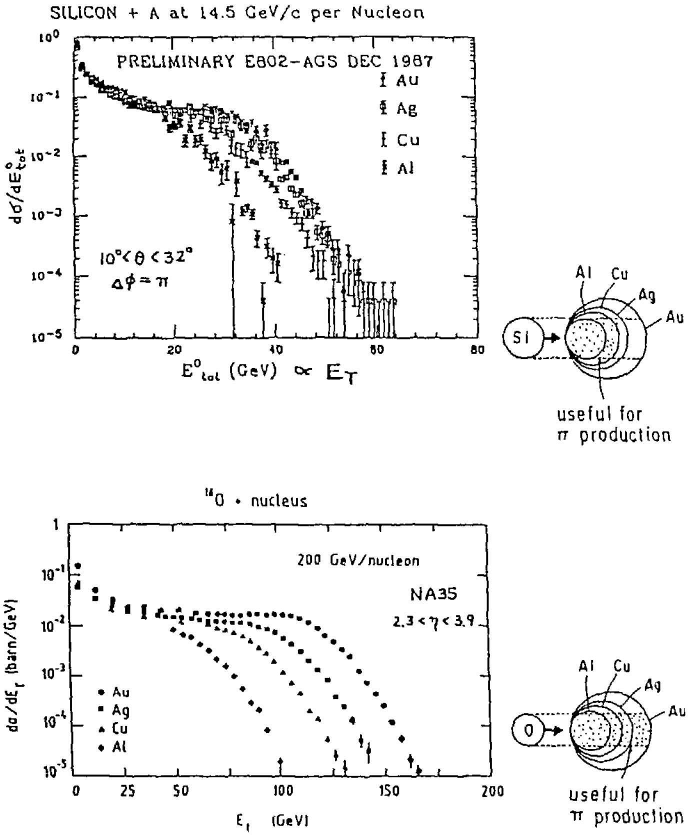

Fig. 3: *Typical transverse energy distributions in the BNL (above) and CERN (below) energy regimes.*

figure[6,7] is from CERN with 200 A GeV ^{16}O beams on the same combination of targets.

First, look at the upper figure. Data were taken in the angular range of $10^0 < \theta < 32^0$ which corresponds to ~ 1 rapidity unit in the mid-rapidity region ($-0.5 < \eta_{cm}(NN) < 0.7$) and, very crudely speaking, that corresponds to angles of $50^0 < \theta_{c.m.}(NN) < 120^0$. The Pb glass is sensitive to electromagnetic showers primarily from π^0 and, thus, the sum of the pulse heights from the Pb glass array is named E^0_{tot}. Namely, the energy flow primarily from neutral particles was detected at large c.m. angles. The maximum value of E_T does not increase with target mass after a certain mass number ($A_T \cong 100$). Naively one would expect that the thicker the matter of the target, the more energy can be deposited into the matter to induce a larger transverse energy flow E_T. In central collisions the thickness of nuclear matter increases by 40% from Cu to Au, whereas the observed increase in E_T^{max} is less than 10%. No significant increase in E_T is observed from Ag ($A_T \cong 100$) to Au ($A_T \cong 200$).

This saturation feature seems to be related to nuclear transparency. If the Cu (or Ag) nucleus is already "black" as viewed from the projectile, then, even if the target thickness (in terms of nuclear matter thickness) were increased further, the energy deposited in the matter would remain constant. This would induce the saturation feature in the E_T distribution. Here, the word "black" is used to mean that pion production is completed within the thickness of the target nuclear matter.

On the other hand, the situation is completely different in the CERN energy domain. The data shown in the lower figure, which cover the c.m. angles similar to those for the upper figure, exhibit that the maximum values of E_T increases monotonically as the target mass increases. In addition the increase in E_T^{max} is approximatly proportional to the nuclear matter thickness of the target nucleus: from Cu to Au the increase is by 40%. This fact suggests that the target nucleus is "grey" at the CERN 200 A GeV energy domain.

Note that there has been a discussion if the saturation feature observed in upper figure of Fig. 5 is due to the limited solid angle of the calorimeter. Although this possibility cannot be totally excluded, our data on pion rapidity distribution, which will be shown later (Fig. 8), suggests that it is unlikely. The rapidity distribution of pions is almost flat in the mid-rapidity region, and the Pb detectors used for the measurement of E_T are sensitive primarily to pions. Namely, the saturation feature would be seen even if the solid angle is 4π, as long as pions are detected.

Of course, E_T data alone cannot provide us with a definite conclusion on nuclear transparency. To study this subject further, we then look

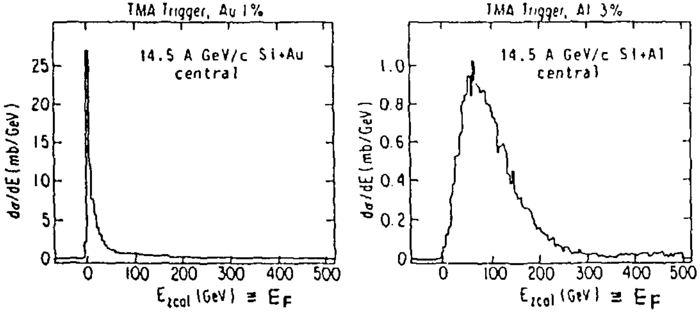

Fig. 4: Forward energy flow (E_F) measured at BNL.

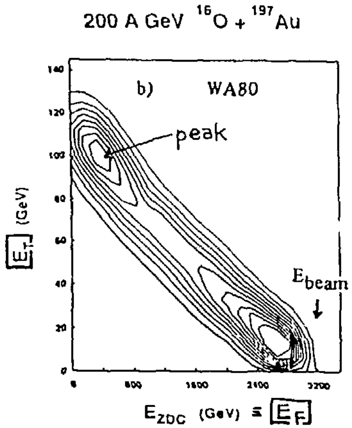

Fig. 5: Forward energy flow (E_F) measured at CERN.

at the data on the forward energy flow, E_F. Shown in Fig. 4 are the E_F spectra in the central collisions of 14.6 A GeV/c $^{28}Si + ^{197}Au, ^{27}Al$.[6] For the ^{197}Au target a sharp peak is observed at $E_F \cong 0$, implying that *no energy flows at 0 degrees, presumably due to the fact that the* ^{197}Au nucleus is "black". Recently the E814 group[8] studied the forward energy flow in more detail in 14.6 A GeV/c ^{28}Si + Pb collisions, and quantitatively found that the forward energy flow within 0.8° is on the order of 0.5% of the total energy carried by the projectile ^{28}Si. Again, this observation is consistent with the fact that the Pb nucleus is "black".

On the other hand, the data at CERN,[9] shown in Fig. 5, tells us that, even if we select high E_T (central collisions) in 200 A GeV $^{16}O + ^{197}Au$ collisions, a finite energy flow (E_F) is observed at forward angles at the level of 400 GeV which is 1/8 of the total energy carried by the ^{16}O projectile. These data again support the scenario that the nucleus is "grey" at 200 A GeV.

2.2 Nuclear Transparency and Stopping Power

As mentioned in the preceding section, the definition of "black" in the preceding section is that pion production is almost 100% completed within the matter thickness of the target nucleus. Then, how is the "transparency" related to "stopping power"? The matter thickness of the Au or Pb nucleus is equivalent to (5-6)λ_{NN}, where λ_{NN} is the mean-free path of the nucleon in normal nuclear matter. This fact *implies* that all incident nucleons experience 5-6 NN collisions if the nucleus is "grey" (partially transparent). The definition of "grey" is that, even after these NN collisions, the incident nucleon retains sufficient energy to penetrate through and, *if additional nuclear* matter exists, to experience additional inelastic NN scatterings. On the other hand, the definition of "black" is that the incident nucleon loses its entire energy after a *few* NN collisions (or, *at least before* 5-6 NN collisions). Therefore, the incident nucleon will be slowed down inside the Au nucleus, which we call "stopping". In this case, the formation of a baryon-rich high-density region can be expected, *because projectile* nucleons crush into the target matter and are confined inside it. Therefore, the nuclear transparency and stopping power is mutually correlated.

2.3 At Which Energy Does the Heavy Nucleus Turn from Black to Grey?

From the data shown in the preceding sections, we learn that the formation of high-density matter is expected in the BNL energy domain, whereas it *may not be likely to be at the* CERN 200 A GeV energy. The data further indicate that the transition energy at which the nucleus

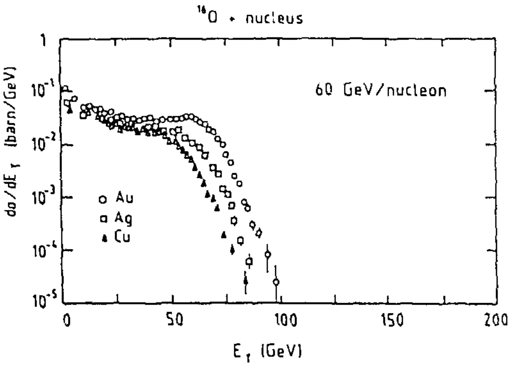

Fig. 6: Transverse energy distributions in ^{16}O + A collisions measured by NA35 group at CERN.

turns from black to grey is just in between 15 A GeV and 200 A GeV. By looking at the E_T data at 60 A GeV,[7] which shows a saturation feature in E_T against target masses (see *Fig. 6*), my guess is that the nucleus turns from black to grey at beam energies on the order of 60~100 A GeV. At these energies the values of γ_{cm} are γ_{cm} = 5-7, so that the formation of high-density matter up to ρ = (10-14)ρ_0 would be expected with heavy-ion beams. The beam energy higher than 100 A GeV does not help to form high-density matter, because the target nucleus then becomes transparent.

2.4 Current Efforts to Study Nuclear Transparency

In Sec. 2.1 the data of transverse and forward energy flows are discussed. Many other efforts are still in progress to study nuclear transparency. One key experiment is the measurement of baryon distribution. If the incident flux of nucleons is slowed down in the interior of the target nucleus, the baryon distribution must be centered at around that c.m. frame. On the other hand, if the nucleus is transparent, the baryon distribution should show two peaks, one close to the target rapidity and the other to the projectile rapidity. Unfortunately, no data on this subject have been published. Preliminary data from BNL[10] and CERN[11] suggest that a single peak-like structure in the rapidity plane is observed at BNL, whereas two broad peaks seems to be observed at CERN, which is in agreement with the above scenario. However, more careful and more convincing evidence on this point will be needed in the future.

3. IMPLICATION OF LIGHT-PARTICLE SPECTRA

Then, do we have clear experimental evidence to show the formation of high-density matter? At the present moment, the answer is "no". More research is needed to pin down this interesting question. In this section I show our recent data on *light-particle emission in heavy-ion collisions and describe an implication of the data.* Needed future research to pin down this question is described in Sec. 4.

3.1 Data of Energy Spectra

Shown in Fig. 7 are the recent data of particle spectra measured in 14.6 A GeV/c ^{28}Si + ^{197}Au collisions.[12] In particular, the central collision is interesting, so that we concentrate on the data of the top 7% of high-multiplicity events. At 14.6 A GeV/c the projectile and target rapidities are given by y_P = 3.43 and y_T = 0. The NN center-of-mass frame corresponds to y_{cm}(NN) = $y_P/2$ = 1.72, and the geometrical c.m. frame, which is defined as ^{28}Si plus the region of ^{197}Au grilled by the ^{28}Si projectile at zero impact parameter, corresponds to y_{cm}(geom) = 1.23. Note that about 80 nucleons from ^{197}Au are involved in the latter case.

Particle spectra of $\pi^{\pm}$, $K^{\pm}$, and p in the mid-rapidity region (1.2 < y < 1.4) are plotted as a function of transverse kinetic energy (T_T) which is defined by

$$T_T = m_T - m_0 = \sqrt{p_T^2 + m_0^2} - m_0, \qquad (8)$$

where m_0 is the rest mass of the observed particle and m_T is called the transverse mass. The data are fit by the following exponential shape (Boltzmann shape), as shown by solid curves in the figure,

$$\sigma_{inv} \propto m_T \cdot \exp(-m_T/T_B). \qquad (9)$$

Then, the value of T_B is 126 MeV for $\pi^{\pm}$, 160 MeV for K^+, and 187 MeV for p. For K^- the statistics are not good enough to conclude an accurate value of T_B. The observed value of T_B contains a large error (140 ± 25 MeV for K^-). The quantity T_B is called the temperature by thermodynamical theorists, because the spectrum shape from a thermalized system is given by a Boltzmann type which is expressed by the

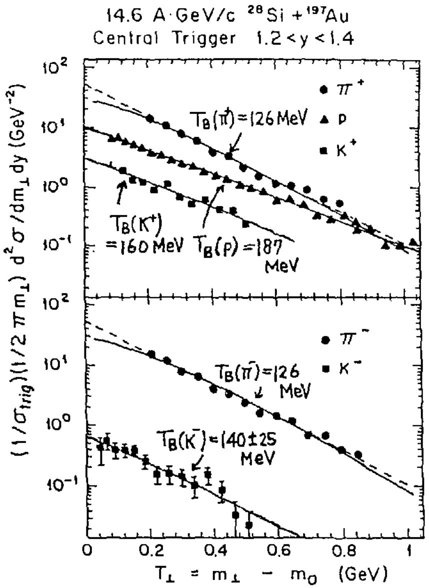

Fig. 7: Light particle spectra measured by E802 group at BNL. Data for the top 7% high-multiplicity events were selected. Spectra in the mid-rapidity region are shown.

above formula. Of course, thermalization may not take place in high-energy nuclear collisions, so that we use in the article this T_B as a simple parametrization. Clearly, however, this T_B is related to the average kinetic energy carried by product particles and, thus, indicates how nuclear matter is heated at the stage when these particles are emitted.

The data indicate that the value of T_B seems to increase progressively as the mass of the product particle increases, $T_B(\pi) < T_B(K) < T_B(p)$. This point will be discussed in Sec. 3.4.

3.2 Data of Yield Ratios

By integrating the spectrum over T_T, one can obtain the particle yield, dN/dy, in the mid-rapidity region. The values of dN/dy are plotted in Fig. 8 as a function of rapidity, y. Except for protons, dN/dy is almost constant in the mid-rapidity, at least in the region of the geometrical c.m. frame and the nucleon-nucleon c.m. frame. Relative yield ratios in this region are given by

$$\begin{aligned} N(K^+)/N(\pi^+) &\sim 20\ \% \\ N(K^-)/N(\pi^-) &\sim 4\ \% \end{aligned} \tag{10}$$

These numbers should be compared with K^+/π^+ = 3-5% (±2%) and K^-/π^- = 2-3% (±2%) for pp collisions at similar beam energies. Namely, the K^+/π^+ ratio in heavy-ion collisions seems to be enhanced at least by ~ a factor of 4 as compared to that in pp collisions, whereas there is no clear evidence that K^-/π^- is enhanced. Transverse momentum (p_T) dependences of these ratios[13] revealed that the enhancement of K^+/π^+ is more in the high-p_T region.

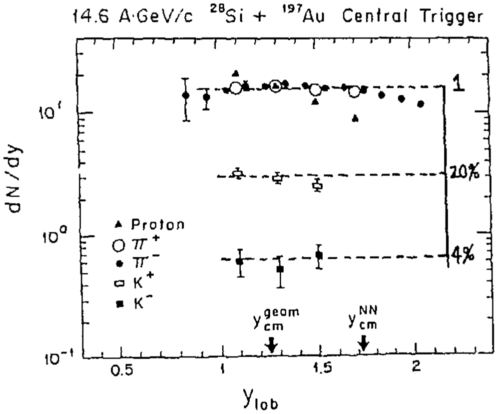

Fig. 8: Integrated yeilds, dN/dy, of the particle spectra shown in Fig. 7. Integration was done over the transverse energy.

3.3 Exotic Explanation of the Data

Theorists were intrigued by these data, in particular, the K^+/π^+ enhancement. The first suggestion, proposed two years ago, was the K^+ distillation effect in high-density nuclear matter (see Fig. 9).[14-16] If a quark-gluon plasma is created in a baryon-rich high-density region, which is more likely to be created in the BNL energy domain, then a large number of u and d quarks from valence quarks exist, while fewer u and d. If $s\bar{s}$ pairs are created there, then it is easy for $\bar{s}$ to find its partner u to create $K^+(=u\bar{s})$, whereas it is not easy for s to find its partner $\bar{u}$ to form $K^-(\bar{u}s)$. Therefore, K^+ could be enhanced but not K^-. This scenario qualitatively explains the above observations. Another scenario on K^+/π^+ enhancement in high-density hadronic matter has also been proposed.[15,16]

However, one should be very careful about the above explanation. First, we do not know from the observation alone if the K^+ is enhanced or the π^+ is suppressed. In a hadronic gas, particles like π^+, π^-, K^- might be easily absorbed by forming resonances (for example, $\pi^- NN \rightarrow \Delta N \rightarrow NN$), whereas it would be difficult for K^+ to be absorbed. This results in a large K^+/π^+ ratio. Secondly, the contribution from final-state interactions, such as $\pi^+ + n \rightarrow K^+ + \Lambda$, is not negligible, since a large number of pions are created and they can interact again with neutrons inside the Au target. These effects have to be carefully studied.

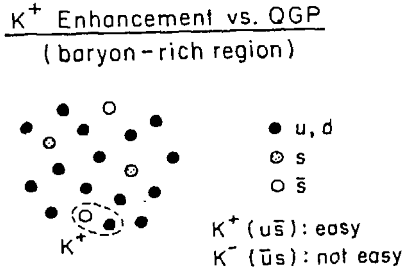

Fig. 9: An exotic explanation for K^+ enhancement.

3.4 Current Effort to Explain the K^+/π Anomaly

Currently, efforts to explain the observed anomalous enhancement of K^+/π^+ ratio are in progress from both experimental and theoretical positions. From the theoretical side an extensive calculation of the rescattering effects was done by the Frankfurt group,[17] which in fact explains the observed K/π ratio reasonably well. The problem here, however, is that the absolute value of the pion yield is overestimated by a factor of two.[18] Therefore, the entire problem of the observed anomaly is still an open question. From the experimental side, on the other hand, an extensive study for pA collisions is in progress.

In this subsection I would like to describe my personal opinion on this problem. I think that the observed K^+/π^+ enhancement and the slope difference among π, K and p are mutually related to each other. For pA collision data, I cannot show them because they are too preliminary, but the general trends seem to be as follows:

1. Concerning the slope, $T_B(\pi) \cong T_B(K) \cong T_B(p)$ for pp and pA collisions. The slope difference is observed only for the case of Si + Au collisions.
2. The K^+/π^+ ratio increases approximately by a factor of 2 from pp to pA ($A \cong 200$) collisions and another factor of 2 from pA to Si + Au collisions.
3. The absolute value of the K^+ yield in the mid-rapidity region in pA collisions ($A \cong 200$) is nearly equal to 1/28 of the K^+ yield in Si + Au collisions.

In addition, we learned that most of the conventional models overestimate the pion yield by a factor of 2 for Si + Au collisions.[18]

If all particles are emitted from a common thermal source, then the value of T_B should be independent of particle type. Even if the thermalization has not been achieved, the Lund model, which ignores all rescatterings, also predicts that the value of T_B is independent of particle type. Then, why are the observed values of T_B different in Si + Au collisions? My very tentative explanation is that in Si + Au collisions a high density region is created, which is likely to happen at the AGS energy domain as described in the previous section, and this compressed region finally explodes. If this is the case, a radially exploding flow[19,20] could induce a larger value of T_B for a heavier-mass product particle.[21] In addition, a part of the available energy carried by the projectile nucleus is used for the compression energy so that the pion multiplicity could be reduced more than that predicted by the conventional theories.[22] Therefore, the K^+/π^+ ratio increases due to the suppression of π^+ The compressional energy is then converted to kinetic energies of heavy particles like protons.

At this point I would like to remind you that the situation at the

BNL-AGS is very different from what we learned at the Bevalac. At the Bevalac energy domain we know that $T_B(\pi^+) < T_B(p) < T_B(K^+)$.[23] In Ref. 23, I pointed out that this fact is due to the difference of mean-free paths of the product particles: K^+ probes the earliest hot stage of the collision, whereas π does the latest cold stage, due to the fact that the mean free path of pions is much shorter than that of K^+. The protons, in this case, observe the intermediate stage of the collision between K and π. Since it is not feasible to create high-density matter at the Bevalac energy domain (at most $\rho \cong 3\rho_C$ according to Eq. (1)), this mechanism, due to mean-free path, would dominate among others at this energy domain. At the AGS energy domain, however, the compression and explosion can be a principal mechanism to create the slope difference among the observed particles.

Of course, the rescattering process should also take place, and this process, if it exists, should be observed already in pA collisions. My rough idea is that the observed factor of 2 enhancement from pp to pA is due to K^+ regeneration due to rescatterings, and another factor of 2 from pA to Si + Au is from pion suppression due to compression. This scenario is of course too preliminary, and Miklos Gyulassy and I are working together on this issue in a more quantitative way. However, if this preliminary scenario is correct, then the observed K^+/π^+ enhancement is an implicit reflection of the formation of high-density matter.

4. TOWARD HIGH-DENSITY NUCLEAR MATTER

4.1 K^+K^+ Interferometry

At both BNL and CERN one of the very important tasks in the future is to find probes that sample an early, hot and compressed stage of the collision, at which the most interesting phase of nuclear matter would be created. It is believed that particles with long mean free paths will probe this early stage of the collision. For example, leptons, lepton pairs, and direct photons are, therefore, the ideal tools. Among hadrons, K^+ has a relatively long mean free path so that it is also a powerful tool. In this connection, it is very intriguing to determine the source radius at which K^+'s are emitted, by the method called Hanbury-Brown/Twiss correlations (Fig. 10), because if the above scenario is correct, then K^+'s would be produced from a source with radius smaller than $\pi^\pm$'s would be.

Once the source radius of R is determined by this interferometry, then there is a hope to experimentally determine a value of the density at which K^+'s are emitted, since the density is defined by

$$\rho = m_N/V = m_N/((4/3)\pi R^3), \qquad (11)$$

where m_N is the nucleon number involved in this volume. This value can be determined from the measurement of nucleon multiplicity in coincidence with the boson interferometry. So far, all the data taken by $\pi\pi$ interferometry at the Bevalac and CERN show that $\rho < \rho_0$ when probed by pions,[23,24] presumably due to the fact that pions probe the latest and, thus, the expanded cold stage of the collision.

E802 at BNL has already observed a clean $\pi\pi$ interferometry, and this group is planning to measure K^+K^+ correlations in the near future (E859). Also, at CERN the measurements of K^+K^+ and K^-K^- interferometry are planned (NA44). It is the hope that such measurements provide a rather direct information on the density value achieved in heavy-ion collisions, if the high density matter is ever created.

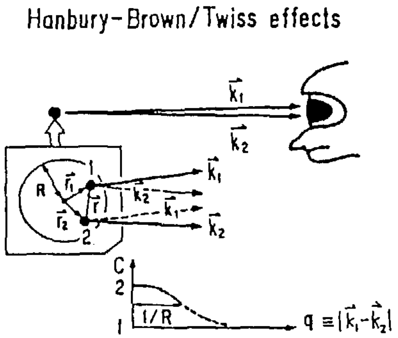

Fig. 10: Hanbury-Brown/Twiss correlations.

4.2 Strangelets

In the BNL energy domain one of the interesting features is a large K^+/π^+ ratio, as discussed in the previous section. Although the mechanism of this large ratio has not been clear, it implies that the ratio of Λ/π should also be large, because K^+ production is associated primarily with Λ production. In the central ^{28}Si + ^{197}Au collision the multiplicity (M) of Λ per event is estimated to be $M(\Lambda) \cong M(K^+) \sim 10$. These Λ's together with protons and neutrons may stick

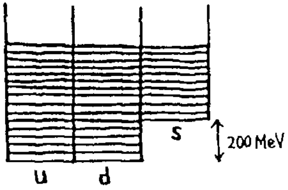

Fig. 11: Schematical illustration of strangelet formation.

together to form new matter with a rich content of strangeness, if such matter exists.

Theoretically, there is a good reason to expect the formation of strangeness-rich matter in the high-density domain, in particular, if quark matter is created.[25-27,14,15] This is called the "strangelet". Suppose that quark matter is created by u and d quarks alone. Then, the Fermi energy of the u and d quark gas is on the order of 500 MeV, which is much larger than the s-quark mass of 200 MeV. Therefore, it is cheaper for the system to include s-quarks than to retain with u and d alone (see Fig. 11). E814 at BNL has tried to measure this exotic particle.[28] So far, no positive evidence of the existence of the strangelet has been observed. However, the run was done only for two full days, so that it is premature to conclude anything definite from the past data. Anyway, it is an interesting task.

The particle Λ consists of uds quarks. The baryon number two strangelet is called H-particle. If the energy level of H-particle is below $\Lambda\Lambda$, then this H-particle is stable. So far, searches for H-particle have been carried out mainly by ^{3}He(K^-,K^+)Hn reactions using high-intensity K^- beams. Heavy-ion beams are also regarded as a powerful tool to search for this H-particle.[29] It would be a new challenge.

These new efforts are again very interesting from the viewpoint of high density matter.

3.2 Possible New Phases of High-Density Nuclear Matter

So far, theorists intuitively expect that the quark-gluon plasma would be created at density of $\rho \sim (1.8/0.8)^3 \sim 10\rho_0$, as shown in Fig. 12. This logic came from the fact that the nucleon has a radius of 0.8 fm, whereas the internucleon diatance in normal nuclear matter is 1.8 fm. However, we must admit that this is a simple guess. No serious lattice QCD calculations have so far been done for high-density matter. Reliable calculations are available only for high-temperature

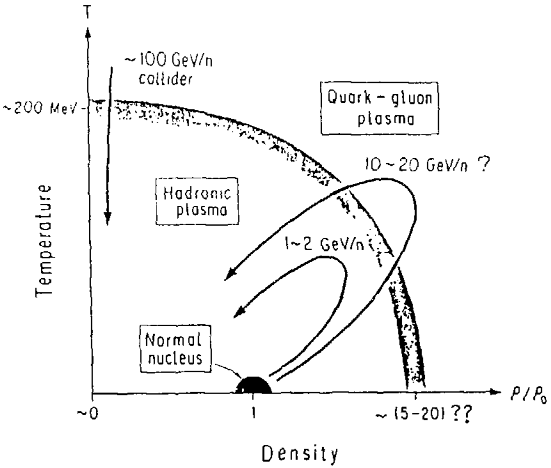

Fig. 12: Expected phase diagram of nuclear matter.

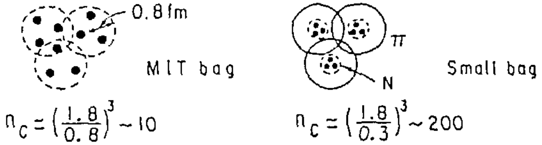

Fig. 13: Overlap of nucleons at density of $\sim 5\rho_0$, as sketched by two different models of the nucleon.

"baryon-free" region.[30] Therefore, from QCD point of view, it is fair to say that nothing is known for high-density matter.

Can we realistically expect the formation of quark-gluon plasma in the high-density domain? I do not know the answer, but I would like to point out two arguments on this subject. The first one is related to the size of the nucleon. If one looks at the form factor of the proton measured by electrons, it can also be interpreted that the proton consists of a bare proton with radius of about 0.3 fm surrounded by a pion cloud. Namely, the radius of the proton is determined by the pion cloud and not by a bare nucleon (see Fig. 13). Based on this observation, the famous chiral (small) bag model was proposed, as a modified model of the MIT (large) bag model. If we admit that the bare nucleon radius is 0.3 fm, then nucleons will lose their identity only at an extremely high density on the order of $(1.8/0.3)^3 \rho_0 \sim 200\rho_0$ to melt into a soup of quarks and gluons! This density is an order of magnitude higher than the simple guess of $10\rho_0$ described above.

The second argument is related to the coupling constant f_π. Recently, it was pointed out that the value of f_π could be smaller in the environment of nuclear matter than in the free space.[31] As the density of nuclear matter increases, we may expect $f_\pi \to 0$,[32] and the chiral symmetry might recover at a certain density. In this case, a new phase, similar to quark-gluon plasma might be expected. This density could be lower than $10\rho_0$.[33]

In any case, the physics of high density matter is still unknown theoretically. Serious QCD calculations are definitely needed. Nevertheless, from the viewpoint of experimentalists, the search for high-density matter and the study of its nature is the most challenging subject in future heavy-ion physics. We know in the universe the existence of high-density matter is neutron stars. Studying the nature of the interior structure of neutron stars is very intriguing.

So far, many theorists have also suggested interesting phases associated with high-density matter, such as strangelets, pion condensation,[34] Lee-Wick matter,[35] Δ-matter,[36] etc. None of these exotics has ever been discovered. Heavy-ion beams will be a useful tool for the study of these, also.

3.1 Facilities for the Study of High Density Matter

At this point let us consider an environment that can be created by heavy-ion collisions. As described in Sec. 2 the beam energy at which the colliding nuclei turn from black to grey is on the order of 50-100 A GeV. Let me take the number of 50 A GeV for the moment. In this case $\gamma_{cm} \cong 5.2$. Therefore, $\rho \cong 10\rho_0$ from Eq. (1). Namely, the matter density which is comparable to that observed for neutron stars

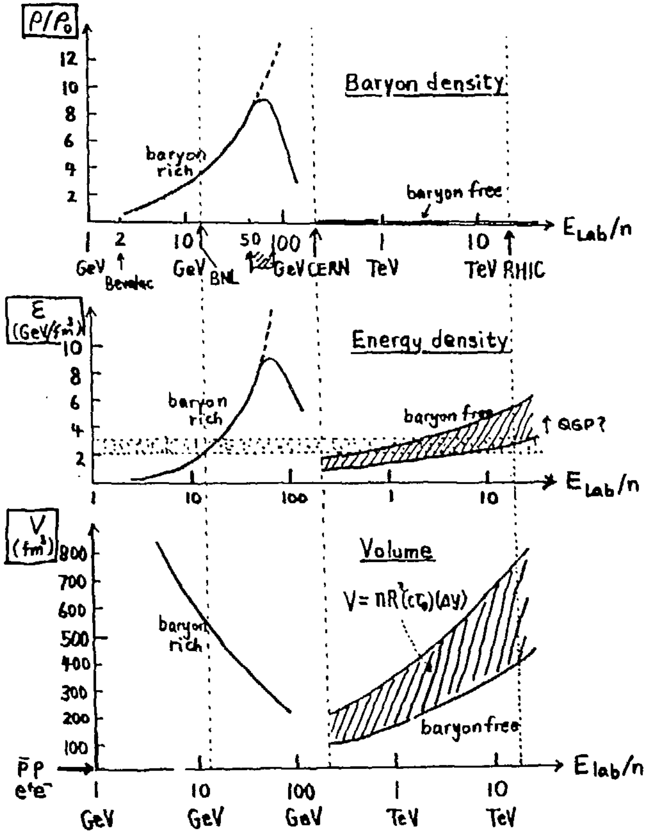

Fig. 14: Baryon density (ρ), energy density (ε) and nuclear matter volume (V), which can be attained by the nucleus-nucleus collisions. Eqs. (1)-(5) are used for the calculations.

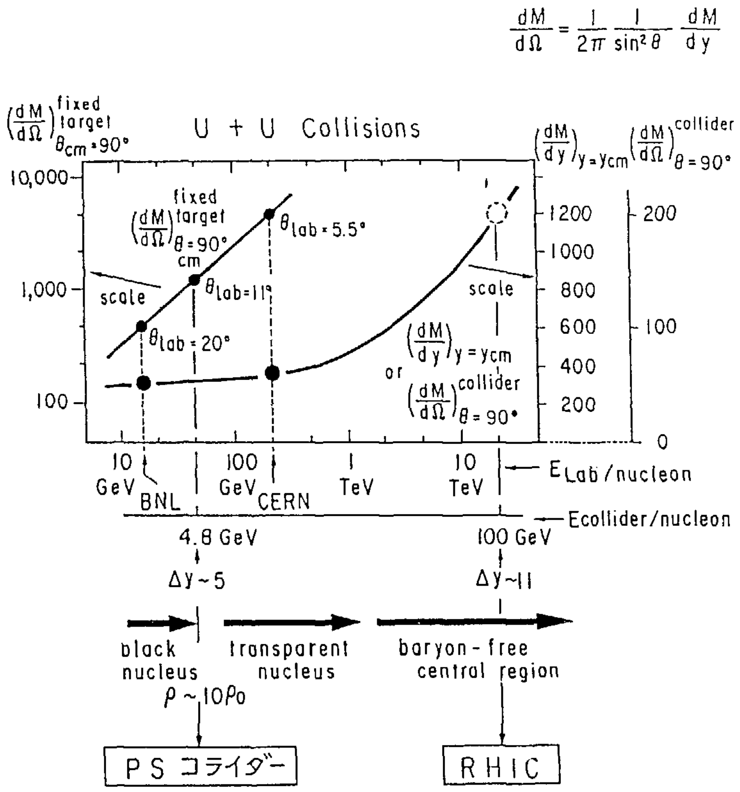

Fig. 16: Expected event multiplicities in U + U collisions at various energies.

could be achieved.

Eq. (3) further tells us that the energy density of $\varepsilon \cong 8$ GeV/fm^3 could be achieved, as shown in Fig. 14. This number is larger than the energy density expected in the baryon-free region at the accelerator RHIC (see Eq. (5) and Sec. 1.1). Since the volume involved in this collision is $V \cong$ (a few 100) fm^3 in a U + U collision, the highest energy density could be achieved over the extended volume on the order of a few 100 fm^3 by this collision at 50 A GeV [Note that e^+e^- collisions can create a much higher energy density but over a very small volume of ~ 1 fm^3.]

Toward the research of high-density matter, the available accelerators at BNL (AGS at 14.5 A GeV), together with that at CERN (SPS at 60-200 A GeV, in particular the lower end of the energy), are very useful. From this point, the future results at both BNL and CERN are extremely interesting.

Also, I point out that thoughts about creating a new colliding facility toward the research of high-density matter are informally but actively in progress in Japan. The idea there is to have a heavy-ion collider at beam energies of 5-7 GeV per nucleon at KEK, using the existing PS (Proton Synchrotron) as a heavy-ion booster and an injector into a colliding ring. I call this the "Heavy Ion PS Collider". The equivalent beam energy in the fixed target mode is about 50-90 GeV per *nucleon, and is perfectly suitable for the research of high-density* matter, if the logic described in this article is correct. The advantages there are two fold. One is that the multiplicity density in the *mid-rapidity region is much smaller (by a factor of 30) in a collider* mode than in a fixed target mode (see Fig. 15), so that the particle tracking would be much easier there. The other is that the particle *momenta in the mid-rapidity region are much smaller* (by a factor of 10) in a collider mode than in a fixed target mode, so that the particle identification is much easier, again, there. If this PS Collider were *constructed, that would be totally complementary to RHIC!!*

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