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Highly Excited Nuclear Matter*

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It is suggested that very hot and dense nuclear matter may be formed in a transient state in "head-on" collisions of very energetic heavy ions with medium and heavy nuclei. A study of the particles emitted in these collisions should give clues as to the nature of dense hot nuclear matter. Some simple models regarding the effects of meson and N^* production on the properties of dense hot nuclear matter are discussed.

I. INTRODUCTION

Heavy cosmic-ray particles impinging on nitrogen nuclei in the atmosphere have produced characteristic patterns. These patterns are the result of small momentum exchange between the collision partners accompanied by an excitation of both partners. The originally stationary partner disintegrates and forms a more or less isotropic star. The moving partner would form a similar star in its rest system which, however, appears in the lab as a narrow forward-directed jet. It is indeed highly plausible that collisions of this kind should be the most prevalent ones. Full-body collisions with big momentum exchange are less probable and could be studied with cosmic rays only to a limited extent.

The Bevalac, producing nuclei with 2 GeV per nucleon,[1] could be used to study the rare phenomena of strong momentum exchange. The ideal situation would be to shoot a fully accelerated uranium atom on another uranium atom where roughly half the energy would be available in the center-of-mass system. This would provide several hundred MeV per nucleon in the center-of-mass system. In general, for the collision of two identical nuclei the energy per baryon, ϵ, in the center-of-mass system will be

$$\epsilon = Mc^2(1 + E/2Mc^2)^{1/2}, \tag{1}$$

where E is the lab kinetic energy per nucleon of the incident nucleus and M is the nucleon rest mass. In the near future, the uranium-on-uranium collision is out of the question. However, argon on argon may be quite feasible, and experiments of argon on uranium are also quite interesting. In the latter case we have the advantage of bigger cross sections than for argon on argon, but somewhat lesser energy per nucleon.

In the case of two equal nuclei the resulting picture which we expect to hold is that three regions may develop: a segment of the target nucleus which is not directly in the path of the projectile and which is left behind producing the customary star, a segment of the moving nucleus which does not overlap the target nucleus and which produces the customary forward jet, and finally an overlapping segment which is at rest in the center-of-mass system and which forms hotter material producing a slower and more strongly diverging jet. The most interesting collisions would be restricted to the few percent of the cases where this third phenomenon predominates and where the strong forward jet, as well as the star, is weak. In this case the products emitted by the very hot nuclear matter produced in the full collision could be most easily studied. A measure of the probability of "bull's-eye" collisions (angular momentum = 0) is J_{max}^{-2}. For argon on argon at 2 GeV per incident nucleon this would be on the order of 10^{-6}. However, an actual angular momentum $\frac{1}{10}J_{max}$ already gives a reasonable approximation to the simple limiting case and has a probability of 0.01.

At present it is not possible to predict how this interesting hot nuclear matter will behave. One might assume, naively, that the two nuclear materials simply interpenetrate to produce a density twice normal nuclear density. As the mean free path of a nucleon in nuclear material is approximately 2 F, comparable to the radius of argon, this guess may not be terribly far off the mark. Nevertheless, by the time the interpenetration has occurred in a medium nucleus one can count on a considerable amount of momentum exchange and disorder and also on the production of a number of mesons comparable to the number of nucleons. For light nuclei the momentum exchange is apt to be incomplete.

For head-on collisions of heavier nuclei the mean free path is considerably shorter than the distance to be traversed. In that case a shock wave may develop that could lead to densities higher than twice the usual nuclear density.

The nucleon-nucleon collisions (approximately 40 mb cross section) are dominated by single-pion production (approximately 20 mb cross section) and double-pion production (approximately 10 mb cross section). In Sec. II we show that there indeed seems to be a good opportunity to approach something like thermodynamic equilibrium for the nucleons and mesons, even though the time available for the whole phenomenon will be less than 10^{-22} sec. Estimates made under a variety of conditions concerning the interaction between the particles lead to temperatures on the order of 100 MeV.

The study of head-on collisions leading to the formation of a shock wave might give some information on the compressibility of dense nuclear matter. This in turn might be useful for making estimates of the compressibility of dense neutron matter, which is of considerable interest because of its bearing on the maximum mass of neutron stars.[2,3] The properties of dense hot nuclear matter are also important for understanding popular models of the early universe.[4-6] Section III discusses the production of dense nuclear matter in heavy-ion collisions.

II. MESON PRODUCTION

To discuss the properties of matter in our hot nuclei it is necessary to take into account the production of mesons. The cross section for meson production at energies of interest is on the order of 30 mb. Taking the density of nucleons to be twice nuclear density, this leads to an equilibration time, for exciting meson degrees of freedom, of $\approx 6\times 10^{-24}$ sec. On the other hand the time available for meson production is the disassembly time of our hot compound nucleus. In the "hydrodynamic" approximation this is equal to $0.2R/c_s$, where R is the radius of the compound nucleus and c_s is the speed of sound (the factor 0.2 simply reflects the fact that for a uniform-density sphere half the mass lies within $0.2R$ of the surface). Taking the speed of sound to be that in an ideal gas of nucleons and mesons ($\approx\frac{1}{2}c$ at a temperature of 140 MeV) and assuming that the compound nucleus results from the coalescence of two nuclei of atomic number A we find that the disassembly time exceeds the equilibration time if

$$A^{1/3} \gtrsim 4 .$$

Therefore, collisions of medium and heavy nuclei can lead to compound states in which equilibrium with respect to meson emission and absorption may be established. In cosmic rays where nuclei of $A \leqslant 8$ predominate the conditions of equilibrium are not likely to be fulfilled.

The presence of meson degrees of freedom will lead to higher specific heats and lower equilibrium temperatures than would be obtained if there was no meson production. The most elementary way to represent the meson degrees of freedom would be to use an ideal gas of pions. Then the number density n_π and energy density e_π of the pions would be given by

$$n_\pi = 3\left(\frac{h}{\mu c}\right)^{-3}\int_0^\infty \frac{4\pi\eta^2 d\eta}{\exp[z(\eta^2+1)^{1/2}]-1}\,,$$
$$e_\pi = 3\left(\frac{h}{\mu c}\right)^{-3}\mu c^2\int_0^\infty \frac{4\pi(\eta^2+1)^{1/2}\eta^2 d\eta}{\exp[z(\eta^2+1)^{1/2}]-1}\,, \qquad (2)$$

where μ is the pion mass, θ is the temperature in MeV, $z = \mu c^2/\theta$, and η is the meson momentum is units of μc. The integrals appearing in Eq. (2) may be evaluated in terms of modified Bessel functions.[7] If we assume that the nucleon density is twice normal nuclear density and $E = 2$ GeV/nucleon then we obtain $\theta = 146$ MeV and $n_\pi = 0.11$ F^{-3}. In the collision of two argon nuclei about 27 mesons would be produced.

The ideal-gas model for the meson degrees of freedom greatly oversimplifies the real situation because the pions will constantly be interacting with nucleons and with each other. Mesons not bound to nucleons will feel a "potential" due to a meson-nucleon interaction. For pions of low energy this potential is known to be small due to cancellations between different isospin states. At higher energies the potential is somewhat uncertain, but we do not expect that it would be large enough to substantially affect the number of free pions. Even if one assumed that the pion mass were zero, corresponding to a strongly attractive potential, the density of free pions calculated from Eq. (2) would be increased by only $\approx 25\%$ for $E = 2$ GeV/nucleon.

Besides π mesons there is also the possibility that heavier mesons such as the η and ρ will be present. The numbers of these mesons can be estimated from Eq. (2) by replacing the pion mass by the heavier meson mass and by multiplying by the appropriate statistical weight. For example, at a temperature $\theta = 146$ MeV one finds that ρ mesons with a mass of 765 MeV and statistical weight of 9 would be about 30% as numerous as pions.

One of the most serious errors in the free-meson model arises from the fact that pions can be bound to nucleons to form resonant states. In the energy range of interest the scattering is dominated by the formation of the $\Delta(1236)$ pion-nucleon resonant state. Indeed, for energies near the center of the resonance the mean free path of a pion at twice normal nuclear density will be so short that the pion will be spending 90% of its time "resonating" with nucleons. Thus as a first approximation one might treat hot nuclear matter as a gas of N's and other baryon resonances, hereafter called N^*'s.

As a simple example suppose that the hot nucleus consists of a mixture of nucleons in their ground state and nucleons in the $\Delta(1236)$ state. (Note that for $E = 2$ GeV per incident nucleon a sizable fraction of a free-pion gas would have energies inside the 120-MeV width of this state.) The $\Delta(1236)$ has $J = \frac{3}{2}$, $I = \frac{3}{2}$ and so has a statistical weight of 16. The population of the $\Delta(1236)$ state relative to the nucleon ground state will be $4e^{-\Delta/\theta}$, where $\Delta = M_\Delta c^2 - Mc^2$. For $E = 2$ GeV/nucleon we find that $\theta \simeq 160$ MeV and that 40% of the baryons exist in the $\Delta(1236)$ state. For the case of argon on argon the disintegration of these would lead to 32 mesons, which one may compare with the 27 mesons obtained from the free-meson model. Thus the two exceedingly crude estimates given lead to comparable numbers of mesons.

Of course, at these temperatures one should also take into account the higher-mass resonant states: $N(1470)$, $N(1520)$, $N(1535)$, etc. If we neglect the interaction of the N's and N^*'s then the thermodynamic properties of such a gas will be determined by the mass spectrum of these "states."

What will be the effect of higher resonances? Models of the strong interactions based on the "bootstrap" idea lead to a density of states that increases exponentially with mass. This results from the fact that each new resonant state can combine with particles of lower or equal mass to make more resonant states.[8] In particular, the statistical bootstrap model leads to a density of states of the form[9,10]

$$N(m) = Cm^{-3}e^{m/\theta_0}\,, \tag{3}$$

where θ_0, the "maximum temperature" of hadron matter, is about 174 MeV as determined from high-energy scattering experiments.[5] The parameters C and θ_0 will depend somewhat on whether or not strange particles are included in the mass spectrum. In the situation we are considering we do not in fact expect that equilibrium with respect to strange-particle production would be reached. However, the resulting uncertainty in θ_0 is probably smaller than the present experimental error in θ_0. If we assume that the mass spectrum of the N^* states has the form given in Eq. (3) the average energy of a baryon will be given by

$$\epsilon = \tfrac{3}{2}\theta + Mc^2\frac{E_2(x)}{E_3(x)}\,, \tag{4}$$

where $x = (Mc^2/\theta)(1 - \theta/\theta_0)$ and E_2, E_3 are the exponential integral functions. In Eq. (4) we have used the nonrelativistic approximation for kinetic energy, which is sufficient for our purposes. For θ not too close to θ_0 Eq. (4) can be approximated as

$$\epsilon \simeq Mc^2 + \tfrac{3}{2}\theta + \frac{\theta\theta_0}{\theta_0 - \theta}\,. \tag{4$'$}$$

By equating the expression for the average energy of a baryon as given in Eq. (4) to the initial center-of-mass energy of the nucleons we can find how the temperature of an ideal gas of N's and N^*'s varies with the lab kinetic energy of the incident nucleus. This is shown in Fig. 1 along with the temperature for an ideal gas of just nucleons (dashed curve). Neglecting interactions between particles, the actual temperatures will lie between these curves. In the next section we shall consider the effects of interactions between the particles.

III. PRODUCTION OF DENSE MATTER

Let us consider the head-on collision of two heavy nuclei. It is the folklore of kinetic theory that approximately three collisions suffice to form a strong shock wave.[11] A nucleon going through uranium at these energies will, on the average, have five collisions. Hence, it is not implausible that *some* of the material in the colliding nuclei will be shocked in head-on collisions. Clearly, the shocked volume will not be the entire nucleus, but the volume of shocked material will increase with the size of the projectiles. The compression in a relativistic shock wave, defined as the ratio of proper densities, is given by[12]

$$n/n_0 = \gamma(1+\beta^2 e/P)\,, \tag{5}$$

where $c\beta$ is the velocity of the incident nucleus as seen from the shocked material, $\gamma \equiv (1-\beta^2)^{-1/2}$, e is the proper energy density, and P is the pressure of the hot compressed nuclear matter. It should be noted that the shocked nuclear matter is at rest in the center-of-mass system, so that $\gamma = (1+E/2Mc^2)^{1/2}$. Since $e = n\epsilon$ where ϵ is energy per baryon in the center-of-mass system, Eq. (5) can be written in the form

$$n/n_0 = (1+E/2Mc^2)^{1/2} + nE/2P\,. \tag{6}$$

For a nondegenerate ideal gas of baryons $P = n\theta$,

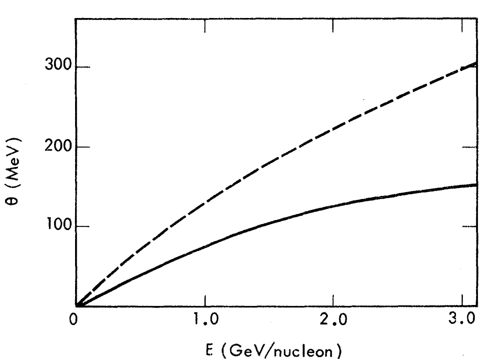

FIG. 1. Nuclear temperature resulting from the head-on collision of a nucleus with laboratory kinetic energy per nucleon E with an identical stationary nucleus. The dashed curve assumes that the hot nuclear matter can be described as an ideal gas of nucleons. The solid curve is for an ideal gas of N's and N^*'s where the N^* mass spectrum has the form given by Eq. (3).

where θ is the temperature, so that Eq. (6) becomes

$$n/n_0 = (1+E/2Mc^2)^{1/2} + E/2\theta\,. \tag{7}$$

Using the temperature for an ideal gas of nucleons (dashed curve in Fig. 1) Eq. (7) predicts a shock compression of ≈ 5 for $E = 2$ GeV/nucleon. In the absence of repulsive interactions even greater compressions would occur due to rapid equilibration with respect to meson degrees of freedom. For example, using the temperature for an ideal gas of N's and N^*'s (solid curve in Fig. 1), we obtain a compression of ≈ 9 for $E = 2$ GeV/nucleon. However, it is not realistic to neglect the interactions between nucleons at densities much higher than normal nuclear density. Also, at small values of the temperature Eq. (7) must be modified to take into account the fact that nucleons obey Fermi statistics.

We can estimate at what densities the Pauli principle and nucleon-nucleon forces must be taken into account from the compressibility of cold nuclear matter. Theoretical calculations[13] of the compression modulus at normal nuclear density give

$$n_0^2\left(\frac{\partial^2\epsilon}{\partial n^2}\right)_0 \simeq 15 \text{ MeV}\,. \tag{8}$$

Thus we see that the incompressibility of nuclear matter would not be important at twice normal density (simple interpenetration) but almost certainly will be important at higher densities. It turns out that the Pauli principle and nucleon-nucleon forces contribute about equally to the compressibility modulus at normal nuclear density. At densities much higher than normal nuclear density the incompressibility of nuclear matter probably results mainly from nucleon-nucleon forces rather than the Pauli principle,[14] but is rather uncertain due to the fact that the short-range interaction of nucleons is not well understood. In any case the nucleon-nucleon forces, which make nuclear matter more incompressible as the density is increased, will counteract the effects of meson and N^* production which tend to make nuclear matter more compressible.

In Fig. 2 we show what compression would be produced in nuclear matter by a shock wave for three different model equations of state. Curve (a) corresponds to an ideal gas of N's and N^*'s, assuming that the mass spectrum for N^*'s has the form given in Eq. (3). Curve (b) is for an ideal gas of nucleons. Curve (c) corresponds to the equation of state $P = e - nMc^2$. This is a reasonable approximation to the equation of state at high densities in the limit of extreme incompressibility when the speed of sound in nuclear matter is near the speed of light,[15] i.e., $\partial P/\partial e \simeq 1$. The actual compression of nuclear matter will presumably lie somewhere between curves (a) and (c).

Figure 2 shows that different assumptions regarding the equation of state of compressed nuclear matter can lead to quite different densities in the shocked state. Thus different equations of state of nuclear matter could be experimentally distinguished if one could infer the density of the shocked nuclear matter. One possibility which we shall consider would be to measure the number of pions produced. In one extreme [curve (a)] a great deal of the initial energy goes into producing N^*'s which decay into pions and nucleons. In the other extreme [curve (c)] most of the initial energy goes into work against the nucleon-nucleon repulsion. Thus the number of pions present in the compressed state should be greatest for case (a) and least for case (c).

In order to discuss how the number of pions varies with shock compression, let us assume

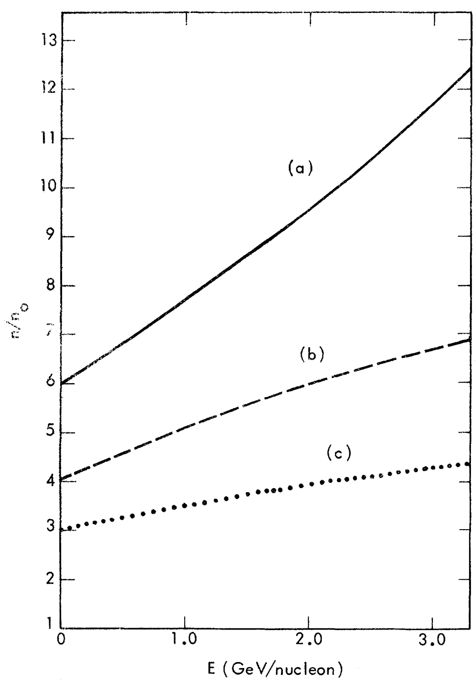

FIG. 2. Nuclear shock compression that would result from the head-on collision of a heavy nucleus with laboratory kinetic energy per nucleon E with an identical stationary nucleus. Curve (a) assumes that the compressed nuclear matter can be described as an ideal gas of N's and N^*'s. Curve (b) assumes that the compressed nuclear matter can be described as an ideal gas of nucleons alone. Curve (c) assumes that the pressure of compressed nuclear matter is given by $P = e - nMc^2$.

that all pions are bound to nucleons and that the interactions of the N's and N^*'s are all the same. Then the energy per baryon has the form

$$\epsilon = \epsilon_{\text{int}} + \tfrac{3}{2}\theta + \overline{m}c^2 , \tag{9}$$

where $\overline{m}(\theta) = ME_2(x)/E_3(x)$ and ϵ_{int} is independent of θ. For fixed ϵ the excitation energy, $(\overline{m}-M)c^2$, will decrease as ϵ_{int} increases. In order to relate the excitation $[\overline{m}(\theta) - M]c^2$ to the density of shocked nuclear matter a relation between ϵ_{int} and the pressure is needed. According to the virial theorem the pressure will be given by

$$P = n\theta - \tfrac{1}{6}n^2 \int_0^\infty r \frac{d\phi}{dr} g(r) 4\pi r^2 dr , \tag{10}$$

where ϕ is the internucleon potential and $g(r)$ is the pair correlation function. (We are using the nonrelativistic virial theorem since $\theta \ll Mc^2$.) If we integrate the second term by parts we obtain

$$P = n\theta + \tfrac{1}{2}n^2 \int_0^\infty \phi g(r) 4\pi r^2 dr + \tfrac{1}{6}n^2 \int_0^\infty r\phi g'(r) 4\pi r^2 dr . \tag{11}$$

The second term is just $n\epsilon_{\text{int}}$. Let us assume that the potential is positive and repulsive, i.e., $\partial\phi/\partial r < 0$. Since $g'(r)$ will then be positive when ϕ is large, the third term will be positive. Therefore, we have

$$P \geqslant n\theta + n\epsilon_{\text{int}} . \tag{12}$$

The equality will approximately hold when the potential is "soft", i.e., the logarithmic derivative of $g(r)$ is small. Using (12) together with Eq. (6) we obtain the inequality

$$\frac{n}{n_0} \leqslant \left(1 + \frac{E}{2Mc^2}\right)^{1/2} + \frac{E}{2(\theta + \epsilon_{\text{int}})} . \tag{13}$$

For a fixed value of E this gives the maximum shock compression as a function of ϵ_{int}. The range of possible shock compressions is shown in Fig. 3 for the case $E = 2$ GeV/nucleon. The figure is plotted so that the ordinate is the excitation energy $(\overline{m}-M)c^2$ measured in units of the pion mass. The allowed values for the compression n/n_0 and excitation energy $(\overline{m}-M)c^2$ are indicated by the shaded region. Figure 3 suggests that if few pions are produced, the shock compression will probably be near its minimum value $(2\gamma + 1)$. If many pions are produced the shock compression may be large or small depending on whether the baryon-baryon repulsion is "soft" (solid line) or "hard" (dashed line).

The number and energy distribution of the particles emerging from head-on collisions may be quite different from the distributions in the compressed state. As the hot nuclear matter expands equilibrium will be maintained until a density is reached where the equilibration time is longer than the expansion time. Thereafter the number and energy distributions of the particles will be approximately frozen. These energy distributions reflect the radial hydrodynamic expansion as well as the thermal motion. Measurement of the energy distributions in the center-of-mass system should give information on the frozen temperatures of the particles (it should be kept in mind that different species of particles may have different frozen temperatures).

As the matter expands adiabatically from the compressed state the variation of temperature with volume is determined by the ratio P/c_v, where c_v is the specific heat at constant volume. Thus in the case of a large interaction energy where P is large and c_v is small the temperature will drop rapidly, leading to a low frozen temperature. If interaction energy is small then c_v will be large because of meson production, and the frozen temperatures will not differ so greatly from the temperature in the compressed state. Thus experimental measurement of the frozen temperatures may shed some light on the strength of short-range baryon-baryon interactions and whether the short-range repulsion is "soft" or "hard."

We assumed in the model just discussed that all the pions that are present are bound to nucleons to form N^* particles and that interactions of

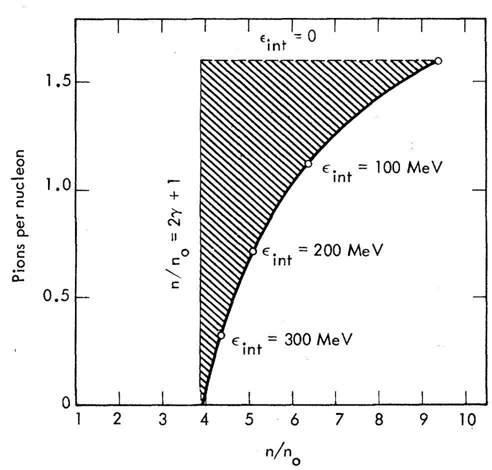

FIG. 3. Number of pions per nucleon in compressed state as a function of the shock compression. It is assumed that the compression nuclear matter can be represented as a gas of N's and N^*'s and that N's and N^*'s all have identical interactions. The solid line corresponds to a very "soft" repulsive interaction and the dashed line corresponds to a "hard-sphere" impulsive interaction. We have chosen $E = 2$ GeV/nucleon.

all baryons are the same. But it may happen that the N^* states disappear as the density is increased due to the effect of greater repulsive potentials for the N^*'s. Several of the most prominent pion-nucleon resonant state, e.g., $\Delta(1236)$, appear to have about 1 F radius.[16] Thus when the separation between baryons becomes much smaller than it is in normal nuclei (1.8 F) the proliferation of resonant states with increasing energy may be destroyed.

If it turns out that N^* particles can exist at high densities, then the N^* particles abundantly formed in shocked nuclear matter might have a tendency to form "N^* nuclei"[17] containing dense cores of N's and N^*'s. For example, the Δ-nucleus analog of the α particle would have a baryon density approximately five times normal density (if the size of the Δ permitted, one could place 16 Δ's and 4 N's into a given orbit).

We have heretofore discussed only the production of π mesons (or their resonant states) and how their number and spectrum might be informative as to the properties of dense shocked matter. Because strange particles are not copiously produced (relative to π's) they will give only a minor correction to the calculation of density and temperature. However, because of strangeness conservation in strong interactions, whatever K mesons are produced will escape. Now if the chance of producing a K in a nucleon-nucleon collision at these energies is 1%, the number of K mesons may very well be a sensitive measure of the number of nucleon-nucleon collisions. If the colliding nuclei pass through each other without forming a shock wave then the number of strange particles produced will be modest and has been previously calculated.[18] However, if an equilibrium situation is produced the number of collisions will be considerably increased, perhaps by a factor of 3, and many more K mesons will be produced and emitted. Hence, although strange particles will not be major constitutents of the hot nuclear matter that may be produced, they may very well be a useful diagnostic tool. These considerations will be modified if π-π collisions lead to a significant number of K mesons.

IV. CONCLUSIONS

Head-on collisions between energetic heavy nuclei should lead to multiple-prong stars at rest in the center-of-mass system, in contrast with the more frequent peripheral collisions. The result of the experiment would be the observation of the disintegration products, namely nucleons, mesons, and strange particles. It might be quite difficult to figure out what actually has happened. However, examination of the number and spectrum of pions and strange particles should shed light on a variety of questions, including the compressibility of nuclear matter, N^*-N interactions, and perhaps the hadron mass spectrum.

What seems to us exciting is the production of matter in a new regime of temperature and density. In particular, temperatures may be attained which are not far below the "maximum temperature" of matter. In addition it may be possible to produce nuclear densities in the laboratory which are of astrophysical interest.

Since the experiment which we are discussing explores regions very far from our experience, it is reasonable to expect surprises. This expectation is in fact one of the strong motivations for performing the experiment. The somewhat detailed discussion of the number of mesons produced, of the energy distribution, and of the creation of strange particles will probably correspond to the bulk of the experimental results. It may well be necessary to account for all of these details before arriving at what may be the main result of the experiment: the unexpected phenomena.

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