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Space Station as Quark Matter Factory

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Space Station as Quark Matter Factory

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Abstract:

We review the theoretical arguments indicating that hadronic matter dissolves into a quark gluon plasma at energy densities only one order of magnitude above the energy density in nuclei and point out that such energy densities can be achieved in nuclear collisions at 10 - 1000 AGev.

1. Introduction

In this talk I review the theoretical evidence suggesting that a new form of matter, called the quark gluon plasma, could be created during collisions of very high energy cosmic rays with nuclei. The novel reaction that I will consider is

$$\mathrm{Fe}(\sim 1\mathrm{erg/A}) + \text{Space Station} \rightarrow \text{Quark Matter} + X \quad . \tag{1}$$

Whether those nuclei are part of an emulsion stack put up there by hopeful earthbound physicists or part of the hull or part of an astronaut's brain, when a Fe nucleus with energies on the order of a few ergs per nucleon (ATev) strikes, quark matter is likely to be produced. As I will show the theoretical evidence for the existence of this primordial matter is strong. Futhermore, the production of that matter seems to require only one order of magnitude increase of the energy density over that in normal nuclei. The evidence is so strong that the nuclear science community will construct a relativistic nuclear collider (RNC) to study this stuff in the laboratory. However, it is obvious that cosmological accelerators will always have an edge on earthbound facilities since they provide beams (albeit with low luminocity) up to the limiting energies $E \sim 10^{20}$ eV. Thus cosmic ray studies at the space station offer the possibility to preview unexplored energy domains and look for new forms of matter.

For the purposes of this talk, I will consider the energy domain $\lesssim 10$ ATev, that may become accessible to earthbound experiments within a decade. I will point out that there exists two complementary energy domains: (1) the stopping domain $E \lesssim 100$ AGev and (2) the scaling domain with $E \gtrsim 1$ ATev. In the first domain we can expect to produce high baryon density plasmas with $\rho \approx 10\rho_0$ and energy densities $\epsilon \gtrsim 10\epsilon_0$. Recall that $\rho_0 \approx 0.15\mathrm{fm}^{-3}$ is the saturation density of nuclei and $\epsilon_0 \approx m_N\rho_0 \approx 0.15\mathrm{Gev/fm}^3$ is the ground state energy density. In the second domain, energy densities $\gtrsim 10\epsilon_0$ are reached at much lower baryon densities due to an enourmous multiplicity of produced pions. Current cosmic ray studies (see talk of Miyamura) are providing important tests on the validity of these theoretical conjectures.

2. Quark Matter

High energy experiments suggest that Quantum Chromodynamics (QCD) is the correct theory of strong interactions. The novel implications of that theory for the properties of matter at very high densities have recently been clarified[1]. The major theoretical advance that has made it possible to deduce fairly rigorous conseqences of QCD is large scale Monte Carlo calculations on space time lattices[2] [3]. In this section, I review the calculations that point to the existence of a phase transition of hadronic matter to a quark gluon plasma.

Let us start from hadron phenomenology and ask if there is there anything peculiar to make us suspect that hadronic matter may exist in only a small corner of the temperature and baryon density plane. As is well known, the density of hadronic states increases exponentially with the mass scale[4], $\rho_H(m) \propto e^{m/T_c}$. This so called Hagedorn spectrum leads to a partition function, $Z = \mathrm{tr} e^{-\beta H}$, that becomes singular at a critical temperature $T_c \approx m_\pi$. However, in terms of energy density, that singularity occurs only for $\epsilon \rightarrow \infty$. Therefore, that singularity should be of no practical concern. However, when the finite extension of hadrons is taken into account[5], that singularity moves to finite energy density. Assuming that the volume occupied by a hadron increases linearly with its mass, $V(m) = m/4B$ where $B \approx .2$ Gev/fm^3, it was found that not only is Z still singular at $T = T_c$, but that singularity occurs at finite $\epsilon = 4B \approx 1$Gev/fm^3. Therefore, we can anticipate that something drastic is going to happen in hadronic matter when the energy density reaches that critical value.

The same conclusion is reached also in the context of the MIT bag model of hadrons. In that model quarks are confined to finite volumes by the vacuum pressure B. Inside those bags the quarks and gluons move freely in a perturbative QCD vacuum. Each hadron occupies a volume with $V^{-1} = \rho_H \approx 3\rho_0$. So long as the density of hadrons is less than ρ_H, the relevant degrees of freedom are hadronic. However, for $\rho > \rho_H$ the bags overlap and the relevant degrees of freedom are those of quark and gluons. Therefore, in this model the critical energy density is $m_H \rho_H \sim 0.5$Gev/fm^3.

Now, let us consider matter from the point of view of QCD. A unique feature of QCD is the property of asymptotic freedom. Because of vacuum polarization, the coupling constant $\alpha_S = 4\pi/((11 - 2N_f/3)\log(q^2/\Lambda^2))$ depends on the distance scale, q^{-1}. For the observed number of flavors $N_f = 6$, the coupling becomes weaker and weaker at distance scales smaller than the QCD scale $\Lambda^{-1} \sim 1$ fm. At high temperatures the only distance scale is $q^{-1} \sim T^{-1}$, which obviously decreases with T. Similarly, at high baryon densities the relevant distance scales vanish as μ^{-1} with increasing chemical potential. Thus, at high temperatures and/or high baryon densities the QCD coupling vanishes. With small α_S, the energy density assumes the simple Stefan-Boltzmann form

$$\epsilon(T, \mu) = aT^4 + bT^2\mu^2 + c\mu^4 \ , \tag{2}$$

where the coefficients depend only on the number of colors and flavors in the plasma[1]. Corrections to Eq.(2) appear to order α_S. What perturbation theory shows is that the properties of hadronic matter at high T or μ are extremely simple and different than we would expect from nuclear theory. The primordial matter is essentially a noninteracting ideal gas of quarks and gluons. Moreover, perturbation theory[6] shows that this simple state of affairs should change drastically at $T \sim \Lambda \lesssim 200$ Mev because the coupling constant becomes large. If we estimate[6] the phase transition point at which the quark gluon plasma transforms into hadronic matter by requiring the perturbative corrections to be on the order of unity, then $\epsilon \sim 1\text{Gev/fm}^3$ again emerges as the critical energy.

The most rigorous evidence for the existence of a deconfining transition from hadronic to quark matter comes from lattice QCD calculations[2] [3]. In terms of the QCD action , the partition function is expressed in path integral form as a sum over all possible gluon and quark field configurations weighted be the exponential of minus the Euclidean action. This integral is evaluated by approximating the continuum space-time by a periodic lattice of typical dimension $N_t N_s^3$, with $N_t \approx 4, N_s \approx 10$. Typically this leads to a 10^4 dimensional integral that is evaluated with Monte Carlo techniques using only a few hundred hours of Cray time.

Fig.(1) shows the results of the lattest calculations[3] that include light dynamical quarks. The dimensionless ratio ϵ/T^4 is shown in part (a) as a function of temperature in lattice units. To convert into physical units, another physical quantity, such as the string tension or the nucleon mass, must be calculated in the same lattice units. At this time only the ratio of the transition temperature to the lattice unit Λ_L is known with some confidence. Rough estimates of the string tension indicate that $\Lambda_L \sim 2^{\pm 1}$ Mev. Therefore, the critical temperature is $T_c \sim 200$ Mev, as expected on the basis of the qualitative arguments noted before. The most important point to emphasize is that lattice theory predicts a strong first order transition. The precise value of T_c in Mev will be determined in the near future as additional physical quantities will be measured on the lattice. The nature of the QCD transition is revealed in part (b) of Fig.(1). The curve labeled WL shows the expectation value of the Wilson line[1]. The simplest interpretation of that quantity is that $\langle WL \rangle = e^{-F_q/T}$, where F_q is the free energy of a static isolated quark placed into the plasma. Note that $WL \to 0$ at $T = T_c$ as the plasma is cooled from above. This is the evidence that it costs an infinite amount of energy to place an isolated color charge into matter below a critical energy density $\propto T_c^4$. Therefore, quarks and gluons must be confined below a critical energy density $\sim 1\text{Gev/fm}^3$. Futhermore, the curve labeled $\langle \bar{\psi}\psi \rangle$ shows that the confinement transition is also associated with the breaking of chiral symmetry.

3.Stopping Domain and Baryon Rich Plasmas

Next we point out that this interesting energy density domain is accessible with cosmic ray collisions at energies 10 - 100 AGev. At Bevalac energies $\lesssim 2$ AGev heavy nuclei stop each other[7] in their center of mass. Obviously, the maximum energy density accessible depends on the stopping power of nuclei. New data on p + A at 100 Gev[8] indicates that the maximum stopping energy is between 10 and

100 AGev. Recent analysis[9][10] of that data indicates that the energy loss per unit length of a baryon in nuclear matter is given by

$$dE/dx = -E/\Lambda_p \tag{3}$$

where $\Lambda_p = 8 \pm 2$ fm is the momentum degradation length. The thickness of nuclear matter required to reduce the incident rapidity, y_0, of a baryon by one half is therefore

$$L^* = \Lambda_p(y_0/2 - \delta y) \ . \tag{4}$$

In Eq.(4), $\delta y = \log(m^*/m_N) \approx 0.4$ takes into account the effective mass of the baryon[10]. This implies that two nuclei with thickness $2R$ can stop each other (in the center of mass frame) only up to laboratory energies

$$E_{max} \approx \frac{m^*}{2} e^{4R/\Lambda_p} \lesssim 30 \pm 15 \text{AGev} \ . \tag{5}$$

An independent way to estimate this maximum energy is to note that Lorentz time dilation implies that the interaction region increases linearly with energy[11]. For a fractional energy loss x, the longitudinal distance scale involved is thus[10]

$$\ell = xE_0/\sigma \ , \tag{6}$$

where $\sigma \approx 1$ Gev/fm is the empirical string tension. We expect that $x \sim 1/4$ - $1/2$ as the typical fractional energy loss. The maximum energy for stopping is therefore determined by $\ell = 2R$. Remarkably, this condition also gives $E_{max} \sim 30-60$ AGev.

Simple kinematic considerations[12] provide a lower bound on the baryon and energy densities that can be attained in the stopping domain. Using Eq.(5), we obtain therefore $\rho \gtrsim 2\gamma_{cm}\rho_0 \sim 10\rho_0$ and $\epsilon \gtrsim 2\gamma_{cm}^2\epsilon_0 \sim 40\epsilon_0$. In fact if shock waves are generated, then densities twice as large could be achieved[13]. Therefore, we see that energy densities well beyond the critical one can be achieved in the stopping domain. The unique feature of this domain is that in addition to high energy densities high baryon densities are achieved as well. Thus, cosmic ray studies in this energy range offer the possibility of exploration of high baryon density plasmas.

4.Scaling Domain and Low Baryon Density Plasmas

We turn finally to cosmic ray collisions in the multi ATev domain. From the previous section it is clear that at such energies nuclei are transparent to each other. The rapidity of the baryons can be shifted on the average by only 2.5 units[8]-[10] after traversing the diameter of the heaviest nuclei, and therefore if the incident rapidity gap is ~ 9, then in the central 4 units of rapidity the baryon density is small. There is, however, a large density of hadrons[14] in the central region. We will now estimate the energy densities achieved as a function of the rapidity density dN/dy.

The main simplification comes from the approximate constancy of dN/dy at high energies. That constancy implies[15] that the physics is approximately boost invariant along the beam axis. That means that quantities such as the energy density $\epsilon(z,t,x_\perp)$ can in fact only depend on the proper time variable $\tau = \sqrt{(t^2-z^2)}$ and $x_\perp$. In that case there is no energy dependence of the local dynamics. In this so called scaling domain, the conservation law $\partial_\mu T^{\mu\nu} = 0$ for the energy momentum flux assumes the simple form[16]

$$\frac{d\epsilon}{d\tau} + \frac{\epsilon + p}{\tau} = \frac{\frac{4}{3}\eta + \xi}{\tau^2} \ , \tag{7}$$

where $p = c_0^2\epsilon$ is the pressure and η, ξ are transport coefficients estimated in Ref.[16]. Only in the scaling domain do the complex Navier Stokes equations reduce to Eq.(7). In order to estimate the initial energy density as a function of final rapidity density, we note[17] next that

$$dN/dy = A_\perp \tau_f \sigma(\tau_f)/4 \tag{8}$$

where $\sigma(\tau)$ is the entropy density, $A_\perp$ is the transverse area of the beam, and τ_f is the freeze out time after which the system expands freely ($\tau\epsilon$ = constant). For an ideal quark gluon plasma $\sigma \propto \epsilon^{3/4}$. The simplest way to understand Eq.(8) is to note that in the scaling domain the volume element δV associated with a group of particles with rapidities between y and $y + \delta y$ is just $A_\perp \tau \delta y$. Thus, the particle density at the freeze out time is $\rho(\tau_f) = \delta N/\delta V$. Since the entropy per particle of relativistic particles is 4, Eq.(8) follows.

The final step is to use $d\epsilon = T d\sigma$ and $\sigma = (\epsilon + p)/T$ to show that[16]

$$\tau_f \sigma(\tau_f) = \tau_0 \sigma(\tau_0) + \int_{\tau_0}^{\tau_f} \frac{d\tau}{\tau} \frac{\frac{4}{3}\eta + \xi}{T(\tau)} = \tau_0 \sigma(\tau_0) \left(1 + \frac{b}{2K} \frac{1}{\tau_0 T_0}\right) \ , \tag{9}$$

where $b = (\frac{4}{3}\eta + \xi)/T^3 \gtrsim 2 - 4$ is the estimated magnitude of the transport coefficients, and $K \approx 12$ is the Stefan Boltzmann constant for the plasma. Eqs.(8,9) provide the relation between the final rapidity density and the initial entropy density. The equation of state of course relates the entropy density to the energy density $\epsilon(T)$ and the pressure $p(T)$ as a function of temperature. We used Bag model equations of state[17] and the above relations in Ref.[16] to obtain the numerical estimates shown in Fig.2. Our main conclusion is that for rapidity densities $dN/dy \gtrsim 300$ as seen in the famous Si+Ag JACEE event[14], initial energy densities well in excess of an order of magnitude above normal nuclear densities are achieved relatively independent of the large uncertainties in the equation of state and transport coeffecients. Therefore, the quark gluon plasma seems indeed within reach of cosmic ray collisions. The plasma formed in such high energy collisions differs from that produced in the stopping domain mainly in that the baryon densities are low. Therefore, the two domain complement each other and offer insights into different parts of the uncharted high ρ and T plane.

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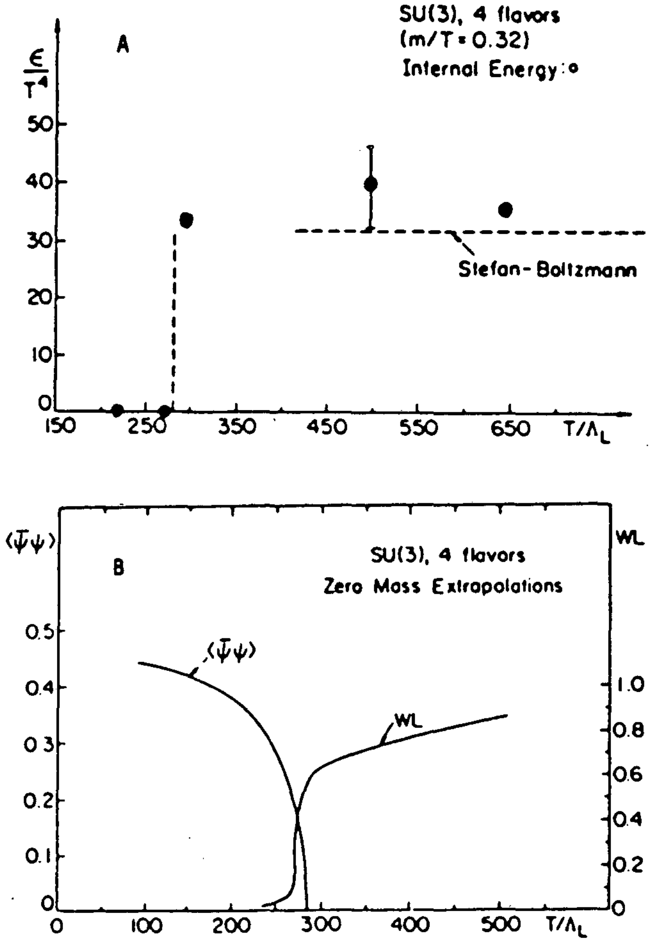

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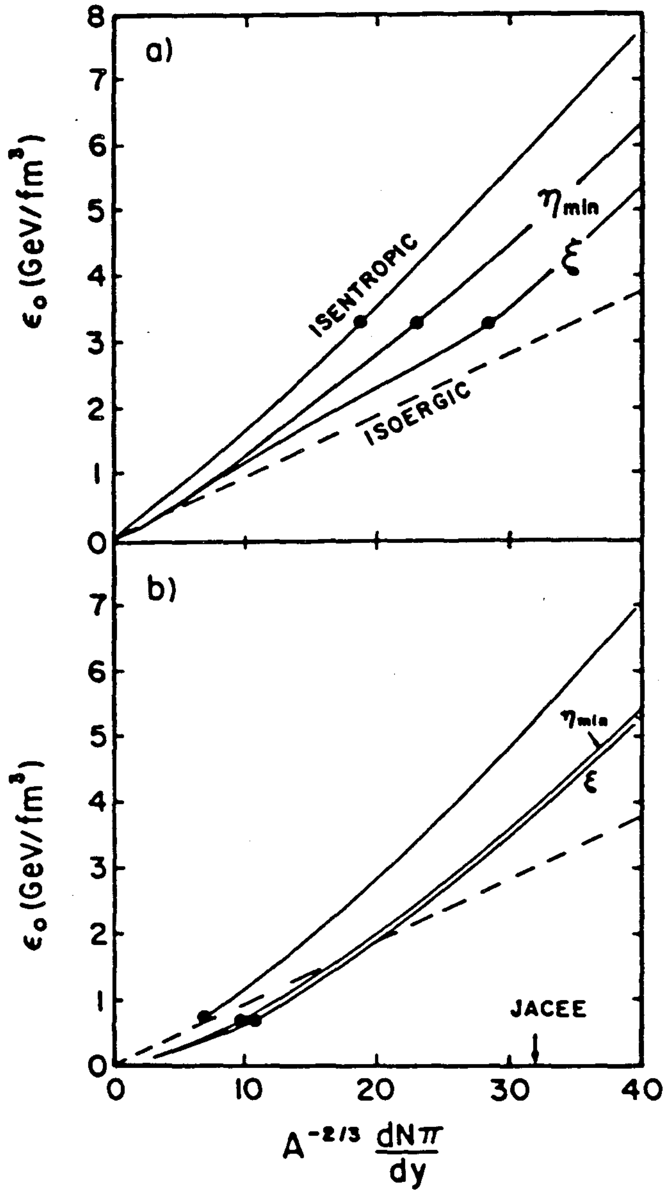
Figure Captions:

1. Results of lattice QCD calculations[3] showing the evidence for a first order transition from hadronic matter to a quark gluon plasma at a temperature ~ 200 Mev.



2. Estimates of the initial energy density as a function of final rapidity density reduced by the geometrical factor $A^{-2/3}$ based on scaling Navier Stokes theory[16] for a variety of reasonable equations of state and transport coefficients.

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