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THEORETICAL PERSPECTIVES ON RHIC PHYSICS

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We discuss the status of the relativistic heavy ion collider (RHIC) project at Brookhaven, and assess some key experiments which propose to detect the signatures of a transient quark-gluon plasma (QGP) phase in such collisions

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We discuss the status of the relativistic heavy ion collider (RHIC) project at Brookhaven, and assess some key experiments which propose to detect the signatures of a transient quark-gluon plasma (QGP) phase in such collisions

1. Introduction

The scientific objective of the relativistic heavy ion collider (RHIC) is to create and explore the properties of exceptional states of nuclear matter under extreme conditions of density ρ and temperature T. In quantum chromodynamics (QCD), the underlying theory of strongly interacting quarks and gluons, one expects to find a transition between an interacting hadron gas phase and a quark-gluon-plasma (QGP) phase. In the QGP phase, the quarks and gluons, normally confined in hadrons, are free to migrate over an extended nuclear volume. The main focus of RHIC physics will be on the search for signatures of QGP formation. Since the QGP, if it can be produced at all, is a transient phase with a very short lifetime, the question of obtaining a clear signature of its formation is a difficult one. Since only SU(3) color singlet hadrons are known to arrive in detectors, one must demonstrate that the dynamically complicated rehadronization process does not wash out the signatures of QGP formation. It is unlikely that a single experimental signature will be sufficient to conclusively demonstrate the existence of QGP, as opposed to a dense hadron gas in thermal and chemical equilibrium. One will have to correlate information from a variety of experimental sources, and understand the inner workings of non-perturbative QCD in much greater depth, in order to present a convincing case for QGP formation. On both the experimental and theoretical sides, this task is very challenging, but therein lies much of its appeal! It is already clear from the first round of relativistic heavy ion experiments at Brookhaven and at CERN that such collisions, in the central regime, result in the formation of dense matter. Estimates based on the Bjorken formula give energy densities in excess of 1 GeV/fm^3 at CERN energies (200 GeV/A), and extrapolations to RHIC give 3–4 GeV/fm^3, which should suffice for QGP formation. RHIC offers a unique possibility to recreate, in the laboratory, conditions which prevailed in the early universe, i.e., the first 10^{-5} – 10^{-6} sec after the Big Bang. The study of such high density matter will yield information on the nuclear equation of state, which is crucial for the description of the dynamics of supernovae.

2. The RHIC Project at Brookhaven

The conceptual design and technical aspects of the RHIC facility are discussed in detail in Ref. 1. There have also been several workshops[2–4], in which a variety of possible experiments and detectors for RHIC have been proposed. Here we outline only the main features of the machine.

RHIC will consist of two intersecting superconducting storage rings to be constructed in a 3.8 km tunnel (already existing from the earlier ISABELLE proton-proton collider project). There are six intersection regions, four of which are planned to be used in the first complement of heavy ion experiments. The energy per beam is variable, from 30 – 100 GeV/A for gold beams. Ion beams from protons to gold can be accelerated, with an average luminosity of 2×10^{26} cm^{-2} sec^{-1} for gold and 1.4×10^{31} for protons. The beam lifetime is about 10 hours.

The RHIC project is due to start construction in FY 1991, with a six year funding profile. If this schedule is maintained, physics experiments could commence in 1997.

3. Theoretical Perspectives

Relativistic heavy ion collisions in the central regime are characterized by the formation of dense, hot hadronic matter, or with some luck, a zone of quark-gluon plasma. The multiplicity of particles emitted is large: for central Au + Au collisions at RHIC energies, we expect several thousand pions to be produced. In the collision debris, we also expect to find antibaryons ($\bar{p}$, $\bar{\Lambda}$, $\bar{\Xi}$, etc.), hadrons containing heavy quarks (J/ψ and D mesons with charmed quarks[5] and objects with b quarks[6]), and possibily antinuclei $\overline{A}$ and multiply strange clusters ("strangelets", H dibaryons, etc.). Heavy ion encounters offer unique possibilities for fabricating such rare composite objects, particularly those incorporating multiple units of strangeness ($|S| \geq 3$, for instance). We return later to a discussion of such strange clusters.

Relativistic heavy ion collisions are characterized by several time scales τ relevant for a discussion of the space-time evolution of the system. For the example of Au + Au collisions at 100 GeV/A, the time $R/\gamma \approx 0.1$ fm/c is needed for the two Lorentz-contracted nuclear disks to pass by each other. Here the energy density is momentarily huge, but most of the constituents interpenetrate without hard collisions. A mixing time of order 0.3 – 1 fm/c is required for the scattering probability of co-moving quarks and gluons to become substantial; times of order 0.3 fm/c were predicted[7] on the basis of perturbative gluon-gluon scattering, while 1 fm/c represents the more common Bjorken assumption. This mixing interval corresponds to the formation of energy densities of order 3 – 10 GeV/fm^3, sufficient in principle to create QGP. Already at times of order 2 – 4 fm/c, we enter a mixed phase. In the case of a first order phase transition, the system is a mixture of quark/gluon and hadron phases in the usual sense. In the absence of a first order transition, which may well be the case[8], the situation is less clear; in this case, the number of degrees of freedom still increases rapidly with energy density, whereas the temperature probably changes very little. Finally, at a breakup time of order 30 fm/c, the hadrons (mostly pions) decouple; here typical conditions correspond to an energy density of 0.03 GeV/fm^3 and temperature $T \approx 120$ MeV. This is the "pion liquid" stage discussed extensively by Shuryak[9].

Many possible *signatures* for QGP formation have been proposed. It is not possible to discuss these in any detail here; instead, we refer the reader to a number of recent conference proceedings[10-12] and review articles[13] for a complete exposé. A list of key topics includes collective flow, strangeness enhancement, J/ψ suppression, thermal lepton pairs, direct photon production, particle interferometry, multiparticle correlations and energy flow, and high transverse momentum jets. Rather than repeating the motivations for studying these various probes of dense matter, I will focus on one particular topic, namely the possibility of producing stable multiply-strange clusters.

4. Considerations on Stable Strange Clusters

The most widely discussed candidate for a stable six quark system is the doubly strange H dibaryon[14], a $J^\pi = 0^+$, $I = 0$ particle of SU(3) flavor singlet character. The production rate of the H in heavy ion collisions has been estimated by several different methods,[15,16] and appears to be accessible even at the 15 GeV/A fixed target program at the Brookhaven AGS. If the H exists, it could also form bound states with other H particles or with a nuclear core.[17,18] For instance, a simple case of an "H-nucleus" would be $H + d$, which would have a favorable charge to mass ratio $0.22 \leq Z/A \leq 0.25$ below that for ordinary nuclear fragments. If their weak decay lifetime is sufficiently long (≥ 1 ns or so in the rest frame), it is practical to detect them even in the high multiplicity environment of a heavy ion collision.

In the SU(3) chiral soliton (Skyrme) model, there are predictions[19-21] of a variety of light clusters with multiple strangeness, which could be stable with respect to strong and possible even mesonic weak decays. The dibaryon spectrum of the soliton model is quite distinct from that of the six quark bag model; for instance, an $I = 2$, strangeness $S = -2$ dibaryon, which couples to $\Sigma^-\Sigma^-$, is bound in the soliton model and unbound in the bag picture. These predictions are very speculative, but sufficiently dramatic to warrant an experimental test.

In conventional meson exchange models, the long (π) and medium (σ) range forces are not sufficiently strong to produce bound states like $\Sigma^-\Sigma^-$ or $\Sigma^-\Sigma^-n$, for instance. Thus if such objects exist, they will not be "quasimolecular" states close to a hadronic threshold, but rather deeply bound states which rely on short range effects for their existence. They are likely to be formed at the early, dense matter stage of a heavy ion collision, rather than by a coalescence process at a late stage of the dynamical evolution, as the weakly bound deuteron, for instance.

Table 1: Maximum Energy Release Q for Weak Decay Modes of Bound Multistrange Dibaryons

Decay Process	Q (MeV)
$(\Sigma^-\Sigma^-) \rightarrow \Sigma^- n\pi^-, \Sigma^- n e^- \bar{\nu}$	118, 257
$(\Sigma^-\Xi^-) \rightarrow \Sigma^-\Sigma^-$	124
$(\Xi^-\Xi^-) \rightarrow \Xi^-\Sigma^-, \Xi^-\Lambda\pi^-$	124, 66
$(\Xi^-\Omega^-) \rightarrow \Xi^-\Xi^-, \Xi\Xi\pi$	351,212
$(\Omega^-\Omega^-) \rightarrow \Omega^-\Xi^-, \Omega^-\Xi\pi, \Omega^-\Lambda K^-$	351, 218, 63

Once formed, a tightly bound strange cluster is not likely to be dissociated by encounters with co-moving particles in an expanding fireball.

To see that $\Sigma^-\Sigma^-$, $\Sigma^-\Sigma^- n$ and other combinations of Σ^-'s and neutrons are unbound in conventional exchange models, consider the long range attractive potential V_c from single pion exchange and the second order pion tensor potential V_T. We have

$$\frac{V_c\,(\Sigma^-\Sigma^-,\, {}^1\mathrm{S}_0,\, I=2)}{V_c\,(pp,\, {}^1\mathrm{S}_0,\, I=1)} \approx \left(\frac{g_{\Sigma\Sigma\pi}}{g_{NN\pi}}\right)^2 \left(\frac{M_N}{M_\Sigma}\right)^2 \approx 0.6 \tag{1}$$

since $g_{\Sigma\Sigma\pi} = 2\alpha_p\, g_{NN\pi} \approx g_{NN\pi}$ for an F/D ratio $\alpha_{ps} \approx 1/2$ in SU(3). The tensor part is proportional to $(\tau_1 \cdot \tau_2)^2$ and hence

$$\frac{V_T\,(\Sigma^- n,\, {}^3\mathrm{S}_1 \rightarrow {}^3\mathrm{D}_1 \rightarrow {}^3\mathrm{S}_1,\, I=3/2)}{V_T\,(pn,\, {}^3\mathrm{S}_1 \rightarrow {}^3\mathrm{D}_1 \rightarrow {}^3\mathrm{S}_1,\, I=0)} \approx \frac{1}{9} \tag{2}$$

Thus V_T, which plays an important rôle in binding the deuteron, is largely suppressed by the isospin factor in the $\Sigma^- n$ case. Similarly, systems with Ξ^-'s and neutrons will not be bound by long range pion exchange forces, since $g_{\Xi\Xi\pi} = (2\alpha_{ps} - 1) g_{NN\pi} \ll g_{NN\pi}$.

Some of the possible multistrange dibaryon states in the SU(3) soliton model are listed in Table 1, together with the energy release Q for weak decay processes for systems bound at the strong decay threshold. The binding energies of these configurations are quite model dependent, but could be as large as 20% of the rest mass in the Skyrme model.[20,21] As one can note from Table 1, a binding energy of 5% is already sufficient to stabilize the $\Sigma^-\Sigma^-$ state against mesonic weak decay. This would leave only the leptonic weak mode, which presumably corresponds to a lifetime of order 10^{-8} sec or longer. Such long-lived negatively charged objects would be detectable in AGS or RHIC experiments.

5. Production of Exotic Strange Objects at RHIC

Let us suppose that QGP has been formed in a RHIC collision. Among the decay products of the QGP, we might expect to find light multi-strange stable fragments of the type described in Section 4, if they are indeed bound. Heavier "strangelets" are difficult to form in central collisions from a baryon-poor plasma; here one should investigate the production of strange objects in more peripheral RHIC collisions (with detection in the forward region). Although (K^-, π^-), (K^-, K^+) and other hadronic reactions may be used to generate one or two hyperons, relativistic heavy ion collisions represent the optimum way of producing systems with multiple units of strangeness.

Qualitatively, we expect that the production of strange clusters (assumed stable) such as H, Hd, $\Sigma^-\Sigma^-$, $\Sigma^-\Sigma^-n$ should be enhanced if a QGP is formed. This has been demonstrated recently[22] in the context of a sequential fission model for the QGP rehadronization process. This approach has been used by Arvay *et al.*[23] to estimate baryon, antibaryon and K/π meson yields. One starts with a QGP in thermal and chemical equilibrium at temperature T and baryon chemical potential μ_B. It is assumed that the plasma expands and cools to the phase boundary. The rehadronization process is viewed as a sequence of random binary fissions, in which quarks are plucked out of the plasma one by one, and assigned to a left (L) or right (R) bag according to a probability distribution

$$\begin{aligned} P_L &= (1 - x_L)/2 \\ x_L &= \hat{Q} \cdot \vec{L}/|\vec{L}| \end{aligned} \tag{3}$$

Here $\hat{Q}$ and $\vec{L}$ are the color vectors of the quark and left-hand bag, respectively. The presence of the factor x_L mitigates against the buildup of large color fluctuations on either bag. Nevertheless, after distribution of the quarks, the daughter bags are usually not in color singlet states. Color neutralization is achieved through the production of additional non-strange and strange (with a suppression factor of 0.2) quark pairs. The Q or $\overline{Q}$ is then directed to the left bag to decrease the net color. The production of $Q\overline{Q}$ pairs ensures that the entropy does not decrease during the hadronization process, as occurs in naive quark recombination models. A Monte Carlo algorithm is used to generate different binary fission chains and calculate statistical averages for the various cluster abundances.

The binary fission approach to QGP rehadronization has been applied[22] to calculate the relative production rates of light matter and antimatter clusters with baryon number $B = \pm 2, \pm 3, \pm 4$. For each color singlet cluster $Q^n s^m$ with n non-strange and m strange quarks, we apply a spin-isospin weight to project out the component with the desired spin-isospin quantum numbers $\{J, T\}$. Typical predictions for QGP hadronization with $T = 154$ MeV, $\mu_B = 300$ MeV, are

$$\begin{aligned} N\left(\Sigma^-\Sigma^-n\right)/N\left({}^3\mathrm{He}\right) &\approx 0.9 \\ N\left(Hd\right)/N\left({}^4\mathrm{He}\right) &\approx 8.6 \\ N\left(HH\right)/N\left({}^4\mathrm{He}\right) &\approx 0.6 \end{aligned} \tag{4}$$

for the production of $\Sigma^-\Sigma^- n$ ($J = 1/2$, $I = 5/2$), $Hd(J = 1, I = 0)$ and $HH(J = 0, I = 0)$ bound states. The large relative production of Hd relative to ^{4}He is due to a favorable ratio 189/22 of spin-isospin weights. For the above $B = 3, 4$ systems, the number N of strange and non-strange objects is seen to be of the same order of magnitude. This represents a considerable enhancement of the strange clusters with respect to the yield from a thermalized hadron gas; in the latter case, one expects a penalty factor typically of order 0.1 for the production of each unit of strangeness. The situation for the H/d ratio is similar. Note that the $\overline{H}/H$ ratio approaches unity as $\mu_B \to 0$; for $T = 158$ MeV, $\mu_B = 100$ MeV, for instance, we have $N(\overline{H})/N(H) \approx 0.4$.

The binary fission model for QGP hadronization was tested by computing $\overline{\Lambda}/\Lambda$ and $\overline{\Xi}/\Xi$ ratios, recently measured in the NA35 and WA85 experiments[24]. We obtain

$$
\begin{aligned}
N\left(\overline{\Lambda}\right)/N\left(\Lambda\right) &\approx 0.17 \\
N\left(\overline{\Xi}\right)/N\left(\Xi\right) &\approx 0.33
\end{aligned}
\tag{5}
$$

for $T = 158$ MeV, $\mu_B = 100$ MeV, close to the observed values 1/4 and 0.4 respectively.

6. Concluding Remarks

If a QGP is formed at RHIC, light multi-strange clusters, if they are stable, should be produced with abundances comparable to that of the non-strange cluster (d, ^{3}He, ^{4}He) of the same baryon number. If systems like $\Sigma^-\Sigma^-$, $\Sigma^-\Sigma^- n$ or Hd are indeed stable, and their weak decay lifetimes are sufficiently long, they can be detected as fragments of anomalous charge/mass ratio. Neutral strange clusters can be observed through dissociation processes like $Hp \to \Lambda\Lambda p \to 3p + 2\pi^-$. In the central regime at RHIC, small clusters of strange antimatter $\overline{S}$ should be formed with measurable rates. These could be detected through the annihilation process $\overline{S}A \to nK + X$ on a nuclear target A. The signature would be a burst of K^+ or K^0 mesons emerging from a target far from the production vertex of $\overline{S}$.

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