RELATIVISTIC HEAVY ION COLLISIONS

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I. Two Puzzles

At present, most physicists feel that we have finally arrived at a closed system of physical laws, with QCD for the strong interaction and a unifying gauge theory for the weak and electromagnetic forces, plus of course Einstein's theory of general relativity. However, there are a few things that are not completely satisfactory. Of the participating fundamental particles, only the leptons and the photon have been observed directly. The intermediate bosons and the graviton, we hope, can be detected in the near future. All the rest, the quarks and the gluon, we believe can never come out in the open and that therefore direct observation will always be impossible.

In view of this, our strong belief in this grand scheme must not be due entirely to direct experimental evidence, but rather be based on the esthetic simplicity of the theoretical foundation and the compelling conclusion of our mathematical deduction.

1. Missing symmetry

The basis of all these theories rests entirely on the symmetry[1] under local transformations with respect to either the internal gauge variables or the space-time variables. Yet, in reality, almost all the symmetry quantum numbers are found to be, or believed to be, not conserved. Even the best-established conservation law, that of the baryon number, is now also believed to be violated. Surely, this is somewhat puzzling.

2. Color confinement

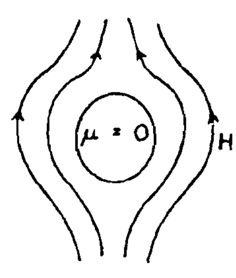
Another puzzle is the problem of quark or color confinement, which makes half of the elementary particles, quarks and gluons, non-direct observables. The explanation of both puzzles is to invoke the properties of the vacuum.

In the first case of the missing symmetry we require the vacuum, though Lorentz invariant, to be a coherent mixture of states of different quantum numbers. Therefore the vacuum expectation value of any quantum-number-carrying spin-0 field ϕ can be different from zero:

$$\langle \phi \rangle_{vac} \neq 0 \ . \tag{1}$$

In the second case, color confinement, we assume the QCD vacuum to be a condensed state of gluon pairs so that it is a perfect color dia-electric (i.e., color dielectric constant $\kappa = 0$). This is in complete analogy to the description of a superconductor as a condensed state of electron pairs in the BCS theory, which results in making the superconductor a perfect dia-magnet (with magnetic susceptibility $\mu = 0$). When we switch from QED to QCD we replace the magnetic field $\vec{H}$ by the color electric field $\vec{E}$, the superconductor by the QCD vacuum, and the QED vacuum by the interior of the hadron. As shown in Figure 1, the inside by the outside and the outside by the inside. Just as the magnetic field is expelled outward from the superconductor, the color electric field is pushed into the hadron by the QCD vacuum, and that leads to color confinement. This situation can be summarized as follows:

QED Superconductivity as a Perfect Diamagnet		QCD Vacuum as a Perfect Color Dielectric
$\vec{H}$	$\longleftrightarrow$	$\vec{E}$
$\mu_{inside} = 0$	$\longleftrightarrow$	$\kappa_{vacuum} = 0$
$\mu_{vacuum} = 1$	$\longleftrightarrow$	$\kappa_{inside} = 1$
inside	$\longleftrightarrow$	outside
outside	$\longleftrightarrow$	inside



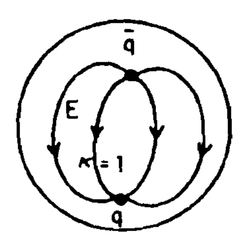


Figure 1. Superconductivity in QED vs. quark confinement in QCD.

II. Microscopic vs. Macroscopic World

In both of the above cases the system of elementary particles no longer forms a self-contained unit. The microscopic particle physics depends on the coherent properties of the macroscopic world, represented by these operator averages in the physical vacuum state.

If we pause and think about it, this represents a rather startling conclusion, contrary to the traditional view of particle physics which holds that the microscopic world can be regarded as an isolated system. To a very good approximation it is separate and uninfluenced by the macroscopic world at large. Now, however, we need these vacuum averages; they are due to some long-range ordering in the state vector. At present our theoretical technique for handling such coherent effects is far from being developed. Each of these vacuum averages appears as an independent parameter, and that accounts for the twenty-some constants in the present weak and electromagnetic gauge theory. A comparable number of parameters is also needed in any of the grand unified theories. Consequently, we must view our present theoretical framework as at least partly phenomenological. After all, who has ever heard of a fundamental theory that requires a grand total of twenty-some parameters?

On the experimental side, there has hardly been any direct investigation of these coherent phenomena. This is because hitherto in any high energy experiment, the higher the energy the smaller has been the spatial region we are able to examine. Likewise, in nuclear physics we have so far concentrated mostly on nuclear matter at a constant density. Consequently, we have avoided the opportunity to study coherent effects in either high energy or high density. In order to explore physics in this fundamental area, relativistic heavy ion collisions offer an important new direction.

III. Relativistic Heavy Ion Collisions

1. General discussions

A normal nucleus of baryon number A has an average radius $r_A \cong 1.2\, A^{\frac{1}{3}}$ fm and an average energy density

$$\mathcal{E}_A \cong \frac{m_A}{(4\pi/3)\, r_A^3} \sim 130 \text{ MeV/fm}^3 \qquad (2)$$

Each of the A nucleons inside the nucleus can be viewed as a smaller bag which contains three relativistic quarks inside; the nucleon radius is $r_N \sim .8$ fm and its average energy density is

$$\mathcal{E}_N \cong \frac{m_N}{(4\pi/3)\, r_N^3} \sim 440 \text{ MeV/fm}^3 \qquad (3)$$

Our purpose is to study the physics of objects which, in their rest frames, can extend over several fm and have energy densities much greater than that inside a single nucleon. If this is possible, then inside such an object the usual concept of nuclear physics (regarding nucleons as units) must break down; new physics may thereby emerge.

When two heavy nuclei collide, to begin with there is the problem of Coulomb repulsion which must be overcome in order to reach the nuclear surface; that requires a c.m. energy/nucleon of $\gtrsim 20$ MeV. Next, in order to penetrate the nucleonic surface, it is necessary to overcome the strong repulsive force between nucleons due to ω and ϕ exchange. Thus, we must have a c.m. energy of about several GeV/nucleon or higher. This then brings us to the energy range of accelerators such as ISR, ISABELLE, etc.

2. Coherence vs. incoherence

The total high-energy cross section of a proton-nucleus collision is known to be given by the geometrical area of the nucleus; that of a high-energy nucleus-nucleus collision is therefore also expected to be similarly determined. We have

$$\sigma_{A'A}(\text{total}) \propto (A'^{\frac{1}{3}} + A^{\frac{1}{3}})^2$$

where A and A' are the baryon numbers of these two nuclei. More specific information concerning coherence or incoherence can be obtained by examining some inclusive reactions such as

$$A' + A \rightarrow \pi + \cdots \qquad (4)$$

at high energy.

For orientation purposes, let us first assume complete incoherence during the reaction; i.e., each collision is like a single nucleon on a single nucleon and there is no shadowing, no absorption and no re-scattering. The process at a given impact parameter b may be illustrated by Figure 2. The shaded

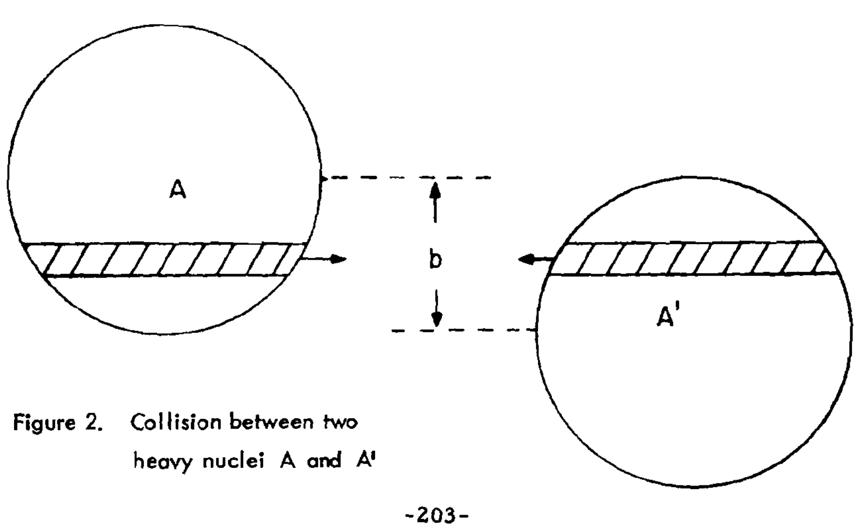


Figure 2. Collision between two heavy nuclei A and A'

regions in A and A' denote two circular cylinders of nucleons facing each other. The number of nucleons contained in these two cylinders is respectively proportional to $A^{\frac{1}{3}}$ and $A'^{\frac{1}{3}}$. Thus, for incoherent collisions their rate for reaction (4) is proportional to $A^{\frac{1}{3}} A'^{\frac{1}{3}}$. Adding the contributions due to all such cylinders and averaging over the impact parameter, we see that

$$d\sigma_{A'A}(\text{incoh}) \quad \propto \quad A'^{\frac{1}{3}} A^{\frac{1}{3}} (A'^{\frac{1}{3}} + A^{\frac{1}{3}})^2 \quad , \qquad (5a)$$

so that for $A' = A$

$$d\sigma_{AA}(\text{incoh}) \quad \propto \quad A^{\frac{4}{3}} \qquad (5b)$$

and for a single proton ($A' = 1$) on A

$$d\sigma_{pA}(\text{incoh}) \quad \propto \quad A \quad . \qquad (5c)$$

We now define any deviation from these A and A' dependences as due to coherent processes. The coherence may either serve as a suppression (such as the shadowing effect), or act as an enhancement (e.g., due to multiple scattering). In any case, its operational meaning is clear.

A case of interest is to examine the A-dependence of

$$p + A \rightarrow \pi^{\pm} + \cdots$$

for $\pi^{\pm}$ with a high perpendicular momentum $k_{\perp}$. The experimental result[2] expressed in the form

$$\left(\frac{d\sigma}{dk_{\perp}}\right)_{pA} = \left(\frac{d\sigma}{dk_{\perp}}\right)_{pp} A^{\alpha}(k_{\perp}) \qquad (6)$$

gives for $\pi^{\pm}$

$$\begin{aligned} &\alpha(k_{\perp}) \sim .9 && \text{when} \quad k_{\perp} \lesssim 1\ \text{GeV} \\ \text{and} \quad &\alpha(k_{\perp}) \sim 1.1 && \text{when} \quad k_{\perp} \sim 4\text{-}6\ \text{GeV} . \end{aligned} \qquad (7)$$

The former is a suppression, the latter an enhancement. The corresponding values for other particles in the high $k_{\perp} \sim$ 4-6 GeV region are

$$\begin{aligned} \alpha(k_{\perp}) \sim\ & 1.15 && \text{for} \quad K^- \\ & 1.2 - 1.3 && \text{for} \quad K^+ \\ & 1.3 - 1.4 && \text{for} \quad p \text{ and } \bar{p} \ . \end{aligned} \qquad (8)$$

The slight suppression in the low $k_{\perp}$ region can be readily understood by taking into account the shadowing effect. The relatively large enhancement in the high $k_{\perp}$ region, especially for p and $\bar{p}$, is more complicated.

Since $d\sigma$ decreases very rapidly with $k_{\perp}$, at high $k_{\perp}$ one is more sensitive to rare but more interesting events. The rapid rise of $\alpha(k_{\perp})$ is due partly to multiple scattering. But it may also be due in part to a completely different mechanism (one that is similar to the well-known formation of antideuteron and anti-He[3] in a high-energy pp collision). In Figure 2, when the two Lorentz-contracted (shaded) columns of particles hit each other, the quark and the antiquark that form the final pion may come from two separate collisions. Since the probability of having an additional collision is proportional to $A^{\frac{1}{3}} \cdot A'^{\frac{1}{3}}$, one should therefore multiply (5a) by such a factor. In a p + A reaction, such a mechanism gives an enhancement factor of $A^{\frac{1}{3}}$, making $d\sigma_{pA} \propto A^{\frac{4}{3}}$ for π and K. For p and $\bar{p}$, there is the possibility of a triple collision, which carries an enhancement factor of $A^{\frac{2}{3}}$, giving $d\sigma_{pA} \propto A^{5/3}$. Similarly, in an A + A collision, the corresponding enhancement factor would be $A^{\frac{2}{3}}$ for π or K (making $d\sigma_{AA} \propto A^2$), and $A^{\frac{4}{3}}$ for p or $\bar{p}$ (making $d\sigma_{AA} \propto A^{8/3}$).

3. The central problem

The most crucial questions in an ultra-relativistic heavy-ion collision are:

1) Can extended objects of very high energy densities (>> energy density inside a proton) be produced?

2) If produced, how can they be detected and how can we analyze their properties?

These two problems have recently been studied by several people.[3-5] The answers to both questions are affirmative, especially with colliders of ISABELLE-like energy.

Consider the collision between two relativistic heavy ions. In the center-of-mass system, most of the final energy goes to fragments with very large rapidity; these particles hadronize outside the nuclear matter and are therefore not relevant for our purpose. However, at least ~10-15% of the energy will be trapped in the two projectile nuclei and in the central rapidity region. But 10% of ISABELLE-like energy per nucleon is much greater than the nucleon mass. Therefore it is not surprising that we can create extended objects of energy density an order larger than that inside the proton.

We now turn to the second question. If these objects are produced, how can we detect them and how can we analyze their properties?

IV. A Possible Experimental Program

1. Quark-antiquark and gluon plasma

Consider now such an extended object whose energy density is $\mathcal{E}$, radius R and lifetime τ (all in its rest frame). Its interior is assumed to be in a new plasma state, but its exterior consists essentially of normal hadrons. Ideally, it looks like the object shown in Figure 3. In its interior, because

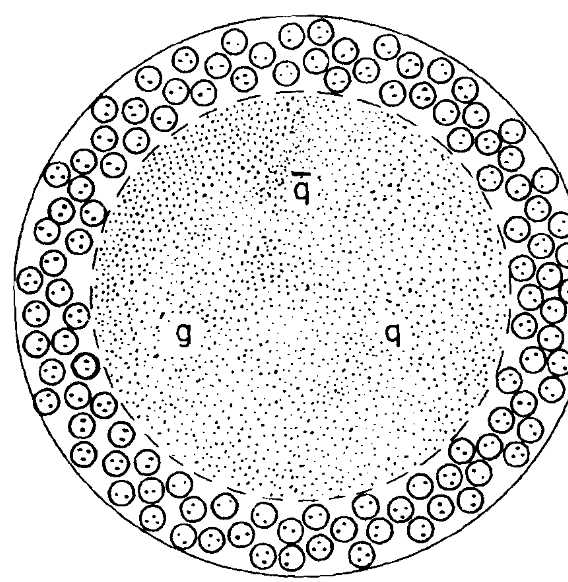


Figure 3.

An object whose interior is a quark-antiquark and gluon plasma.

$$\mathcal{E} \gg \mathcal{E}_N ,$$

the usual hadron bags disappear. Instead there should be a large bag of quark, antiquark and gluon plasma. Normal small hadron bags can appear only on the surface. These different properties are summarized in the following table.

INTERIOR	EXTERIOR
energy density $\mathcal{E} \gg \mathcal{E}_N$	$\mathcal{E} \cong \mathcal{E}_N \sim \frac{1}{2}$ GeV/fm^3
almost exact flavor SU_3 symmetry	almost exact flavor SU_2 symmetry
approximate SU_4 symmetry	approximate SU_3 symmetry
average momentum $\langle k \rangle \sim \left(\frac{\mathcal{E}}{\mathcal{E}_N}\right)^{\frac{1}{4}}$ 300 MeV	average momentum $\langle k \rangle \sim 300$ MeV

However, because the collision is a violent one, there will be all kinds of instability (due to QCD vacuum dynamics, phase transitions, non-central collisions, etc.). In most cases, the inside will simply erupt like volcanoes. Hence, as shown in Figure 4, a fair fraction of the plasma can come out directly without thermalization with the exterior. The lifetime τ of such an unstable object is $\sim$ its radius R.

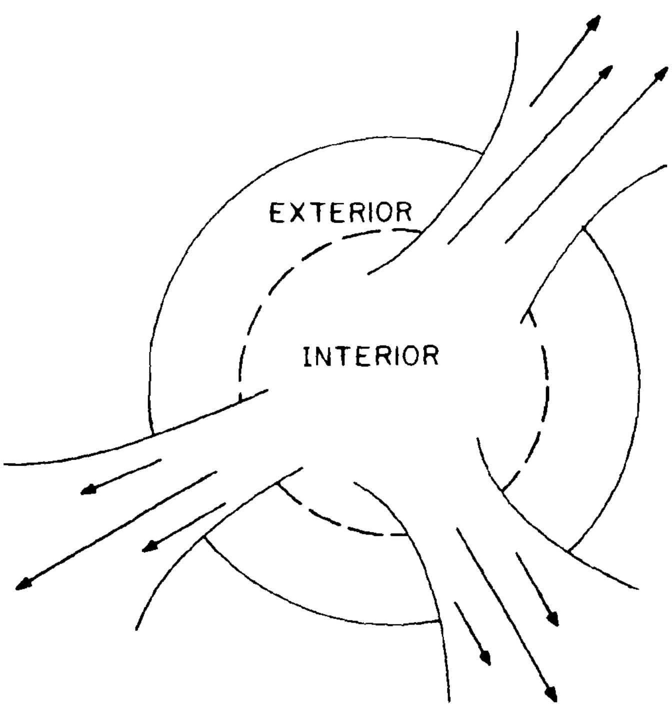


Figure 4. A schematic view of the decay of the extended object when τ is $\sim R$.

2. Detection of volcanoes

To detect such an eruption we take advantage of the fact that the total mesons produced from such an object would be on the order of $10^4 - 10^5$. Hence in a heavy-ion collision we may divide the central and the near-central regions of rapidity y into, say, ten sections. In each Δy sector we may again divide the azimuthal angle ϕ around the line of collision in the center-of-mass frame into, say, ten angular intervals. Per collision, in each $\Delta y - \Delta\phi$ section we would still expect a statistically significant number of mesons, $\sim 10^2 - 10^3$. We can then plot the average K/π ratio in each section. If this ratio has violent variations, from ~ 1 in some sectors to $\sim 1/10$ in others, then this is a clear sign of "volcanoes" with $K/\pi \sim 1$ indicating a direct hadronization of the interior. For corroboration, we may plot $\sum |k_\perp|$ in each of the $\Delta y - \Delta\phi$ sectors, where $k_\perp$ is the meson momentum component perpendicular to the initial line of collision and the sum extends to all mesons emitted in that sector. Again, we should expect that in a volcano-like event the average $|k_\perp|$ could be much bigger than 300 MeV in the $\Delta y - \Delta\phi$ sector that has a high K/π ratio, but ~ 300 MeV if the K/π ratio is about $1/10$.

3. Detection of new metastable objects

Occasionally, we may find that the K/π ratio and $\sum |k_\perp|$ are uniform in all $\Delta y - \Delta\phi$ sectors. This is then a good indication that there is an absence of eruption, and that a metastable object of a large bag of quarks-antiquarks and gluons is formed, as shown in Figure 3. Its lifetime τ can be quite a bit longer. [If there is no bag pressure, no surface tension, and quarks and gluons behave like free particles, then τ should be $\sim \sqrt{3}\,R$. Since none of these assumptions is correct, we expect τ to be $\gg \sqrt{3}\,R$.]

We shall now examine the question of how to determine τ for such a metastable object. The important decay mode of such an object is through the radiation of mesons from its exterior, plus emission of photons and lepton pairs from its interior. The rate of soft-pion radiation is proportional to its surface, and therefore the total number of soft pions emitted is

$$N_\pi = 4\pi\kappa R_\pi^2 \tau \tag{9}$$

where κ can be calculated theoretically and R_π, the mean radius of the π-emitting exterior, can be measured experimentally[6] through the Hanbury-Brown and Twiss method, as we shall see.

Consider the emission of, say, a π^- of momentum $\vec{k}$ from a volume element d^3r_a near the surface together with the emission of another π^- of momentum $\vec{k}+\vec{q}$ from d^3r_b. Because these are identical particles obeying Bose statistics, the total probability of seeing these two pions is proportional to

$$\frac{1}{2}\left| e^{i\vec{k}\cdot\vec{r}_a + i(\vec{k}+\vec{q})\cdot\vec{r}_b} + e^{i\vec{k}\cdot\vec{r}_b + i(\vec{k}+\vec{q})\cdot\vec{r}_a} \right|^2$$

The interference term between these two terms in the sum gives the deviation of the correlation function from unity. Hence, the measurement of such correlation functions can give a direct measurement of the geometry of the surface region. The radius R_π can then be determined. By using (9), together with the experimental values of N_π and R_π, we can infer the lifetime τ. Similar correlation functions can also be observed by using $\pi^+\pi^+$, K^+K^+, K^-K^-, etc. Each of these yields an independent measurement of the same lifetime τ.

In addition, the γ and lepton pairs are emitted directly from the interior. Their emission rates are proportional to the volume of the metastable object. Similar studies of $\gamma\gamma$ correlation and lepton pair-lepton pair correlations can determine the geometry of the interior. Just as in (9), the total number of γ emitted is given by

$$N_{\gamma} = \frac{4\pi}{3} \lambda R_{\gamma}^{3} \tau \qquad (10)$$

where R_{γ} is determined experimentally through the $\gamma\gamma$ correlation function and λ can be calculated according to QCD. Thus τ can again be independently determined. In an entirely similar way we can also use lepton pair-lepton pair to measure the lifetime. [See Figure 5.]

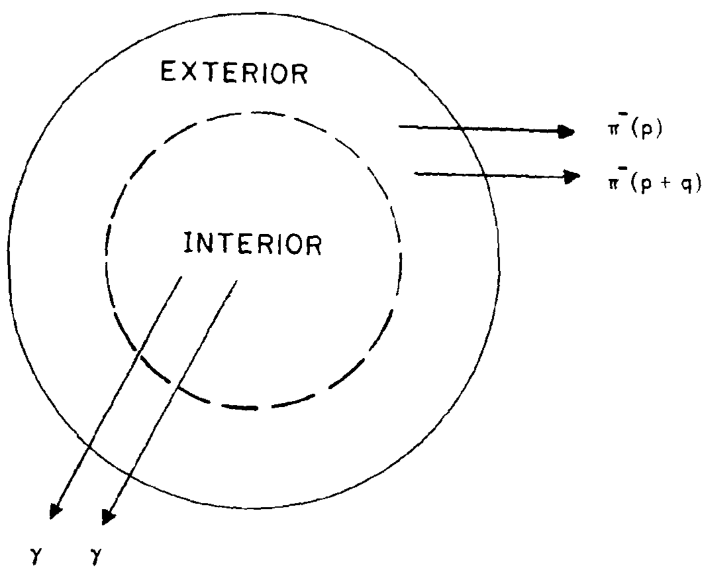


Figure 5. The radius of the surface can be determined by the $\pi\pi$ (or other hadron-hadron) correlation function, and the radius of the inside volume by the $\gamma\gamma$ (or lepton pair-lepton pair) correlation. From these radii and Eqs (9) and (10), one can derive the lifetime τ.

In this idealized experimental program, we take full advantage of the large multiplicity of particles produced. The spirit is to regard each collision as an experiment, similar to the observation of a stellar object. Our strategy is to replace photons radiated from a star by mesons, and neutrinos by photons and lepton pairs. The large radius of these objects and the enormous number of particles involved makes it possible for us to measure their geometrical size through correlation functions. The total multiplicity gives us the equivalent of the integrated luminosity of a star. Thereby their lifetimes can be determined. In this way we can discover an entirely new class of metastable states of large baryon number and high energy density. Their equations of state would give us insight into the physics of the early universe. Remembering that the total heavy ion cross section is $\sim 10^{-24}$ cm^2, even an extremely rare event of $\sim 10^{-10}$ probability has a rate that can be compared favorably with a typical neutrino event.

So far we have refrained from discussing any speculative phenomena in order to show that even at the very minimum we can expect, through relativistic heavy ion collisions, the creation of a new state of matter. Its energy density should be greater than that in the interior of neutron stars. Our usual concepts of nuclear physics are not applicable, but new principles are yet to be uncovered.

It is not inconceivable that in a decade or two, a fair percentage of the high-energy physicists and nuclear physicists will be engaged in this exciting area of research.

Acknowledgments

I wish to thank A. H. Mueller, L. Radicati and W. Willis for discussions.

This paper is based on a talk given at the Niels Bohr Institute in June 1981.

This research was supported in part by the U. S. Department of Energy.

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