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Ultra-Relativistic Nuclei: A New Frontier

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The collisions of ultra-relativistic nuclei provide a window on the behavior of strong interactions at asymptotically high energies. They also will allow us to study the bulk properties of hadronic matter at very high densities.

1 Two Fundamental Issues

There are two important central issues which will be studied through the use of ultrarelativistic nuclei.

The first is the gross structure of high energy hadronic interactions. How do things behave in the limit $E \rightarrow \infty$? Can one understand this simply from first principles in QCD? What is the correct space-time picture of high energy hadronic interactions? It is surprising to me that such simple issues are not really understood, even though we have been studying strong interaction processes for over half a century.[1]

The second issue arises from the use of high energy hadronic interactions as a tool to study the gross structure of hadronic matter in bulk. We use ultrarelativistic heavy ion collisions to produce matter at very high energy density. This matter which has either or both of high temperature and high baryon number density. Is there a phase transition to a deconfined or chirally symmetric quark gluon plasma? What is the equation of state of such matter? Is our understanding of mass generation and confinement correct? [2]

We should ask how these studies fit into our conception of nuclear physics. I think that traditional nuclear physics was the study of nuclei. It turned out that to understand nuclei, one had to posit a theory of strongly interacting matter, and that this theory developed a life and dimension of its own.

The currently accepted theory of strong interactions, QCD, not only incorporates nuclei but all of the interactions of hadrons at any energy. In fact, viewed within the framework of QCD, nuclei are an afterthought, a residual of strong interactions which barely binds nucleons together. Traditionally, nuclear physics was concerned only with the low energy aspects of QCD. In recent year, I think it is fair to say that all aspects of QCD are of interest now to practicing nuclear physicists, and is more a subject of nuclear physics than of particle physics.

Another extension of traditional nuclear physics was from the theory of nuclei to that of high density matter in general. This has had applications in the theory of neutron stars and the big bang early universe. The ideological limits of nuclear physics are a little fuzzy here. Many of us who have studied high energy density nuclear matter have used similar techniques to study the physics of matter at energy density scales many orders of magnitude higher than scales typical of nuclear matter, for example at temperatures of the order of the electroweak scale $T \sim 100\ GeV$ or even the Planck scale $T \sim 10^{19}\ GeV$. Although this has very little to do with nuclei, many elements of the theory of matter at these diverse scales are common, as is the mathematical language used.

Finally, another area which nuclear physics plays a strong role is in complicated dynamics in field theory. This comes simply from the fact that nuclei are complicated objects, and to study them one needs a powerful arsenal of theoretical methods. In QCD, for example, one is studying a strongly interacting field theory with all of its complications. The techniques one uses here generalize to any field theory.

The study of ultrarelativistic nuclei straddles all of the above areas except for one. It is not an attempt to understand nuclei! Ultrarelativistic nuclear physics is a world which has been generalized from traditional nuclear physics, but incorporates much of its soul:

- Strong Interactions
- Bulk Properties of Matter at High Energy Density
- Complicated Dynamical Problems

2 The Ultra-Relativistic Nucleus

2.1 The Un-Relativistic Nucleus

For our purposes, the nucleus is a simple object. I will treat it as an object (oftentimes a cube!) with a characteristic size of $A^{1/3}$ where A is its baryon number. This ranges from $R \sim 1 - 10\ Fm$. Time scales characteristic of nuclei will be in the range $1 - 100\ Fm/c$ which correspond to the time it takes light to travel a proton size to the characteristic time for a sound wave in nuclear matter to propagate across the nucleus. The characteristic baryon density of a nucleus is $\rho \sim .1 - .2\ Fm^{-3}$ and energy density $\epsilon \sim .1 - .2\ GeV/Fm^3$

2.2 *The Ultra-Relativistic Nucleus*

The ultra-relativistic nucleus is almost the simple Lorentz boost of the unrelativistic nucleus. Indeed, the baryon number is Lorentz contracted to a size of order $1/\gamma$ where $\gamma = E/M$ is the Lorentz gamma factor of the nucleus. An essential difference is that meson degrees of freedom are important for the ultra-relativistic nucleus. These can be created in a collisions, and are in fact an important part of the Fock space wavefunction for high energy processes. These meson degrees of freedom have a range of longitudinal energies which vary continuously from the lab energy of the nucleus down to a typical hadronic energy, 200 MeV. The size scale where these components are important is $z \sim 1/p_z$ where p_z is the longitudinal energy. These degrees of freedom therefore smear out the nucleus so it always has a size of at least 1 $Fm \sim 1/200\ MeV$.

The ultrarelativistic nucleus therefore has its baryon number in a size region of order 1 $Fm\ /\gamma$, but its energy density is spread out in a region of size 1 Fm.

This distribution of meson longitudinal energies ranges from $p_z \sim 200\ MeV$ to $p_z \sim \gamma \times 200\ MeV$ If we plot things in terms of rapidity,

$$y \sim ln(E/E_0) \tag{1}$$

where E is the meson energy and $E_0 \sim 200\ MeV$, then it turns out the meson distribution of mesons is a slowly varying function of energy.

In Figure 1, a cartoon for an ultrarelativistic nucleus is shown. The meson degrees of freedom as shown as the circles and extend a distance of order 1 Fm outside the region where the baryon number is concentrated. The baryon number is concentrated in the the thin sheet of matter shown.

The distribution of mesons as a function of rapidity y, dN/dy, has a range of $0 \leq y \leq ln(\gamma)$ for fixed energy of the nucleus. What happens when we increase the value of the energy of the nucleus? Then the range for y increases. Empirically, the fast mesons, those in the original range of rapidity with rapidities closest to that of the nucleus change very little. What happens is we add new degrees of freedom, soft mesons, in the rapidity range of $0 \leq y \leq ln(\gamma'/\gamma)$. The modification of going to higher energy is simply to add more soft mesons to the nuclear wavefunction. Those with momentum close to the nucleus are little changed.

In Figure 2, a rapidity density of partons is shown. In Fig 3, we see the result of going to higher energy. We simply add in more partons at small x. The distribution in in the region of large positive y is shifted, since it now has higher energy, but its shape is the same. The physics of the fast partons is therefore the same, and the new physics of high energy is associated with small x.

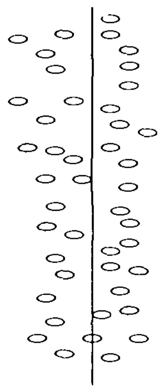

Figure 1: An Ultra-relativistic Nucleus

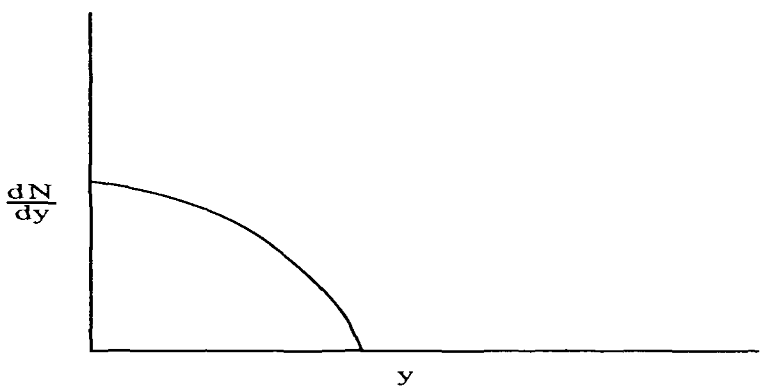

Figure 2: The rapidity distribution of partons

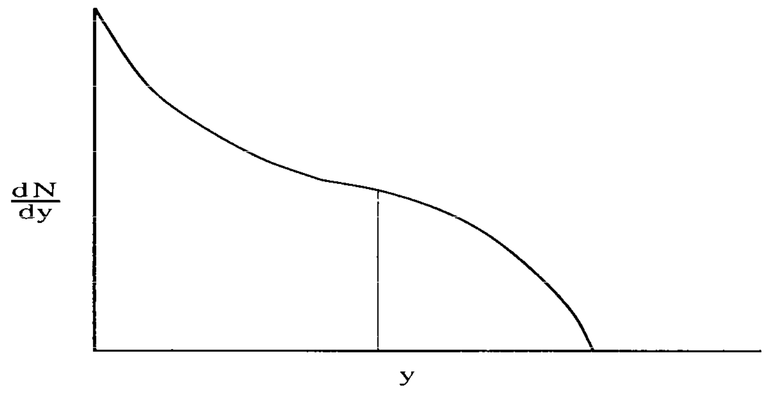

Figure 3: The changed rapidity distribution of partons for higher hadron energy

3 The High Density of Mesons

One can measure the density of partons (a generic word for mesons or gluons or whatever the fundamental degrees of freedom are) in deep inelastic scattering at HERA. If we let $x = \gamma_{parton}/\gamma_{nucleus}$, then it is found that

$$\frac{dN}{dy} \sim \frac{A^{1/3}}{x^{\delta}} \tag{2}$$

(A is the nuclear baryon number.) The number δ is about $.2 - .3$ at the x values typical of HERA.

We see that there are two possible ways to increase the density of partons. We can either decrease the minimum possible x which corresponds to increasing the maximal energy or we can increase A. An increase of A can change this density by about an order of magnitude. To get an order of magnitude increase through the beam energy would require a nucleus with a factor of $10^3 - 10^5$ greater energy. (Going to the center of mass frame would make this requirement a little less strong.) Getting such a higher energy costs a lot of money, since it would require a much larger accelerator.

Clearly, if we want to make the density of partons higher, it makes sense to use nuclei. This of course assumes that the physics is controlled by the density of partons per unit area. Another advantage is that there will be some conceptual simplifications if one can ignore the transverse size of the nucleus, and this is a better approximation if the size of the nucleus is larger.

It is clear that the physics of small x is the physics of high energy since going to higher energy simply adds on the small x component of the hadron wavefunction. One might also help in getting this asymptotic limit by using nuclei. We also see that the physics of high energy is the physics of high energy density matter.

Notice that the density of partons per unit area is dimensionful, $\Lambda^2 = dN/dy/\pi R^2$ has the dimensions of an inverse length squared or an energy squared. When

$$\Lambda >> \Lambda_{QCD} \tag{3}$$

we expect that by asymptotic freedom, the QCD interaction strength is weak, $\alpha_S(\Lambda) << 1$. Therefore, the high energy limit is controlled by the physics of weakly coupled high energy density matter.

4 Experimentally Probing High Density QCD

Traditionally, the study of the small x part of the hadron wavefunction was done using ep scattering. I am arguing here that it might be better for some purposes to do eA.

Experiments with ep have their correspondence in AA at RHIC and LHC. We can estimate the initial energy densities and see that roughly speaking HERA with ep corresponds to the initial energy densities expected at RHIC. HERA with eA corresponds roughly to AA at LHC.

There is a new proposal from Brookhaven National Laboratory to build a 10 GeV electron ring in the RHIC tunnel and scatter the electrons from the heavy ion beam. In addition one could do polarized ep scattering. The energy ranges are a little smaller than that of HERA but the slow variation of the gluon density with x means the physics is not much different. There are also some advantages of eRHIC verses HERA due to the possibility of considering a continuous range of collision energies and higher design luminosities. Such a program would directly complement the existing experimental AA program.

5 AA Scattering

The physics of AA scattering includes the study of the high energy limit of QCD. It will provide the environment where the highest energy densities will be achieved and will therefore correspond to much high energies than could be achieved in say a $p\bar{p}$ collider. In addition, ultrarelativistic nuclear collisions allow us to study matter as a high temperature or baryon number density gas.

There is a subtle difference between the matter which makes up the wavefunction of an ultra-relativistic nucleus and that of a produced quark-gluon plasma. For the wavefunction, the matter is highly coherent, in fact in a single quantum state. The constituents of this matter are virtual and are not propagating real quanta.

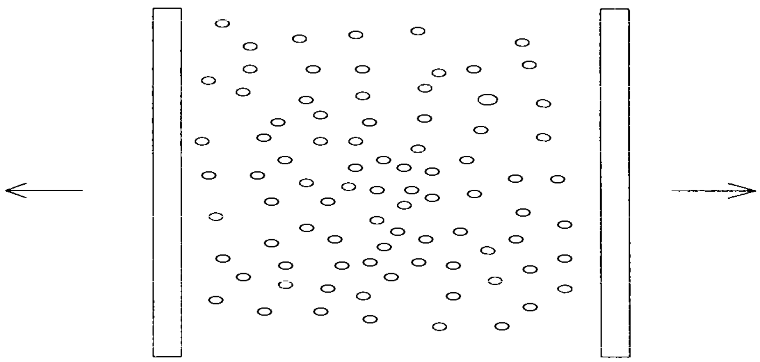

Figure 4: A Collision of Ultra-relativistic Nuclei

Only relatively late in a collision are particles actually produced. In AA collisions, the high density of such produced particles forces them to scatter with themselves many times, eventually producing thermalized matter.

In Figure 4, a collision of two nuclei is shown. After the collision, the very fast degrees of freedom of the two nuclei are unchanged for a time of order $\gamma \times 1$ Fm/c. Here γ is the Lorentz gamma factor for the center of mass. The fast degrees of freedom change in their own rest frame on a time scale $t \sim 1$ Fm/c, but in the center of mass frame, their reaction is time dilated. The parton degrees of freedom are produced quickly. This is because some of them are moving slowly in the center of mass frame. The reaction of these degrees of freedom is not Lorentz time dilated.

This thermalized quark-gluon plasma is produced as a rapidly expanding gas. If the nuclei are large enough, this plasma can exist as a thermalized system for times as large as 20 Fm/c. During this time, the matter which is initialy quarks ands gluons reassembles itself as hadrons, perhaps going through a phase transition which separates quark-gluon matter from ordinary hadronic matter. Eventually, the hadronic matter cools and stops interacting with itself and its remnants are fly off.

The typical energy density we expect when the matter is formed is of order $\epsilon \sim \Lambda^4$. This may be somewhere in the range of $\epsilon \sim 10^2 - 10^4$ GeV^2 for the values of Λ discussed above. This happens in a relatively large region, for gold $R \sim 7$ Fm, where the typical wavelength associated with a 1 GeV scale size is .2 Fm.

One has a fairly complete space-time scenario for the production of matter

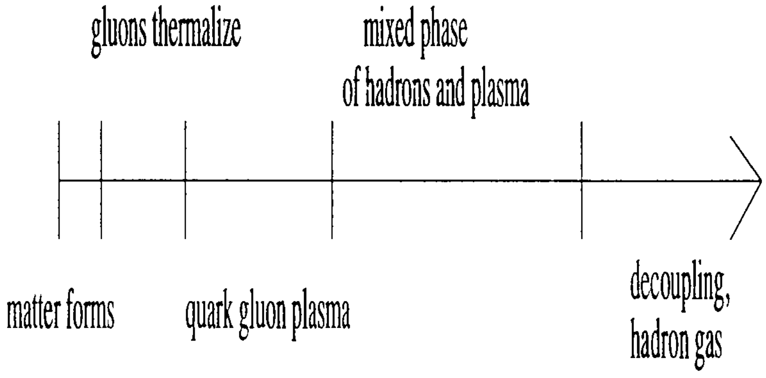

Figure 5: A Time Line for the Evolution of Matter in an Ultra-relativistic Nuclear Collision

in heavy ion collisions. I will go through this picture for the central region of heavy ion collisions in the center of mass frame.

At very early time, $t \leq 1/\Lambda$, the matter is coherent and quantum mechanical. For gold at RHIC energy, $1/\Lambda \sim .2\ Fm/c$. There are gluons in the form of coherent color fields. These fields arise from sources which are very close together, and their field strengths add together coherently.

At a time of the order of $t \sim 1/\Lambda$, the coherent gluon fields begin to radiate gluon quanta. These quanta begin to scatter from one another and thermalize. A typical time for thermalization is of order $t \sim 3 - 5/\Lambda$.

Once the gluons are thermalized, they form a gluonic plasma. Quarks are coming into equilibrium abundances even after the gluonic plasma has thermalized.

At a time of order $t \sim 2 - 3\ Fm/c$, the matter begins forming hadrons. This might take place at a first order phase transition. If so, then there is a coexistence of a plasma phase and a hadron gas phase. If there is no first order phase transition, but a continuous change in the properties of the system, then we should think of the dynamics as evolving from a system where the simple description is in terms of quarks and gluons into one where it is hadrons. This time of evolution can be quite long, perhaps as long as $t \sim 10\ Fm/c$.

A time line for the evolution of matter produced in the central region of the collision of two nuclei is shown in Figure 5.

In the late stages of the collision, the matter expands as a hadronic gas, eventually becoming a pion gas. At some late time, this pion gas decouples, and stops interacting with itself.

6 Basic Physics We Want to Study

There are several goals of the study of high density hadronic matter. If we think we understand confinement, then producing a system where deconfinement occurs provides an entirely non-trivial test of these ideas.

When the system become deconfined, quarks lose their mass. The origin of the masses of particles such as the proton is a mystery in QCD. If one were to take the naive QCD theory and predict the proton mass, it would be of order 100 MeV. It is in fact an order of magnitude larger. We say this happens because chiral symmetry is broken. Chiral symmetry would require that if QCD had massless quarks, all baryons would either be massless or appear in a doubled spectrum with partners of opposite parity. QCD to a good approximation has small mass quarks, but the baryons have big masses and do not appear in doublets. We therefore say that chiral symmetry is broken. How does this happen? Can we systematically study this and test our ideas?

Another very intersting possibility for QCD is that there is a real first order phase transition which separates a quark-gluon plasma from a hadronic gas. If so, this is the strongest first order phase transition we could ever study. The latent heat per particle is of the order of the rest mass energy per particle! In condensed matter physics, the latent heat per particle is 9-10 orders of magnitude smaller than the rest mass!

Such a strong first order phase transition generates large energy density fluctuations. We are all familiar with this phenomenon. When water boils, steam bubbles form which are orders of magnitudes larger than typical atomic sizes. Such density fluctuation might be a signal for a quark gluon plasma transition in heavy ion collisions.

Perhaps more important, such a transition provides an experimental realization of various phase transitions which occur in the early universe. For example, at the electroweak scale, a similar phase transition to that at the QCD scale might occur. Such a transition has been postulated to generate the baryon asymmetry of the universe and seed magnetic fields for galaxies. An essential ingredient in this formation is the formation of density inhomogeneities at the phase transition.

Acknowledgments

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References

1. L. McLerran, Proceedings of 8'th Mexican School of Particles and Fields (and references therein), Oaxaca de Juarez, Mexico (1998).
2. L. McLerran, *Rev. Mod. Phys.*, **58**, 1021 (1986) (and references therein).