IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

PHYSICS OPPORTUNITIES WITH RELATIVISTIC HEAVY ION ACCELERATORS*

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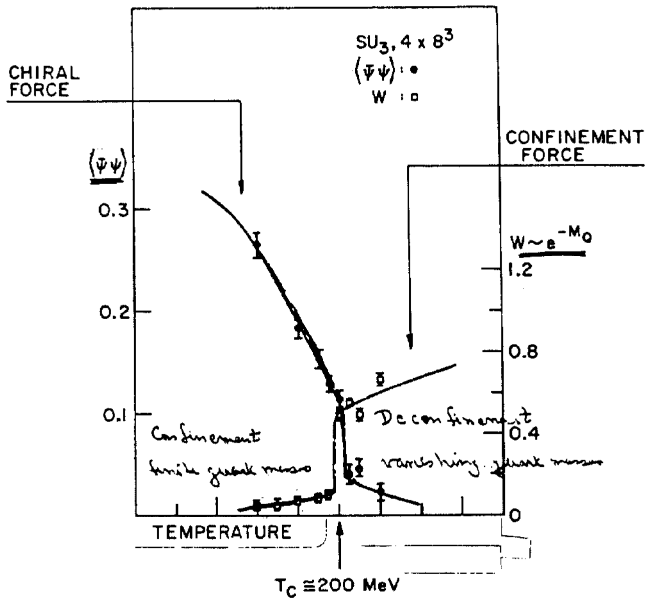
The interest and excitement in the study of relativistic heavy ion interactions has been steadily increasing over the past several years. The reasons are varied; however, the opportunity to enter into a new realm of physics where the theoretical predictions indicate promise of new phenomena must be a major factor. We as physicists are always enticed by new and novel ideas. To be a bit more precise, the physics motivation for a relativistic heavy ion collider with energies of 100 GeV/Amu x 100 Gev/Amu for nuclei of A-200 are, i) this will allow the production in the laboratory of a new state of matter--the quark gluon plasma, ii) the study of such interactions will provide an experimental test of statistical quantum chromodynamics (QCD), i.e., a look at the properties of the QCD vacuum at large distances, iii) such reactions will simulate the conditions of the early universe and, iv) such a collider will allow us to delve into the unknown. If history is any guide then it is clear that any time one can increase an important physics parameter by a factor of 10 (and in this case a factor of 100 over what is presently being done) then you do it! At present the Bevalac at Berkeley is the premier facility for the study of heavy ions with a center of mass capability of 1 GeV/Amu x 1 GeV/Amu. In the near term this capability will be increased at the AGS at BNL (6 GeV/Amu x 6 GeV/Amu) and at the CERN SPS (10 GeV/Amu x 10 GeV/Amu).

Before explicitly discussing the physics motivation for a relativistic heavy ion collider it is profitable to first briefly discuss the present picture in high energy particle physics. Considering constituent particles the catalogue consists of 6 leptons (the electron, muon, and tau, each with its respective neutrino) and six quarks (u,d,c,s,b (t)) each coming in three colors. All have been explicitly observed except the ν_τ and t. These particles interact with each other via electro-weak and strong forces. For instance, pure electron-electron scattering occurs with an exchange of a photon and Z^o. Neutrino interactions take place with $W^\pm$ and Z^o exchange for charged and neutral interactions. The coupling constant is $\alpha = g = 1/137$. This is in contrast to the interactions between quarks (and in turn hadrons) which proceed via the exchange of gluons which in turn come in eight varieties. There is a close analogy of these interactions with quantum-electrodynamics and as such is called quantum-chromodynamics--the main difference being the coupling content α_s (equal to ~.2 at present energy scales) and the allowance of the three gluon coupling (the three photon coupling not being allowed). In this context one can point out three major phase transitions that have taken place since the creation of the universe, one that has recently been investigated with the observation of the W and Z^o and the other two yet to be looked at. Our present conjecture is that all electro-weak strong forces are unified at an energy of 10^{19} GeV, the so-called Grand Unification. At an energy of ~ 10^{14} GeV, a first phase transition occurs where the strong interaction is separated from the electroweak and one has the emergence of quarks, gluons and W's and Z's. Then there appears the so-called desert (which may or may not bloom) until one reaches a mass of ~ 100 GeV. At this point a second phase transition occurs where the electromagnetic and weak separates and one has leptons and photons. Finally, at a mass of ~ 200 MeV a third phase transition occurs, where the quarks and gluons mesh and become hadrons. It is this third area which can be readily explored by heavy ions, this transition between hadrons and the quark gluon plasma. Not only will one be able to produce this new state but more than that,one will be able to apply this theory of QCD to this extended system of constituents. In contrast to most interactions, QCD is a peculiar theory. In most of our experience we are accustomed to potentials V(r) that drop off as 1/r . At small distances the quarks are loosely bound and all of the mesonic and baryonic states with their respective quantum numbers are accounted for this by this simple model. However, at large distances the potential V(r) behaves as linearly with the distance ~ r as such the quarks are infinitely bound, they are confined. These two regions correspond to the perturbative and non-perturbative regions of QCD. It is precisely this long range behavior of quarks and gluons that can be intensified by relativistic heavy ion collisions and only by them. Theoretical calculations via the use of Monte-Carlo formulation of lattice gauge theories have all indicated that such a transition should occur at 200 MeV. The need for heavy nuclei becomes apparent when one considers the energy density (2.5 Gev/f^3) to achieve the above--the functional form goes as $KA^{1/3}$ where K is estimated to be = (1-3). Of equal interest and excitement is the prospect of observing the restoration of a broken symmetry, in this case chiral symmetry. It is well known that at low temperatures this symmetry is broken, the quarks have masses. Again lattice gauge calculations indicate that this symmetry should be restored at a temperature of ~ 200 MeV. Both these effects are shown in Fig. 1. Below T=200 MeV quarks are confined and they have their respective well known masses, above T_c the quarks become deconfined and their constituent masses go to zero. Striking effects. There is a clear analogy to ferromagnetism where above a critical temperature the spins become randomly oriented and the symmetry is restored and ferromagnetism disappears while at lower temperatures the spins are aligned and the symmetry is broken. These are both important effects and are explorable via the study of relativistic heavy ion interactions.

A pictorial display of the interactions of two heavy ions is shown in Fig. 2 at both lower AGS energies 15 GeV/Amu and RHIC energies 100 GeV/Amu. At the lower energy there is maximum stopping power, in that the two nuclei essentially stop each other reaching high nuclear density and low temperature. At higher energies the nuclei become transparent to one another, the target and projectile fragment, again these regions achieving high baryon density, but leaving a central region which is hot and essentially devoid of baryons. This is graphically displayed in Fig. 3 where the temperature is plotted versus the baryon density. The lower horizontal trajectories correspond to the low temperature, high baryon density situation and the upper vertical curve to the hot central vacuum region which simulates the early universe. The name of the game is to traverse the transition region and get into the quark gluon plasma.

*Work performed under the auspices of the U. S.Department of Energy.

DECONFINEMENT AND CHIRAL SYMMETRY RESTORATION



COUPLED, FIRST-ORDER PHASE TRANSITIONS
(KOGUT et al., PRL 50, 393)

Fig. 1.

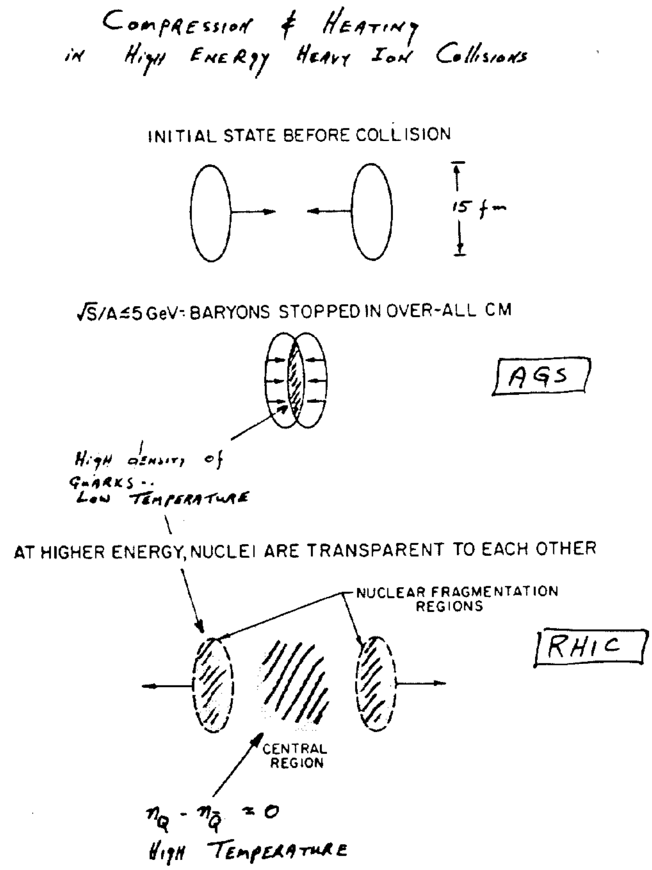


Fig. 2.

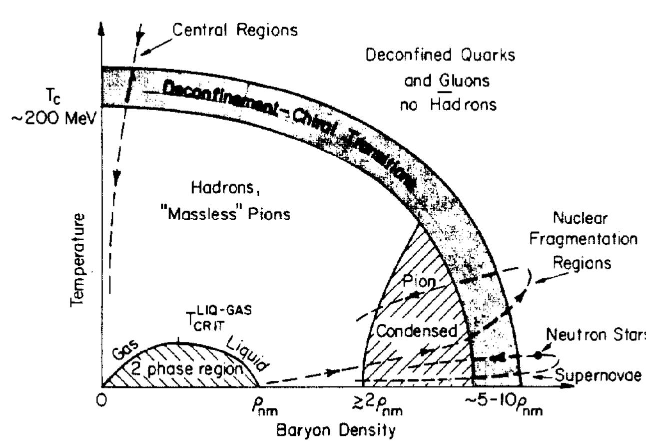


Fig. 3

Fig. 1. Theoretical Monte Carlo calculations concerning the confinement of quarks and chiral symmetry restorations. The left ordinate corresponds to the chiral force $(\bar\psi\psi)$ where a finite value reflects breaking of the symmetry and finite quark masses, with a vanishing value ($>T_c$) yielding vanishing quark masses; the right hand ordinate indicative of a confinement force again a large value corresponding to deconfinement.

Fig. 2. Pictorial display of the interaction of two heavy nuclei at relatively low energies (AGS 15 GeV/Amu) and high energies (RHIC ~ 100 GeV/Amu).

Fig. 3. Plot of nuclear temperature versus baryon density. The transition between hadrons and the quark gluon plasma is a band at $T \cong 200$ MeV and baryon density ~ 10 x normal. Also indicated are several possible experimental excursions.

In order to explore these exciting physics possibilities one wants an accelerator with rather general and generous properties. The peak energy is key and as noted earlier one would like at least a factor of 10-100 above present capabilities. In addition, it is imperative that one be able to comfortably explore the central baryon free region. Information pertinent to this question is shown in Fig. 4 where the total center of mass energy is plotted as a function of the rapidity y.

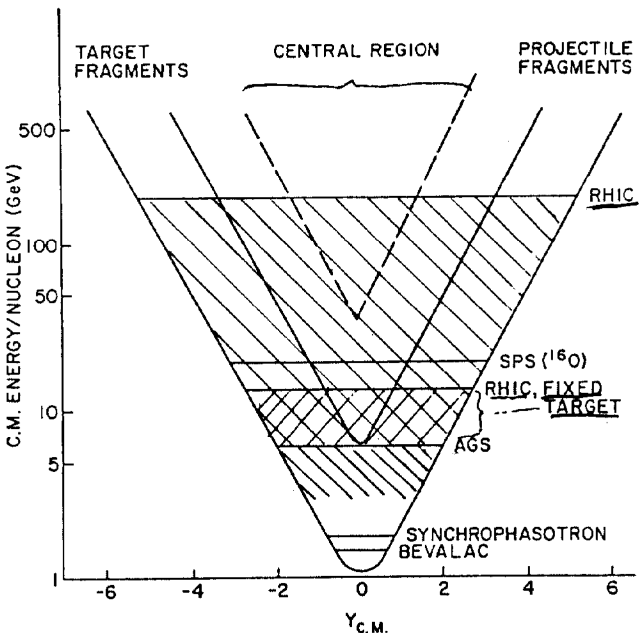


Fig. 4

Fig. 4. Plot of total center of mass energy (Gev/Amu) versus the rapidity y. The various horizontal lines refer to several accelerators and the striped region corresponds to the dynamic range of RHIC, and the cross hatched region the RHIC fixed target mode.

The range of various existing and proposed facilities are noted as well as the width of the target and fragmentation regions, solid lines as extrapolated from pp interactions and dashed lines as extrapolated from pA intersections. It is clear that ~ 200 GeV/Amu is needed to safely allow 2 central units of rapidity. In addition one wants to have the ability to accelerate many nuclear species as well as unequal nuclear species from protons to A $\simeq$ 200. Table I lists such capabilities and luminosities for the proposed RHIC accelerator at BNL. A luminosity > 10^{26}/cm^2/sec would be required for heavy-ions. Since cross sections are expected to be $\simeq$ 10 barns this would yield 10^3events/sec or 10 rare events/sec. Of greater importance is a large dynamic energy range with no gaps so that one can explore below as well as above the threshold of any new phenomena. This can be achieved as is illustrated in Fig. 5 where the energy-luminosity profile is noted for Au on Au colliding beams on the RHIC collider. Lighter nuclei have appreciably larger luminosities and are less difficult technically. All in all from a technical and conceptual point of view one is essentially ready to build such a machine. One notes for these parameters one would achieve a 20 TeV x 20 TeV energy!

TABLE I

INITIAL LUMINOSITY AT TOP ENERGY

	N_B	E/A (GeV/AMU)	LUMINOSITY ($cm^{-2}sec^{-1}$) Crossing Angle (mrad) 0.0	2.0
	$\times 10^9$			
Proton	100	250.7	1.2	0.28 × 10^{31}
Deuterium	100	124.9	11.9	2.8 10^{30}
Carbon	22	124.9	5.8	1.4 10^{29}
Sulfur	6.4	124.9	4.9	1.2 10^{28}
Copper	4.5	114.9	22.6	5.7 10^{27}
Iodine	2.6	104.1	6.7	1.7 10^{27}
Gold	1.1	100	1.2	0.3 10^{27}

Pt Au : $L = 10^{24}\ cm^{-2}\ sec^{-1}$

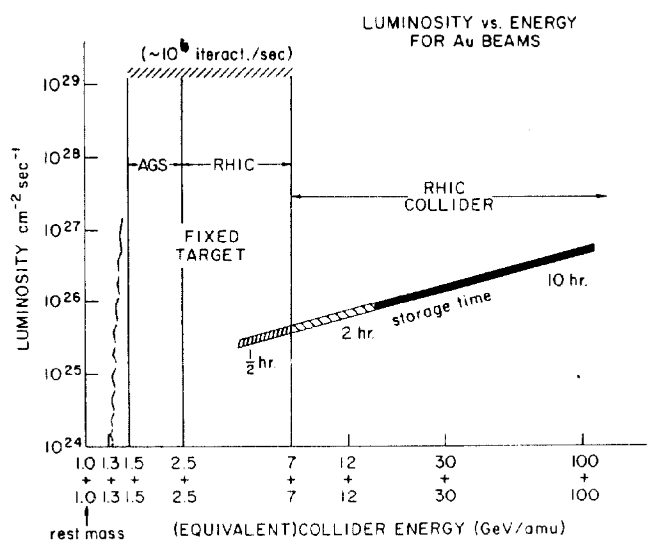


Fig. 5

Fig. 5. Luminosity, center of mass energy profile of RHIC for Gold on Gold interactions.

The next issue is that of experiments and detectors for investigating relativistic heavy ion collisions. As noted earlier one is looking at quark matter in the long distance region of QCD. This is in constrast to experiments in high energy, where it is the hard scattering, short distance behavior that is of interest. As such the phenomena to be studied are of the lower intensity and large multiplicity variety. This has an important influence on the experimental techniques devised to cope with these phenomena. In essence they are of the type used in high energy and medium energy physics; calorimeters with large segmentation $\simeq$ 1,000 cells; tracking chambers either wire or Track Projection Chambers (TPC's); ring imaging Cerenkov counters for lepton detection and, so forth. The possible experimental signatures have been discussed and explored at length at many meetings and conferences. The list is rather extensive; however, before enumerating them I wish to note that this new energy and temperature regime is exploratory. It is in the experimentalists' domain where one must go and look for the emergence of new phenomena without detailed but general theoretical guidance. The global signatures are inclusive particle spectra and particle interferometry which will indicate the temperature and size of the ongoing reactions. Evidence for a phase transition can come from a study of multiparticle correlations, energy flow and flavor content (i.e., change in strangeness Λ, K's, versus π's). One of the nice signatures for restoration of chiral symmetry is resonance fade out--the change in mass of resonances we know and love so well such as the ρ, ϕ, etc. Evidence for the existence of a plasma can be obtained by the use of penetrating probes--those that have long interaction mean free paths such as γ's and ϕ's. They, in contrast to say π mesons, are weakly attenuated by the plasma and as such the γ/π, and ϕ/ω ratio would radically change when a plasma is produced. Other probes are lepton pairs, jets and even W's. Quite an assortment and, of course, others will probably emerge as a function of time. To address the detector issue several workshops were held, the latest at BNL on April 15-19, 1985, with $\sim$100 physicists in attendance. Conceptual designs of several detectors evolved; a calorimeter-based experiment with multiple small aperture spectrometers; a di-muon spectrometer; a large magnetic spectrometer (with TPC capability) and a small angle spectrometer exploring the fragmentation regions. The ability to address the previously discussed physics issues and finding the signatures was considered and was answered in the affirmative. A cost estimate was also made for this suite of detectors--for four interaction regions and a sum of \$55M was derived. This would be sufficient for the first round of experiments.

My final comments have to do with the construction of such a collider. Paul Reardon and his staff (augmented by significant efforts by community physicists and consultants) have produced a proposal, submitted to DOE, for the construction of a relativistic heavy ion collider (RHIC). It makes use of the facilities existing presently at BNL, injector, refrigerator, etc., to arrive at a cost figure of \$134M (FY'84) for the complete accelerator including contingency. It would be very difficult to duplicate this facility at anything near this cost since the replacement of the injector system existing at BNL would cost \$120M (FY'84) and the submitted proposal also utilizes $\sim$\$100M of prior CBA construction funds. The key and pacing element is of course the magnets. A one half length RHIC dipole magnet has been built and successfully tested. It achieved 4.2 Tesla with no training to be compared with a specified RHIC operating field of 3.5 Tesla. Four additional such magnets are being built by industry (Brown-Bovari) and to be tested at BNL this fiscal year. The plan is to contract and build an additional six full length (9.7 meter) arc dipole magnet in FY'86 with quadrupole and correction packages to be built in FY'87. As such an R&D program for implementing a four year construction schedule, starting in FY'88, has been laid out. Improvement in various phases of the design and engineering are constantly being made. However, due to the investment already made at BNL, such a project is ready to be implemented in FY'88 if not sooner if desired.

In summary, I have attempted in this short talk to unveil to you the exciting and important physics opportunities that this new field of relativistic heavy ion physics portends. The ability to appreciably increase the available center of mass energy by one to two orders of magnitude and to be able to explore nuclear interactions in a continuous manner for essentially all possible nuclear species is indeed exciting. One has good reason to expect new phonomena, the most prominent being the quark gluon plasma, but more importantly to find and explore the unexpected that such a unique facility will certainly afford.