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Presented at the NATO Advanced Study Institute, "Hot and Dense Nuclear Matter," Bodrum, Turkey, September 26–October 9, 1993, and to be published in the Proceedings

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THE MESOZOIC ERA OF RELATIVISTIC HEAVY ION PHYSICS AND BEYOND

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INTRODUCTION

In order to understand how matter 15 billion years ago in the form of quarks, gluons and leptons at a temperature of 2×10^{12} °K evolved to become today's Universe, the goal of relativistic and ultra-relativistic heavy ion physics is to understand the equation of state of nuclear, hadronic and partonic matter. This quest is of cross-disciplinary interest. The phase transition from partonic matter to hadronic matter tens of micro-seconds after the beginning of the universe is of interest to cosmology. Fluctuations during this phase transition would influence nucleosynthesis and the understanding of baryonic inhomogeneities in the universe. The nuclear matter equation of state, which describes the incompressibility of nuclear matter, governs neutron star stability. It determines the possible existence of strange quark matter stars and the dynamics of supernova expansion in astrophysics. The existence of collective nuclear phenomena in nuclear physics is also determined by the nuclear equation of state. In relativistic heavy ion collisions collective nuclear flow has been observed and is being studied extensively to obtain a better understanding of the incompressibility of nuclear matter. In high energy nuclear and particle physics, production and excitations of hadronic final states have been studied in detail and are important to an overall understanding of the equation of state of nuclear matter at finite temperature. The possibility in ultra-relativistic heavy ion collisions to create and study highly excited hadronic and partonic degrees of freedom provides a unique opportunity for understanding the behavior of nuclear, hadronic and partonic matter. Study of the QCD vacuum, of particular interest in particle physics, would provide a better understanding of symmetry-breaking mechanisms and the origins of the masses of the various quarks and particles. Creation and study of the quark-gluon plasma, an excitation of the QCD vacuum, is the goal of physicists in the new field of ultra-relativistic heavy ion collisions.

In the pre-Mesozoic days, there were herbivores and carnivores.
In the early days, there were experimentalists and theoreticians.

EVOLUTION OF RELATIVISTIC HEAVY ION PHYSICS - MESOZOIC ERA

The Mesozoic Era spanned the 165 million years from 230 million years ago until 65 million years ago. It consisted of the Triassic, Jurassic and Cretaceous Periods. During this Era the dinosaur species developed, evolved, flourished and vanished. At the same time plant species multiplied. Birds began to develop near the end of this Era and the mammals developed soon after the extinction of the dinosaurs at the end of this Era.

Today we are viewing the "Evolution of Relativistic Heavy Ion Physics." The field recently experienced a transformation which was unexpected and unforeseen in its early days. In this lecture I present the evolution of the field of relativistic heavy ion physics in analogy with the evolution of the dinosaurs in the Mesozoic Era. At the same time, I note that the evolution of high p_t physics and the parton model developed coincidentally in time with that of relativistic heavy ion physics. These developments and the understanding of high p_t (transverse momentum) physics in terms of perturbative quantum chromodynamics are important ingredients helping to end the "Mesozoic Era of Relativistic Heavy Ion Physics" and are the basis of current theoretical developments in the field of ultra-relativistic heavy ion physics.

Triassic Period

The Mesozoic Era started with the Triassic Period which ended approximately 190 million years ago. In this period the early dinosaurs developed. By the end of the period, there were two genetic lines of dinosaurs - the plant-eating ornithiscians, with bird-like hip-bone structure, and the carnivorous saurischians, with lizard-like hip structure. Near the end of this period, there was global mass extinction of most of the large creatures and only the smaller creatures survived into the next period. *

The earliest interests in the possible existence of dense nuclear matter involved primarily its astrophysical implications.[1,2] These investigations concentrated on the possible existence of collapsed nuclei (with radii considerably smaller and densities considerably larger than those of normal nuclei), their properties, their interactions with normal nuclear matter, and the astrophysical consequences of their possible existence. Possible formation and existence during the early universe and in the cores of dense celestial bodies were hypothesized and discussed in terms of the quark model and a composite hadron model.

Jurassic Period

After the Triassic Period came warmer habitats where new dinosaur populations flourished. The first known bird, the Archaeopteryx, emerged and has been linked to the dinosaur. During the same time super-giant dinosaurs, called sauropods, developed. † *Near the end of the Jurassic Period, the climate on earth became arid and the sauropods began to decrease in numbers. The Jurassic Period ended 136 million years ago.*

Experimentalists and theoreticians in the field flourished during this period. With the advent of the first relativistic heavy ion accelerators at the Bevalac in Berkeley and the Synchophasotron in Dubna, searches could be made for abnormal states of dense nuclear matter. Although none were found, many new theoretical ideas came to light. Early speculations of possible exotic states of matter continued to focus on the astrophysical

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* Originally, paleontologists hypothesized that the impact of an extraterrestrial object which formed the one hundred kilometer diameter Manicouagan Impact Crater in Canada was responsible for this catastrophic event. The massive, dust cloud following such an impact would have blocked sunlight, killing most plants, and would have led to starvation of at least the larger dinosaurs. However, recent dating techniques have placed the formation time of the crater several million years before the death of these dinosaurs. Climatic changes may have been responsible, since at this time the large super-continent which spanned the earth was just beginning to break apart. Widespread volcanic activity, geological activity and the appearance of new seas as the super-continent was pulled apart had drastic effects on weather patterns and the dinosaurs as well.

† The sauropods were herbivores, as were the large Diplodocus, Brachiosaurus and Seismosaurus species.

implications of abnormal states of dense nuclear matter.[3] Subsequent field theoretical calculations, assuming chiral symmetry in the σ model, resulted in predictions of abnormal nuclear states and excitation of the vacuum.[4] This generated considerable interest in transforming the state of the vacuum by using relativistic nucleus-nucleus collisions.[5,6] A deconfinement phase transition to quark matter or a quark-gluon plasma[7,8,9] was predicted. At the same time there were also predictions of phase transitions resulting from pion condensation in nuclear matter[10] with possible formation of the condensate in relativistic nucleus-nucleus collisions.[11]

Cretaceous Period

The beginning of this period was marked by a climatic change caused by the drifting apart of the continents. The climate became hot and humid, and shallow seas arose. As the sauropods decreased in numbers, the ornithiscians (bird-hipped herbivores) became dominant. By the late Cretaceous Period, most dinosaurs had developed warm-blooded metabolisms and social tendencies, which aided in their survival. At the same time, plant species that reproduced by flowering and seed distribution grew rapidly. Again with good food sources, the carnivores (e.g. the Tyrannosaurs) grew larger in size.*

At the Bevalac collective nuclear flow[12,13] was discovered, initiating a new "industry" of nuclear flow studies at lower energy accelerators around the world. With predictions of possible chiral symmetry restoration and quark-gluon plasma formation at high energy densities, the focus of the field moved to higher energies. Initial experiments were undertaken with 14.5 GeV/n Si projectiles at the BNL AGS and 200 GeV/n S at the CERN SPS incident on various nuclear targets. The Dual Parton[14] and Lund/FRITIOF[15] string models were developed, generalized and used to describe relativistic heavy ion collisions at CERN fixed target energies. Although no quark-gluon plasma was observed, the experiments suggested that high baryon densities could be produced in the AGS experiments and high energy densities in the CERN experiments.[16] In addition, new models were becoming available. The Lorentz invariant molecular dynamics approach used in the RQMD Model[17] and the Regge-Gribov-Veneziano approach used in the VENUS model[18] predicted substantial baryon stopping at midrapidity, even for the CERN experiments with relatively light ion (A=32) beams.

There were new species of experiments[19,20] operating at the Bevalac, as it was shut down, producing new data on collective nuclear flow and the role of medium effects.† The quest was and still is to extract the nuclear equation of state by separating out compression effects from medium effects from these experiments and new experiments at the SIS accelerator at the GSI. Furthermore, new data is anticipated to investigate nuclear matter in the high baryon density regime using 11.5 GeV/n Au + Au at the BNL AGS and 170 GeV/n Pb + Pb at the CERN SPS. New plans have been made to investigate the high energy density regime using higher energies in heavy ion experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC).

*The Cretaceous Period ended with the extinction of the dinosaurs 65 million years ago.** After extinction of the dinosaurs, new species would develop, including seasonal primates and somewhat later the primates.*

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* Social development along the lines of herding instincts and parental and group care.

† such as the pion dispersion relation, medium effects on pion and delta propagators, resonance widths in-medium, inelastic scattering cross sections in the nuclear medium, and many others.

** One hypothesis is that the impact of an extraterrestrial object with earth 65 million years ago created dust and darkness, upsetting the entire ecosystem of the earth and extinguishing the dinosaurs. This hypothesis originated from the discovery on earth of 65 million year-old deposits of irridium, found rarely on earth but common in asteroids. It was further supported by the recent finding of a 65 million year old crater, approximately 180 kilometers in diameter, on the Yucatan peninsula of Mexico. However, the dinosaurs may have been in decline by the end of the Cretaceous Period and could have vanished before such an impact.

EVOLUTION OF HIGH P_T PARTON PHYSICS - MESOZOIC ERA

Triassic Period

The early quark model[21] was able to describe the static properties of hadrons: hadron spectroscopy, electromagnetic properties and weak decays. However, due to the complexity of the experimentally observed phenomena, hadron dynamics were yet to be successfully described in a theoretically-consistent framework. The observation of scaling behavior of the nucleon structure functions in deep inelastic electron scattering[22,23] led to a description of the hadron, in a frame where the hadron's momentum is infinite, as a system of independent point-like particles.[24,25] This was the basis and origin of the parton model.[26,27]. It immediately led to discussion and predictions of deep inelastic hadronic processes.[28]

Jurassic Period

A connection between the quark and parton models was made and the parton model extended[29] to describe inclusive hadron production at high transverse momentum. The production of highly collimated groups of particles resulting from fragmentation of scattered quarks, called jets, was hypothesized. If a photon were exchanged between incident quarks and the scattered quarks hadronize, then jets of particles would emerge. Furthermore, new elementary parton processes were possible, mediated by the exchange of a spin 1 gluon. The cross section for an exchange of such a gluon would exceed the cross section for photon exchange, which is electromagnetic in nature, by approximately four orders of magnitude. It was then hypothesized that hard-scattered quarks would be emitted from the interaction "back-to-back". The remaining non-interacting "spectator" quarks would continue forward and backward as "beam-jets" resulting in four-jet processes. Proposals were made to measure parton-parton cross-sections directly. However, the early detectors at Fermilab and at the CERN ISR were not designed with the study of these processes in mind. Bjorken[30] pointed out that the use of calorimetry to measure the energy of the hard-scattered partons would for the most part eliminate the problems of parton fragmentation confusing the measurements. Furthermore, Ellis and Kisslinger[31] pointed out that the leading fragment of a jet, which contains the scattered quark as a valence quark, provided a high p_t trigger particle to trigger experiments measuring these high p_t and relatively low cross section processes. They also noted that to be able to interpret the inclusive p_t spectra, better information on structure and fragmentation functions was necessary.

Cretaceous Period

With such good advice, fixed target experiments with specialized jet triggers started accumulating data at Fermilab and CERN. The incident energies of a few hundred GeV, e.g. $\sqrt{s}$ = 20 GeV at the CERN SPS, were too low to successfully study hard parton-parton cross sections. No jets were observed. High multiplicity events dominated over jets.

Subsequently, the Intersecting Storage Ring (ISR) experiments at CERN, $\sqrt{s}$ = 63 GeV, were able to measure large angle jets. Those experiments found that the hard-scattering parton-parton cross sections increased more rapidly (as $\sqrt{s}$) than the high multiplicity events, where $dn/d\eta \sim \ln \sqrt{s}$. This was especially true for $p_t > 2$ GeV/c, where a power law behavior was observed in p_t. Extensive jet studies were then undertaken at the Sp$\bar{p}$S and Tevatron Colliders. Hard parton-parton scattering was measured and found to be described well using perturbative QCD. Furthermore, the structure of nucleons could be described using structure functions in terms of the quark densities.

QCD is able to describe the basic structure and interactions of hadrons in terms of partons. The existence of gluons is postulated in the parton model. The parton evolution is derived from the simple branching transitions

$$q \rightarrow q + g \qquad g \rightarrow g + g \qquad g \rightarrow q + \bar{q}$$

and the Altarelli-Parisi evolution equations.[32] The connection between perturbative QCD and experimental observations is made using a phenomenological approach to describe how partons fragment into hadrons, known as fragmentation functions. (Note that a jet is a collection of hadrons resulting from the fragmentation of a parton.)

THE DYNAMICS OF ULTRA-RELATIVISTIC HEAVY ION COLLISIONS

A new field of theoretical studies has developed using perturbative quantum chromodynamics to calculate the large momentum transfer processes expected in future ultra-relativistic heavy ion collider experiments. This new theoretical approach is a product of the high p_t physics (hard scattering) studied in the "Mesozoic Era of High P_t Parton Physics" and the understanding of low p_t (soft) processes gained from previous relativistic heavy ion studies in the "Mesozoic Era of Relativistic Heavy Ion Physics." A comprehensive description of ultra-relativistic heavy ion physics must necessarily incorporate perturbative QCD to describe the high p_t processes and approaches which describe the low p_t (soft) processes in the ultra-relativistic heavy ion environment.

High P_t Processes

The initial parton distributions in nuclei, the nuclear structure functions, are essential to be able to specify the initial conditions of these collisions. In turn, specific knowledge of the gluon, valence quark and sea quark distributions in the nucleon is required, prior to understanding their distributions in nuclei. There is evidence for the presence of semi-hard processes with $p_t \geq 2$ GeV/c,[33] often referred to as mini-jets:[34,35] the inelastic cross sections are observed to increase with $\sqrt{s}$, the tail of the charged particle p_t distribution (dN_{ch}/dp_t at $p_t \geq 2$ GeV/c) increases with $\sqrt{s}$, the pseudorapidity density of charged particles ($dN_{ch}/d\eta$) increases with ln ($\sqrt{s}$) and fluctuations in N_{ch} increase with $\sqrt{s}$. Extremely hard processes lead to jet production, which has been studied extensively at the colliders. There is systematic data on jet production as seen in Fig. 1 and the production processes are well understood using perturbative QCD. Notice that the jet cross section at $\sqrt{s_{nn}}$ = 200 GeV (RHIC energy) in Fig. 1 is significant and that at $\sqrt{s_{nn}}$ = 6300 GeV (LHC energy) jets will become even more prevalent. These semi-hard and hard scattering processes will influence the evolution of ultra-relativistic heavy ion collisions and must be considered for a complete description.

Nucleon and Nuclear Structure Functions

In order to develop a description of ultra-relativistic heavy ion collisions from the partonic degrees of freedom, the structure functions (parton distributions) of the nucleon and nucleus must be measured over the range of x and Q^2 relevant to future RHIC and LHC heavy ion collisions to be studied. Here $Q^2 = 4EE'\sin^2(\Theta_L/2)$ is the four-momentum transferred to the struck quark in the nucleon, where E is the incident energy, E' and Θ_L the energy and scattering angle of the scattered particle. The variable $x = Q^2/2M(E-E')$ is the ratio of the four-momentum transferred to the energy transferred. It is a measure of the fraction of the total momentum of the nucleon that is carried by the struck quark.

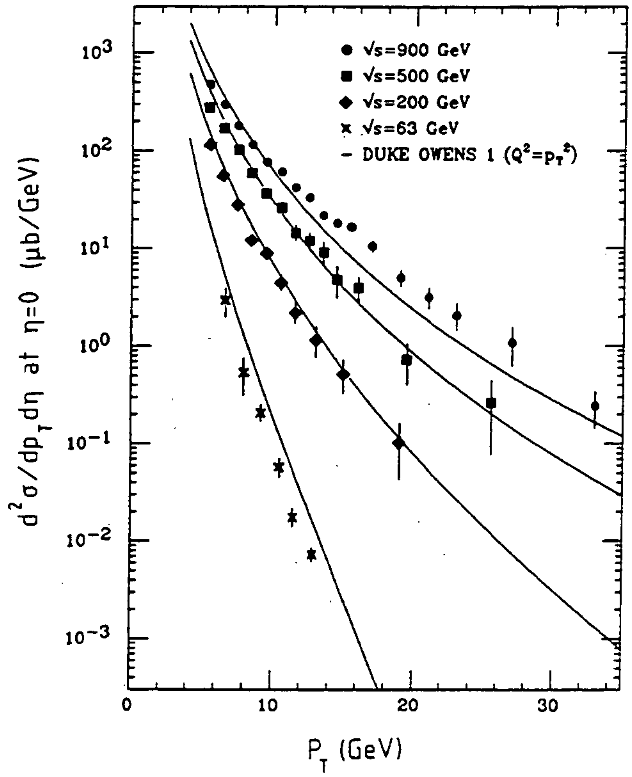

Fig. 1. Inclusive jet production cross section data at $\eta = 0$ for various incident energies.[36]

The regions of x probed by semi-hard and hard collisions will be significantly different for RHIC and LHC interactions. For example, back-to-back gluon jets at midrapidity corresponding to semi-hard ($p_t = 2$ GeV/c) and hard collisions ($p_t = 10$ GeV/c) at the SPS, RHIC and LHC will have the following values of x:

p_t	x at SPS	x at RHIC	x at LHC
2 GeV	2×10^{-1}	2×10^{-2}	6×10^{-4}
10 GeV	1.0	1×10^{-1}	3×10^{-3}

The parton distributions of the nucleon have been studied at fixed target facilities for the x and Q^2 regimes relevant to the SPS and at slightly larger x-values (and lower Q^2 values) than anticipated for semi-hard and hard collisions at RHIC. Only recently in the electron-proton collider at HERA have structure functions of the proton been investigated[37] in the region $10^{-4} < x < 10^{-2}$ at Q^2 relevant to hard collisions at the LHC. Future information from HERA, RHIC and LHC will be necessary to understand the parton distributions of the proton in the x and Q^2 regimes relevant to RHIC and LHC.

The parton distributions of nucleons in the nucleus were first observed to be different from those of free nucleons in the well-known EMC experiments.[38] These initial studies covered the region $0.05 < x < 0.7$. Since then, extensive studies of parton distributions of nucleons in nuclei have been made over the range $6 \times 10^{-4} < x < 1$ at Q^2 values relevant to RHIC and LHC.[39] A schematic curve representing the ratio of cross sections for deep inelastic lepton scattering from heavy nuclei relative to deuterium is displayed in Fig.2. Notice that the ratio rises above 1 near $x = 1$ due to Fermi motion.[40] The EMC effect is observed as a dip at approximately $0.2 < x < 0.6$. Here the valence quark distribution in nucleons of the nucleus is depleted relative to that of a free nucleon. Several explanations have been proposed for this effect, ranging from an excess of virtual pions in the nucleus to enlarged bags of freely-interacting valence quarks. At lower values of x, i.e. $0.07 < x <$

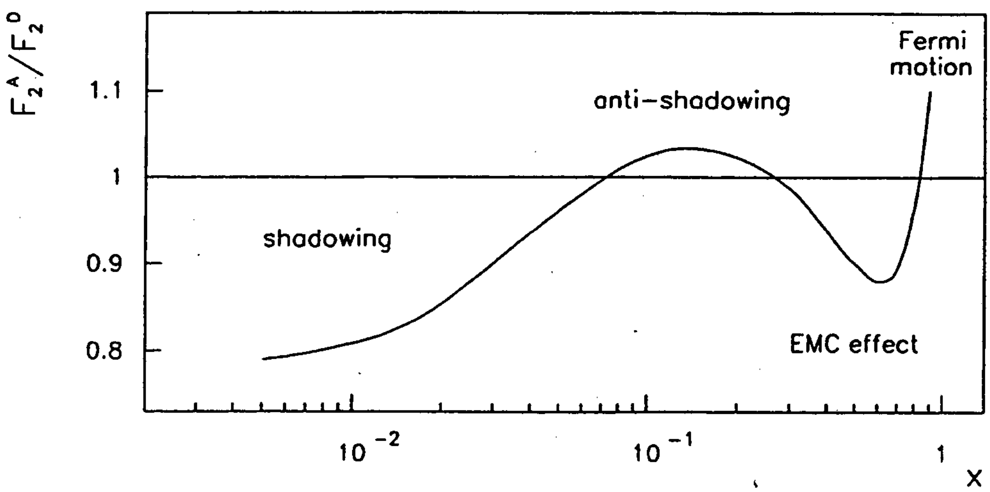

Fig. 2. Schematic curve representing the ratio of cross sections for deep-inelastic lepton scattering from heavy nuclei relative to deuterium.[39] See text for description.

0.2, the ratio rises above 1. This region is known as the anti-shadowing region. For $x < 0.05$ the ratio again shows a depletion and shadowing occurs. Explanations of the shadowing and anti-shadowing regions are intimately related. Shadowing has long been observed in hadron-nucleus interactions.[41] Due to the strong interaction, scattering occurs in these interactions near the surface of the target nucleus and cross sections are proportional to the surface area, i.e. ~ $A_T^{2/3}$. The front surface of the target nucleus shadows the rear target nucleons. This was not expected, a priori, in lepton scattering experiments, where the interactions occur through the transfer of a virtual photon. However, shadowing via real and virtual photo-absorption can be described in terms of the Vector Dominance Model.[42] This can be understood simply from the fact that the photon is sometimes a superposition of hadronic states which have the same quantum numbers as the photon, i.e. the vector mesons. It is not surprising that photon-nucleus cross sections are also shadowed similar to those of hadron-nucleus interactions. Recently, partonic models based on QCD have been developed to describe the shadowing and anti-shadowing observed in deep-inelastic lepton scattering. In these models, the low momentum partons are spread out over a large distance, due to the Uncertainty Principle. This distance is comparable to the separation of nucleons in the nucleus. Thus partons from different nucleons overlap, fuse and increase the number of high momentum partons at the expense of the lower momentum ones. The anti-shadowing and shadowing result naturally from these models. New data from the Fermilab E665 experiment at lower values of x and the CERN NMC experiment are expected to tightly constrain these models in the low x shadowing region. Nuclear shadowing of gluons[43] could have a large effect on the parton evolution and dynamics of ultra-relativistic heavy ion collisions. It will be important to have more information on the gluon shadowing and to measure the effects of nuclear shadowing by systematic studies of pp and pA interactions at RHIC.

Rapid Gluon Dominance

In ultra-relativistic heavy ion collisions a rapid dominance of gluons in the early stages of the collisions has been hypothesized.[44] This can easily be understood by considering the following. Compare the expected behavior of the elementary parton-parton cross sections

$$\sigma(g+g \rightarrow g+g) \;>\; \sigma(g+q \rightarrow g+q) \;>\; \sigma(q+q \rightarrow q+q) \;>\; \sigma(g+g \rightarrow q+g)$$

where q = quark and g = gluon. The resulting parton mean-free paths are such that Λ(quark) ~ 9/4 x Λ(gluon). Thus, on the average gluons interact more frequently than quarks when traversing partonic matter. If we now consider that the branchings $g \rightarrow g+g$ and $q \rightarrow q+g$ occur more frequently than $g \rightarrow q+q$, then in AA collisions if the elementary cross sections are sufficiently large, we expect that gluons multiply more quickly than quarks. In fact, the cross section $\sigma(g + g \rightarrow g + g)$ is expected to be large, and thus gluons rapidly dominate the system. This is exacerbated by the possibility of multiple-gluon branching processes $g \rightarrow ng$, where $n > 1$.

Parton Models for Ultra-Relativistic Heavy Ion Collisions

Several models have been developed recently to describe the evolution of ultra-relativistic heavy ion collisions from the partonic degrees of freedom. These include the HIJING Monte Carlo,[45] Parton Cascade Model,[46] and the Dual Parton Model with cascading and minijets.[47] The general results of these codes are similar in many ways. The primary differences can be attributed to the cut-off momentum used in each code to separate the soft and hard processes, and the different methods of treating the soft processes.

I will outline the approach of one of these models, the Parton Cascade Model (PCM), to give the reader a feeling for what is involved. The PCM is a fully relativistic, space-time approach. It assumes that the short-range parton-parton interactions and the hadronization process factorize. A relativistically co-variant transport equation with a collision term is used. The parton substructure is derived from nucleon structure functions. Parton-parton interactions are calculated using perturbative QCD and the hadronization is governed by the parton fragmentation functions. Displayed in Fig. 3 are the results of the PCM for the time evolution of the pressure, number density, energy density, entropy and temperature in central Au + Au collisions at $\sqrt{s_{nn}}$ = 200 GeV. There is a consensus among the HIJING, PCM and lowest order QCD[48] calculations. Initially there are large energy and parton (primarily gluon) densities, a high "temperature" $T \equiv 4/3(\varepsilon/s)$, rapid entropy production per particle within the first 0.3 - 0.5 fm/c, and thermal equilibration of gluons within the first 1 - 2 fm/c. A hot, gluon (minijet) plasma is formed just after the onset of interactions. It appears to be locally thermally equilibrated. However, an outstanding question is whether rapid chemical equilibration occurs. The model calculations suggest not, primarily due to the small number of quarks. However, better information on the gluon shadowing in nuclei is necessary to be able to make accurate predictions about the parton evolution. The hot, gluon plasma expands becoming a parton gas, which later hadronizes into a hadron gas. Since the models and some of the input distributions are still in an adolescent stage, improvements are expected and predictions may change. In particular, work is needed to bring together in one model a more realistic treatment of the soft interactions coupled to the perturbative QCD treatment of the hard-scattering interactions. An example would be an approach integrating a perturbative QCD description for the hard-scattering processes and a string model description for the soft processes.

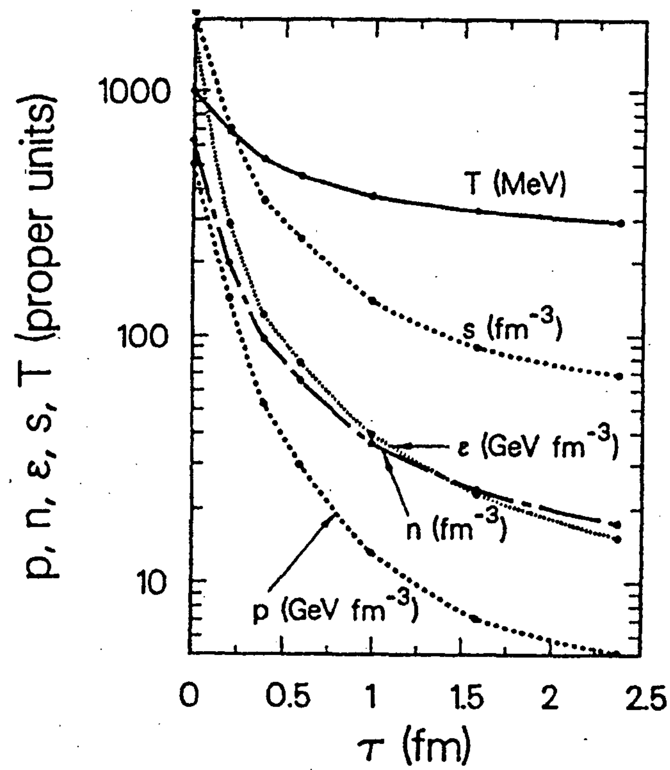

Fig. 3. Parton Cascade Model predictions for the pressure, number density, energy density, entropy and temperature in the local rest frame as a function of time for central Au + Au collisions at $\sqrt{s_{nn}} = 200$ GeV.[49]

FUTURE ULTRA-RELATIVISTIC HEAVY ION EXPERIMENTS

With RHIC and LHC on the horizon, heavy ion collider experiments are presently being designed and constructed to be able to address a range of physics from the soft-scattering processes to the hard-scattering ones. Systematic studies of pp, pA and various AA interactions will be made to understand the underlying structure of the incident nucleons and nuclei. Likewise, systematic studies will be made to obtain a detailed understanding of the space-time evolution, i.e. dynamics, of the AA collision processes. Unless nature is extremely generous and quark-gluon plasma signatures[50] standout visibly, it is most likely that the quark-gluon plasma may be studied only after systematic studies determine the structure of the incident nuclei and the collision dynamics. The physics goals and status of the heavy ion experiments in various stages of development for RHIC and LHC have recently been presented. These include two large experiments at RHIC (STAR[51] and PHENIX[52]), two smaller ones at RHIC (BRAHMS[53] and PHOBOS[54]) and the ALICE[55] experiment at the LHC. I will briefly discuss the STAR experiment and refer the reader to the above references for details on the future ultra-relativistic heavy ion experiments that are presently being planned.

The Solenoidal Tracker At RHIC (STAR)

The detector systems of the STAR experiment at RHIC are shown in Fig. 4. Measurements will be made at midrapidity over a large pseudo-rapidity range ($|\eta| < 4.5$) with full azimuthal coverage ($\Delta\phi = 2\pi$) and azimuthal symmetry. This experiment is designed around a large solenoid magnet with a 0.5 T field for precision tracking. Momentum measurements and identification via dE/dx at low p_t for charged-particles will be made using a silicon vertex tracker (SVT, covering pseudorapidities $-1 \leq \eta \leq 1$)

near the intersecting beams and a time projection chamber (TPC, covering $-2 \leq \eta \leq 2$). Additional tracking of charged-particles will be made in the forward regions (XTPC, $2 \leq |\eta| \leq 4.5$) downstream from the solenoid in external time projection chambers. Triggering on the centrality of collisions will be performed using a central trigger barrel ($-1 \leq \eta \leq 1$) of scintillators and the TPC endcap readout chambers ($1 \leq |\eta| \leq 2$) to trigger on charge multiplicity. Approximate vertex position for on-line triggering will be determined from timing in the vertex position detectors (VPD), which consist of arrays of Cherenkov counters in the forward directions. Also planned are an electromagnetic calorimeter (EMC) just inside the magnet coil to trigger on and measure jets and the transverse energy of events, and a time-of-flight system surrounding the TPC for particle identification at high momenta (in place of the central trigger barrel).

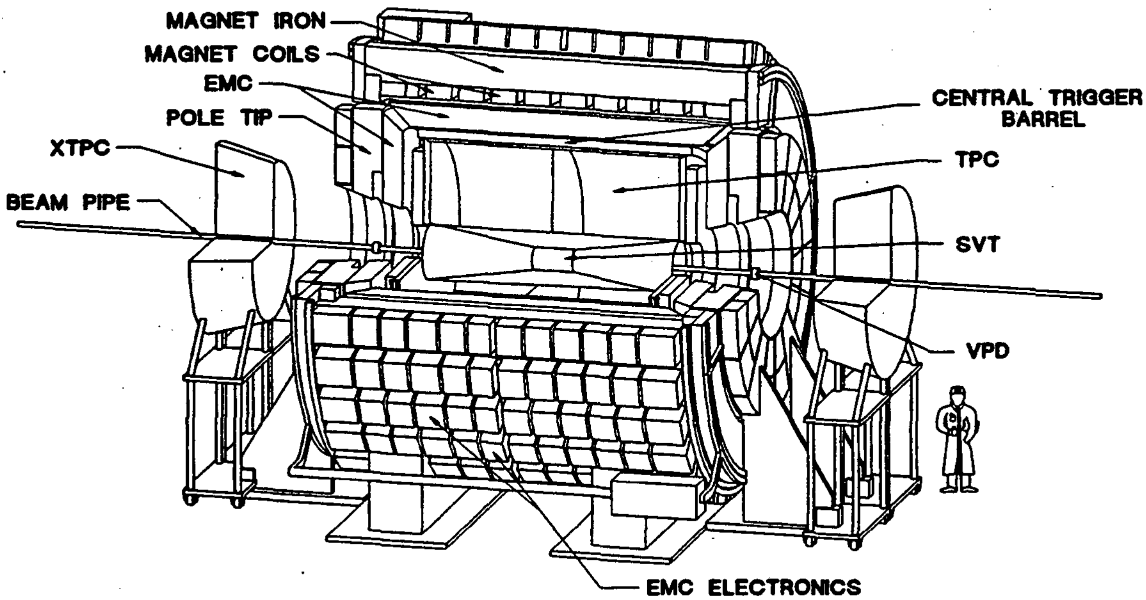

Fig. 4. Layout of the STAR Experiment. See text for description.

Event-by-event measurement of global observables - such as temperature, flavor composition, collision geometry, reaction dynamics, and energy or entropy density fluctuations - will be possible in STAR because of its large solid angle coverage and the very high charged particle densities, $dn_{ch}/d\eta \approx 1000$ expected in nucleus-nucleus collisions at RHIC. This will allow novel determination of the thermodynamic properties of single events. Correlations between observables made on an event-by-event basis may isolate potentially interesting events. These studies will focus on identifying special events with thermodynamic properties characteristic of a quark-gluon plasma as well as determining the collision dynamics.

Measurable jet yields at RHIC will allow investigations of hard QCD processes via both highly segmented calorimetry and high p_t single particle measurements in a tracking system. A systematic study of particle and jet production will be carried out over a range of colliding nuclei from pp through p-nucleus up to Au-Au, over a range of impact parameters from peripheral to central, and over the range of energies available at RHIC. The pp interactions will help establish the gluon structure functions, the p-nucleus interactions will be used to study the nuclear gluon distributions and thus the extent of shadowing of gluons in the nucleus, while the nucleus-nucleus interactions are essential to determine the degree of quenching[56] of hard-scattered partons in the surrounding nuclear, hadronic, and partonic matter. Measurements of the remnants of hard-scattered

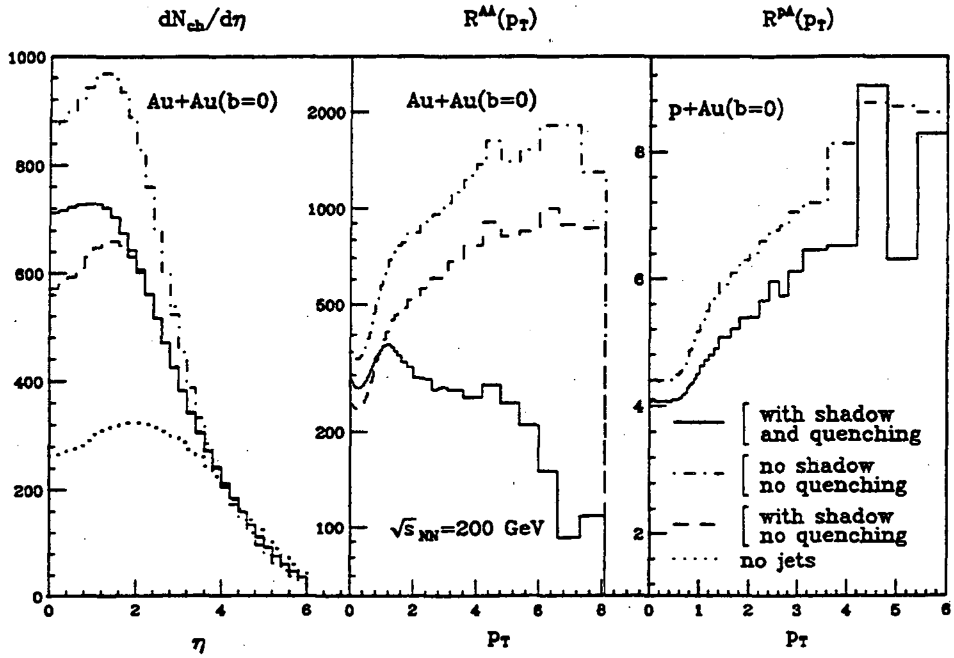

Fig. 5. Predictions of the HIJING Model for the pseudo-rapidity and transverse momentum distributions of charged hadrons in central Au + Au and p + Au collisions at RHIC. Displayed are the pseudo-rapidity distribution for central Au + Au (left panel), the ratio $R^{AB}(p_t)$ of the inclusive p_t spectrum of charged hadrons in central Au + Au collisions relative to that of pp (central panel), and the ratio $R^{pA}(p_t)$ of the inclusive p_t spectrum of charged hadrons in central p + Au collisions relative to that of pp (right panel).[56]

partons will be used as a penetrating probe of the QGP, and will provide new information on the nucleon and nuclear structure functions and parton shadowing in nuclei. An example of the effects of parton shadowing and quenching on the single particle distributions at midrapidity and at high transverse momentum can be seen in Fig. 5.

SUMMARY

Understanding the early stages of ultra-relativistic heavy ion collisions is fundamental to understanding the subsequent evolution of the system and determining the existence and type of phase transition between partonic and hadronic matter. The early dynamics of these collisions involving hard parton-parton interactions can be calculated using perturbative QCD. Various theoretical approaches result in predictions that highly excited ($T_{effective}$ ~ 500 MeV), predominantly gluonic matter will be formed rapidly, within the first 0.3 fm/c of the collision process. The system then evolves through subsequent interactions and reinteractions, effectively cooling and expanding. The most important question affecting potential phase transitions between partonic and hadronic matter is whether chemical and/or thermal equilibrium are reached among the partonic degrees of freedom. Answering such questions requires a detailed understanding of the partonic content of the incident nuclei. Obtaining this information is of interest to both nuclear and particle physicists and will require measurements at various accelerators, including proton-proton and proton-nucleus measurements at high energy colliders. The Relativistic Heavy Ion Collider (RHIC) is being constructed and the Large Hadron Collider is being considered for construction and injection with heavy ions in order to investigate in the laboratory these new and fundamental properties of matter.

I have attempted to place in perspective the evolution of relativistic heavy ion physics and that of high transverse momentum parton physics. Both evolved simultaneously and their intersection has led to new theoretical and experimental approaches to the study and understanding of ultra-relativistic heavy ion collisions. A combination of what has been learned from both fields will be necessary to understand ultra-relativistic heavy ion collisions; the behavior of nuclear, hadronic and partonic matter at high energy densities; and how the Universe evolved from a hot plasma of quarks, gluons and leptons 10 micro-seconds after its beginning to what we now know.

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