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HIGH ENERGY NUCLEAR COLLISIONS

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PL 12: High energy nuclear collisions

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Abstract. The field of nucleus-nucleus collisions at "ultrarelativistic" energies is surveyed with emphasis on photon and lepton measurements. Prospects for future experiments at the Relativistic Heavy Ion Collider and the Large Hadron Collider are discussed.

1 Introduction

The foundations of studies of nucleus-nucleus collisions at relativistic energies were laid in the mid-seventies at the Bevalac facility located at the Lawrence Berkeley National Laboratory. An extensive and very productive program was carried out, making use of beams of highly-ionized heavy nuclei (heavy ions) with energies of 1-2 GeV/nucleon. Insights gained from these studies, together with a number of theoretical developments, led to the somewhat intuitive postulation that at certain sufficiently high combinations of temperature and baryon density, which may be achieved in nucleus-nucleus collisions at sufficiently high energies, quarks and gluons may become deconfined within a volume of nuclear dimensions, leading to the formation of the quark-gluon plasma (QGP). It is believed that the entire universe existed in the QGP state a few microseconds after the Big Bang of creation, before free quarks and gluons hadronized to protons and neutrons. The intriguing possibility of creating this state of matter in the laboratory has driven the construction of several experimental facilities and has given rise to an extensive and vibrant field of research at the intersection of nuclear and particle physics.

This presentation covers three broad topics: a brief introduction to the field of nucleus-nucleus collisions at relativistic energies; a discussion of several topics illustrating what we have learned after more than a decade of fixed target experiments; and an indication of what the future may bring at the Relativistic Heavy Ion Collider (RHIC) under construction at the Brookhaven National Laboratory (BNL) and at the Large Hadron Collider (LHC) planned at CERN.

Present experimental results from nucleus-nucleus collisions at very high energies (colloquially referred to as "ultrarelativistic" energies) have been obtained at BNL's AGS and at CERN's SPS. Both facilities have provided us with beams of heavy ions ranging from relatively light nuclei, such as Be, C, and O, to very heavy ions, such as Au and Pb. The highest energies available are 15 GeV/nucleon at the AGS and 200 GeV/nucleon at the SPS. Since it is not possible in the available time to cover systematically all available experimental results, I have chosen to highlight data obtained from measurements of photons and leptons. These so-called "penetrating probes" have mean free paths that are much larger than the size of a system of nuclear dimensions and are very likely to escape the reaction zone without interacting with the surrounding hot dense medium. Thus, they are likely to provide us with direct information on the conditions that existed at the time of their production. All available measurements making use of these penetrating probes (measurements of photons, electrons, and muons) have been carried out at the SPS and they constitute the most intriguing results obtained thus far. Extensive direct measurements of hadrons have been made both at the AGS and at the SPS. However, hadron measurement results that I present here for illustration purposes were also all obtained at the SPS. This choice was made in part due to the fact that no AGS data have been presented in parallel sessions at this conference and because the points that need to be made do not depend, to any great extent, on the difference in the energies available at the AGS and at the SPS.

Most recent QCD calculations provide us with strong theoretical indications that the phase transition to the QGP is likely to exist. This transition should manifest itself in sudden changes in system properties such as the specific heat, the energy density, and the magnitude of the quark mass scale. From state-of-the-art studies, it is concluded that the critical temperature, T_c, associated with the transition is in the 160- to 200-MeV range at an energy density of 2.5 ± 0.8 GeV/fm^3. For example, QCD calculations on an $8^3 \times 4$ lattice with two dynamical quark flavors [1] exhibit a sharp discontinuity in color mobility (related to deconfinement) as a function of increasing inverse lattice coupling constant (related to the temperature of a thermalized system). At very nearly the same value of the inverse coupling constant, the quark mass is found to drop steeply. This suggests that the quarks (and, hence, the hadrons) loose their mass at the critical temperature. This process is called chiral symmetry restoration, and within the framework of these calculations, it is predicted to manifest itself simultaneously with deconfinement.

The evolution of a head-on, central, collision between two large nuclei such as Pb at the SPS energy of 158 GeV/nucleon is likely to proceed as follows: first, if the target and projectile are not transparent to each other, there will be a rapid buildup of baryon density consisting of target and projectile nucleons. This process is often referred to as "stopping." If the energy density attained at this stage is sufficiently high, partonic matter may be formed. There are two crucial questions at these early reaction stages. If partonic matter is formed, does it achieve thermal equilibrium as would be expected if the QGP is formed? Is chiral symmetry simultaneously restored? In any event, whether the system consists of the QGP or of hot dense hadronic matter, it is known that as the reaction evolves, the initial "fireball" expands both in the longitudinal and in the transverse direction accompanied by cooling.

Hadronization takes place leading, in turn, to chemical freeze-out and, finally, to kinetic freeze-out, i.e., to a complete decoupling of the constituents. Thus, the degree of stopping of the colliding nuclei and the energy density attained in the early phase of the collision relate directly to the probability of QGP formation and play a crucial role in the subsequent evolution of the reaction.

2 Global event characteristics

Proton rapidity distributions, which relate to the degree of stopping, are shown in Fig. 1 for 200-GeV/nucleon S+S and 158-GeV/nucleon Pb+Pb collisions [2]. In the Pb case the proton rapidity distribution peaks at midrapidity, indicating a high degree of stopping. In contrast, in the case of the smaller S+S system, the degree of stopping is lower, as is evidenced by only a partial shift of the original target and projectile protons toward midrapidity. Thus, the highest energy density attained in the early phase of the reaction is likely to be significantly larger in the Pb+Pb case than in the S+S case.

Traditionally, estimates of attained energy densities are obtained from measured transverse energy rapidity (or pseudorapidity) distributions. There is, however, a conceptual problem with this process, since it is not clear to what stage of the reaction the extracted values refer. The buildup of energy density results from the dynamics of the collision (sharp increase in baryon density per unit volume) as well as from particle formation. Yet, only educated guesses are available for the formation time (e.g., 1 fm/c), and it remains virtually a free parameter. It is even likely that the expansion process is initiated before particle formation is terminated. The most frequently used method of estimating the attained energy density is attributed to Bjorken [3]. It assumes longitudinal growth and free hydrodynamic flow in a baryon-free region. Strictly speaking, given the assumptions of the Bjorken approach, it should be applied only to cases where there is a broad (baryon-free) plateau in the $dE_T/d\eta$ distribution, and not to distributions with large midrapidity baryon admixtures as is the case at SPS energies (see Fig. 1). Consequently, applying the Bjorken ansatz to our systems results in overestimates of attained energy densities. This reservation notwithstanding, Bjorken energy densities are found to be in the range of 2.5 to 3 GeV/fm^3 for the reactions considered here. As was pointed out earlier, theoretical estimates of the energy density required for the phase transition to the QGP to take place are also in the 2- to 3-GeV/fm^3 range, with a broad band of uncertainty around this value. Thus, if the required energy densities have not actually been attained at SPS energies, we are probably not very far from this goal.

3 Measurements of single photons

Directly radiated single photons, because of their low interaction probability, are likely to reflect the thermal properties of hot and dense matter, whether

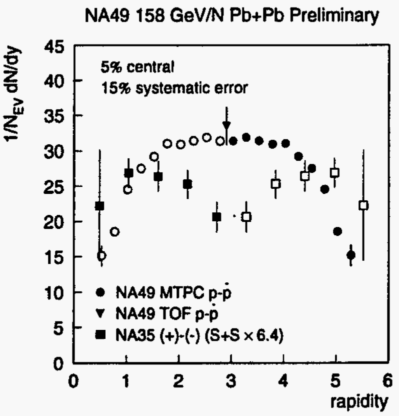

Fig. 1. Rapidity distribution of participant protons in central Pb+Pb and S+S collisions.

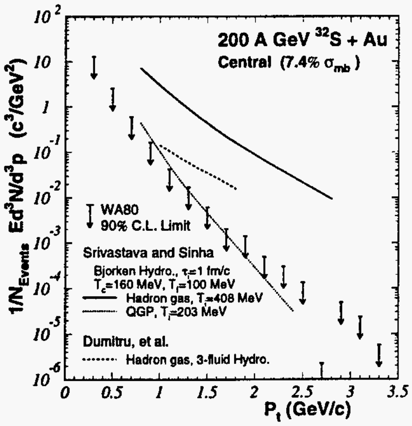

Fig. 2. Upper limits on the excess photon yield for collisions of ^{32}S+Au at 200 GeV/nucleon. For theoretical curves see the text.

it be a hadron gas, the QGP, or a mixture of both. Expected contributions to the observed photon yield from the QGP very probably include $q - \bar{q}$ annihilation and the QCD equivalent of the Compton process in which a quark interacts with a gluon to produce a photon. However, a hot hadron gas is expected to radiate photons with emission rates that are similar to those that are expected from the QGP [4]. The dominant production mechanisms in a hot hadron medium are expected to be $\pi^+\pi^- \rightarrow \rho\gamma$ and $\pi\rho \rightarrow \pi\gamma$. Given a fixed energy density produced in a given collision, a higher temperature is attained in a thermalized system that has a lower number of degrees of freedom. In the case of the QGP, considering spin/polarization, isospin and color, the number of degrees of freedom is 12 for the quarks and 16 for the gluons. For a hadron gas the estimated number of degrees of freedom depends on specific assumptions regarding its constituents. However, even when all plausible hadron resonances are taken into account, the number of degrees of freedom is lower, and hence the predicted temperature and photon yield are higher in a hadron-gas scenario than in a QGP scenario.

The measurement of direct photons is difficult since they are embedded in a very large combinatorial background from the decay of π^0 mesons. The WA80 Collaboration [5] has deduced direct photon yields for ^{32}S+Au at 200 GeV/nucleon on a statistical basis, as a function of p_T, by comparing the total photon yield to that which can be attributed to all long-lived decays. The results, which are sensitive at the 5% level of inclusive photons, are consistent (within 1σ) with the absence of photon excess in both central and peripheral collisions. The deduced upper limits at the 90% confidence level are shown as a function of p_T for central collisions in Fig. 2. Also shown in Fig. 2 are calculated thermal photon production yields [6] expected from a hot hadron gas with only a limited number of degrees of freedom (solid curve) and from the QGP (dotted curve). The dashed curve gives results from more elaborate hadron-gas calculations of Dumitru et al [7]. The upper limits on direct photon production are important in that they rule out the possibility that a high initial temperature may have been attained in the early phase of the collision. Sollfrank et al. have concluded on the basis of reference [5] that the initial temperature of the system could not have exceeded 250 MeV [8].

4 Anomalous *J/psi* suppression in Pb+Pb collisions

The anomalous J/ψ suppression recently observed in Pb+Pb collisions is providing the "nuclear" community with perhaps the most intriguing results. J/ψ suppression was proposed by Matsui and Satz as an unambiguous signature of the QGP in 1986 [9], before the start of the experimental program. The predicted suppression of charmonium states in the QGP is due to the Debye screening of the $c\bar{c}$ binding potential by the freely-moving color charges. Early in the collision process, $c\bar{c}$ pairs are created at small separations, and if they are to lead to the production of a bound vector meson state, they must separate to its appropriate asymptotic size. If the radius of the vector meson of interest is larger than the screening distance, the quark and antiquark may "lose contact," leading to open charm $(D, \overline{D})$ production. Since the screening distance is small in the presence of many colored objects, the conditions for suppression of the J/ψ and the ψ' in the QGP are very good. The NA38 collaboration set out to determine the predicted J/ψ suppression by measuring muon pairs and reported results consistent with the theoretical predictions as early as 1987. There were, however, several developments which cast doubt on the QGP interpretation of the measurements. First, similar effects were found in p-A reactions. Second, several alternative theoretical interpretations were proposed. These include pre-resonance absorption to the $c\bar{c}g$ state and the breaking-up effects of "comovers" in a confined hadronic medium. Before lead beams became available at CERN, extensive J/ψ measurements (relative to the Drell-Yan, D-Y, continuum resulting from the annihilation of light quarks) were made by the NA38/50/51 collaborations ranging from p-p and p-A collisions to oxygen- and sulfur-induced A-A reactions. The results are shown in Fig. 3. It is seen that the J/ψ to D-Y ratios follow closely a straight line when plotted as a function of a geometrical parameter L, which represents the average length of the $c\bar{c}$ path through nuclear matter. (L is related to the impact parameter and, hence, to E_T.) The common view, prior to the availability in 1996 of the lead-beam data, was that all data can be accounted for by absorption and that there was no need to postulate a QGP scenario.

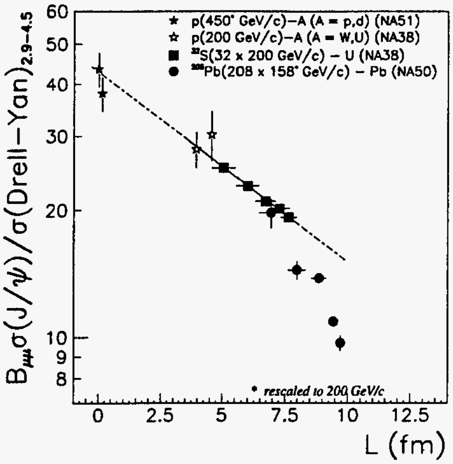

Fig. 3. Ratios of J/ψ to Drell-Yan cross sections versus the average length L of the path in nuclear matter [10].

The recent NA 50 J/ψ results from Pb+Pb reactions at 158 GeV/nucleon are also shown in Fig. 3 [10]. It is seen that the lead data deviate from the earlier systematic trend. Furthermore, there appear to be two "steps" in the data, indicating possible threshold effects. Thus, the J/ψ suppression appears to be much stronger than expected from standard absorption scenarios. Furthermore, the suppression depends strongly on E_T and, hence, on reaction centrality and on energy density. Although these results are still the subject of differing interpretations, many hold the belief that they provide us with strong evidence for collective parton behavior in nucleus-nucleus collisions. To explore these interesting findings further, it would be desirable to have available results on the p_T dependence of the suppression as well as studies indicating the onset of the anomalous suppression, possibly via the investigation of peripheral collisions. Studies making use of inverse kinematics which would minimize absorption in confined matter would also be of interest.

5 Low-mass electron pair production

Also of great interest are the results of the CERES (NA45) collaboration on vector meson production as deduced from measurements of low-mass electron pairs [11]. These data indicate that the chiral symmetry restoration transition may have manifested itself in certain reactions. The electron pairs are measured in the mass range from about 50 MeV to 1.2 GeV by means of "hadron-blind" tracking, using two RICH detectors. Studies of the p-Au reaction at 450 GeV indicate that the inclusive invariant mass spectrum can be fully accounted for by electron pairs stemming from known hadronic decays. In contrast, in the case of the S+Au reaction at 200 GeV/nucleon, there is a large enhancement of the electron pair yield over the yield that can be accounted for by hadronic sources (Fig. 4). The enhancement factor, defined as the ratio of the integral of the data to the integral of hadronic sources, was found to be 5.0 ± 0.7.

The findings of the CERES collaboration stimulated a great deal of theoretical activity. By taking into account in-medium pion annihilation, bremsstrahlung, and other effects, many of the calculations were able to reproduce the data in the ρ-mass region and above. One such calculation is shown in Fig. 5 (dotted curve). However, none of the calculations were able to reproduce the data in the 0.2- to 0.6-GeV mass range, unless effects of chiral restoration lowering of the ρ and ω masses were incorporated in the calculations [12] (see thin solid line in Fig. 5). More recent CERES data from Pb-Au collisions at 158 GeV/nucleon exhibit essentially the same features as the S+Au data, although the observed enhancement was found to be somewhat lower. A comparison of calculations to these results was shown at this conference by P. Filip.

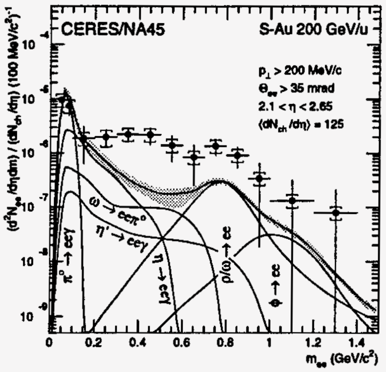

Fig. 4. Dilepton invariant mass spectrum from S+Au at 200 GeV/nucleon. Data are shown together with known hadronic decay contributions.

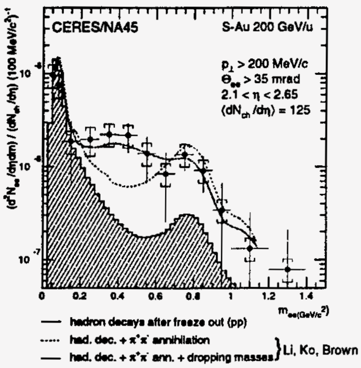

Fig. 5. Same as Fig. 4 but with comparisons to theoretical calculations (see text). Contributions from hadron sources are given by the shaded area.

6 Expansion, hadronization, and freeze-out

The interesting data on strangeness enhancement covered at the conference will not be presented here due to the space limitations. However, measurements of hyperons and antihyperons also provide us with valuable information on primordial yield ratios resulting from partonic coalescence essentially free of reequilibration in the subsequent hadronic expansion phase. The measurements were made by the WA85 collaboration for S+W at 200 GeV/nucleon [13], and an analysis was performed [14] in which various yield ratios describe curves of allowed Hagedorn model solutions in a plane of temperature, T, and baryochemical potential, μ_B. The curves were found to intersect at about $T = 185$ MeV and $\mu_B = 0.24$ GeV. These values can be viewed as an indication of the hadronization phase-transition point at SPS energies.

Transverse mass spectra of all produced particles (with the exception of pions at low m_T values) are reasonably well reproduced by exponential functions from which inverse slope parameters T can be extracted. Values of T are shown in Fig. 6 as a function of particle mass ranging from pions and kaons to deuterons, for particles produced in central Pb+Pb collisions [2]. The inverse slope parameters for the heaviest particles far exceed the Hagedorn limit, and the increase with mass is not consistent with a simple hadronic fireball model in which all T values should be equal for primary emitted hadrons. It is possible that the large T values may be explained by a large transverse flow within the framework of a hydrodynamical model.

A picture that emerges from the above findings is that observed hadrons may not all stem from a common global chemical equilibrium. Species with a large chemical relaxation time, such as hyperons, "freeze-in" at high values of temperature and baryon density. On the other hand, pions and kaons with short relaxation times follow the expansion, staying in equilibrium until their turn comes to freeze-in at a lower temperature and baryon density. Thus, sequential freeze-in stages provide us with markers of successive expansion stages.

Within model assumptions, it is possible to extract from the m_T spectra values of the temperature and of the transverse flow velocity, $\beta_\perp$, at thermal freeze-out [15]. Results are shown for negative hadrons (mostly pions) and for deuterons in Fig. 7. It is seen that many combinations of T and $\beta_\perp$ fit the data equally well. Fortunately, the dependence of the two-pion Bose-Einstein correlation on the average transverse momentum of the pion pair constrains the values of $\beta_\perp$ [16]. This result is also shown in Fig. 7. The conclusion is that at final kinetic freeze-out the temperature of the system is in the 115- to 125-MeV range and that it is expanding in the transverse direction with a velocity of 0.5 to 0.6 c. In addition, from other considerations, it is concluded that at this stage the system has a lifetime of about 8 fm/c and that it has undergone a substantial longitudinal expansion.

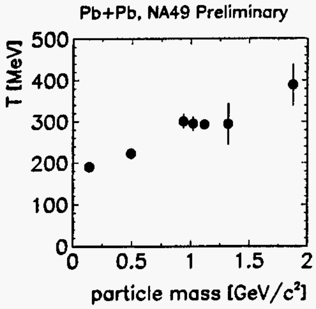

Fig. 6. Inverse slope parameters of various particles produced in central Pb+Pb collisions at 200 GeV/nucleon

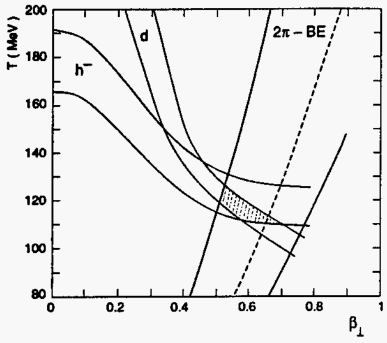

Fig. 7. Temperature vs transverse velocity. Curves depict constraints on the variables from m_T spectra and from particle correlations

7 The future at RHIC and at the LHC

If the probability of QGP formation is marginal at the SPS, there is no question that the required energy densities can be achieved at the new colliders. Simple estimates indicate energy densities relative to the SPS that are a factor of 2 higher at RHIC and a factor of 7 higher at the LHC. Correspondingly, the reaction volumes are expected to be seven times larger at RHIC and twenty times larger at the LHC. All of these factors significantly enhance the QGP discovery potential.

RHIC will be a dedicated heavy-ion machine and is expected to start up in 1999. It will be able to deliver Au nuclei with energies ranging from 30 to 100 GeV/nucleon (at a luminosity of 2.10^{26} cm^{-2} s^{-1}) and protons at 250 GeV (luminosity 10^{32} cm^{-2} s^{-1}). Four intersection regions will house two large experiments (PHENIX and STAR) and two smaller experiments (PHOBOS and BRAMS). PHENIX will concentrate on measurements of penetrating electromagnetic probes (photons, electrons, and muons), although it will also have a hadron-measurement capability. The midrapidity region will be covered by two electron-photon-hadron spectrometer arms in an open axial-field magnet. There will also be two back-to-back muon spectrometers covering large rapidities. STAR is dedicated to hadronic probes. Its centerpiece is a large-acceptance TPC in a solenoid magnet, and emphasis will be on event-by-event measurements of a large number of observables. PHOBOS is essentially a "table-top" experiment consisting on many silicon telescopes and a time-of-flight array. The primary capability of the experiment will be low p_T measurements of hadrons. BRAHMS will measure inclusive hadrons in two movable spectrometer arms. It will be able to make measurements at very large rapidities. In combination, the four experiments will be able to address all conceivable, predicted (as well as unexpected) signatures of the QGP.

At the LHC it is expected that heavy-ion operation will take place during six weeks per year. The expected start-up is in 2005. The energy of lead ions is expected to be 2.8 TeV/nucleon at a luminosity of 2.10^{27} cm^{-2} s^{-1}. Only one dedicated heavy-ion detector, ALICE, is planned, although other detectors (e.g., CMS, see R. Katadze, these proceedings) are planning to develop heavy-ion measurement capabilities. ALICE is a large-scale version of STAR, housed in the L3 magnet, with additional forward–backward muon measurement capability. It is also expected to concentrate on event-by-event measurements. Electrons and hadrons will be measured via tracking in a weak field. A high-resolution EM calorimeter will be used to measure photons.

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