EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN-PPE / 92-92
May, 18th, 1992

ULTRA-RELATIVISTIC HEAVY-ION COLLISIONS: SEARCHING FOR THE QUARK–GLUON PLASMA

J. Schukraft

INTRODUCTION

The subject of ultra-relativistic heavy-ion collisions

With the advent of ultra-relativistic heavy-ion collisions in the laboratory, at Brookhaven and CERN in 1986, a new interdisciplinary field has emerged from the traditional domains of particle physics and nuclear physics [1–2]. In combining methods and concepts from both areas, the study of heavy-ion reactions at very high energies ($E/m >> 1$) denotes a new and original approach in investigating the properties of matter and its interactions. In high-energy physics, *interactions* are nowadays derived from *first principles* (gauge theories), and the *matter* concerned consists mostly of *single particles* (hadrons/quarks). In contrast, on nuclear physics scales the strong *interaction* is shielded and can therefore to date only be described in effective or *phenomenological* theories, whereas the *matter* consists of *extended* systems exhibiting collective features. Combining the elementary-interaction aspect of high-energy physics with the macroscopic-matter aspect of nuclear physics, the subject of heavy-ion collisions is the study of *bulk matter* consisting of *strongly interacting* particles (hadrons/quarks). It may therefore be dubbed 'QCD thermodynamics' or 'condensed-matter physics' of elementary particles. The energy scale is given by Λ_{QCD} (the scale parameter of QCD), the pion mass, or the limiting 'Hagedorn temperature', all of which happen to be of the order of 200 MeV. The physics is therefore inherently the physics of 'soft' processes, and the objects under study are the old-fashioned hadrons (π, K, ρ, p, Λ, ...) and light quarks (u, d, s). The language to be used in this field would ideally be the language of thermodynamics, where complex multi-particle states are described in terms of a few macroscopic variables (temperature, density, entropy, etc.).

Figure 1 shows a streamer chamber picture of a heavy-ion reaction (^{32}S on ^{197}Au) at an energy of 200 GeV/A. The resulting 'mess' looks very much like an experimentalist's nightmare: hundreds of final-state particles widely distributed with no discernible structure (besides the purely kinematic concentration at small angles relative to the beam). In more elementary high-energy reactions (pp, e^+e^-), a search for simplicity and underlying order usually proceeds in a microscopic direction: from individual *particles* via *jets* to *partons*, described by perturbative *QCD dynamics* in terms of *microscopic variables* (centre-of-mass energy $\sqrt{s}$, momentum transfer, ...). In a similar fashion, we hope to find simplicity in the apparent chaotic final states of A–A reactions along a different direction, applying macroscopic and statistical concepts: from *particles* to statistical *ensembles* described by (non-pertubative) *QCD thermodynamics* in terms of *macroscopic* variables (temperature, pressure, ...).

What makes this field particularly interesting is the prediction of QCD that at high energy densities matter should undergo a phase transition to an entirely new state, the quark–gluon plasma (QGP). At low energy densities, quarks and gluons are bound by the strong force into colourless objects, the hadrons (confinement). In addition, the quarks acquire a large effective mass ($m_u \approx m_d \approx 300$ MeV, $m_s \approx 500$ MeV) via interactions between themselves and the surrounding physical vacuum (broken chiral symmetry). When increasing the energy density by increasing the temperature ('heating') or the matter density ('compressing'), a phase transition might occur towards the QGP, the true perturbative vacuum of QCD, where partons are deconfined and chiral symmetry is approximately restored ($m_u \approx m_d \approx 5$ MeV, $m_s \approx 150$ MeV).

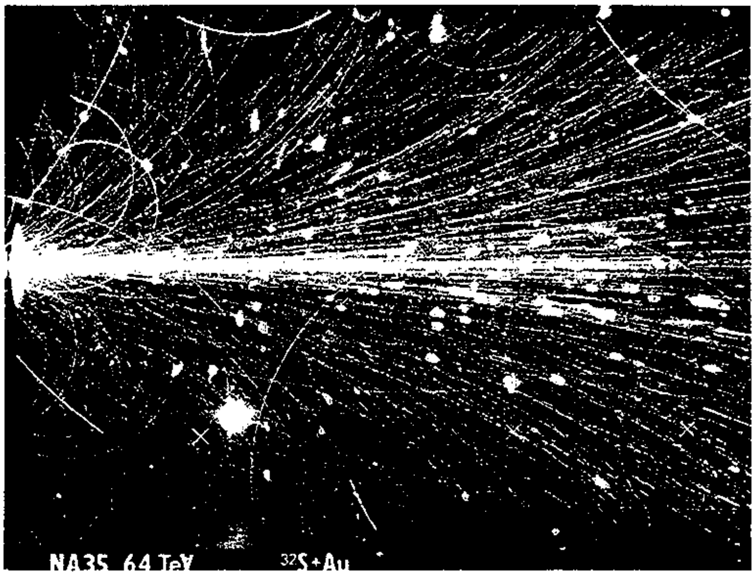

Fig. 1: Streamer chamber picture from experiment NA35 of a ^{32}S on ^{197}Au collision at 200 GeV/*A*.

In the context of the Standard Model, the study of this phase diagram of strongly interacting matter (Fig. 2) is not only of interest to study and test QCD on its natural scale (Λ_{QCD}), i.e. in the non-perturbative sector, but it might also shed light on such fundamental questions as the nature of confinement itself and on the process of spontaneous symmetry breaking, which is made responsible for the origin of the 'effective' quark masses (the pion being the assorted Goldstone boson). The early Universe presumably underwent this very phase transition 10^{-5} s after the Big Bang. Critical phenomena that can occur close to a phase boundary, for example long-range density fluctuations (as in condensing water!), might have a bearing on important aspects of cosmology, such as nucleosynthesis, dark matter, and the large-scale structure of the Universe. In astrophysics, the dynamics of supernova explosions and the stability of neutron stars (density $\rho \approx 10\ \rho_{nucleus}$) depends on the compressibility and therefore the equation of state of nuclear matter, and it is even speculated that the core of neutron stars may consist of cold QGP. The study of extreme states of matter created in high-energy nuclear collisions thus provides us with an opportunity of gaining insight into many important aspects in different fields of physics.

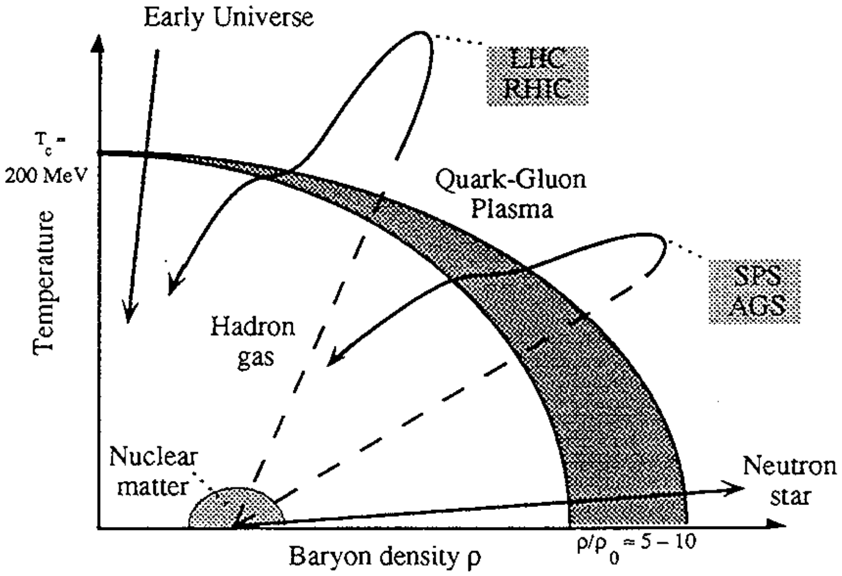

Fig. 2: The phase diagram of strongly interacting matter showing the hadronic phase at low temperature and baryon density, the transition region (mixed phase), and the QGP phase. The solid lines illustrate trajectories followed in supernovae explosions, Big Bang evolution, and possibly in heavy-ion reactions at present and future accelerators.

Geometry and space–time evolution of heavy-ion collisions

Nuclei are extended objects, and therefore their geometry plays an important role in heavy-ion collisions. Figure 3 shows a sketch of a reaction between asymmetric nuclei A and B; the impact parameter b separates the nucleons into participants, with primary nucleon–nucleon collisions, and spectators, which proceed with little perturbation along the original direction. In the first instances of the reaction, the nucleon–nucleon collisions between the two highly Lorentz-contracted nuclei redistribute a fraction of the original beam energy into other degrees of freedom. After a short time, usually taken to be of the order of 1 fm/c, partons materialize out of the highly-excited QCD field, possibly in the state of an equilibrated QGP. The system expands rapidly, mainly along the longitudinal direction, thereby lowering its temperature, and reaches the critical transition temperature T_C after a few fm/c. Potentially, the matter then spends a long time in the mixed phase, in particular if the transition is of first order. It has to rearrange the many degrees of freedom (partons) of the QGP into the fewer available in the hadron phase, with an associated large release of latent heat. In the last and hadronic phase ('hadron gas' or 'hadron fluid'), the still-interacting system keeps expanding, maybe even in an ordered motion ('collective flow'), to very large dimensions until 'freeze-out' occurs, when interactions cease and the particles stream freely away to be detected in the experiments.

Necessary conditions

In order for heavy-ion collisions to fulfil the promises mentioned above, a number of necessary pre-conditions have to be met and verified by results:

In order to use *macroscopic variables,* the system has to be 'big', i.e. the dimensions need to be much larger than the typical scale of strong interactions ($>> 1$ fm) and consist of 'many' particles ($>> 1$).

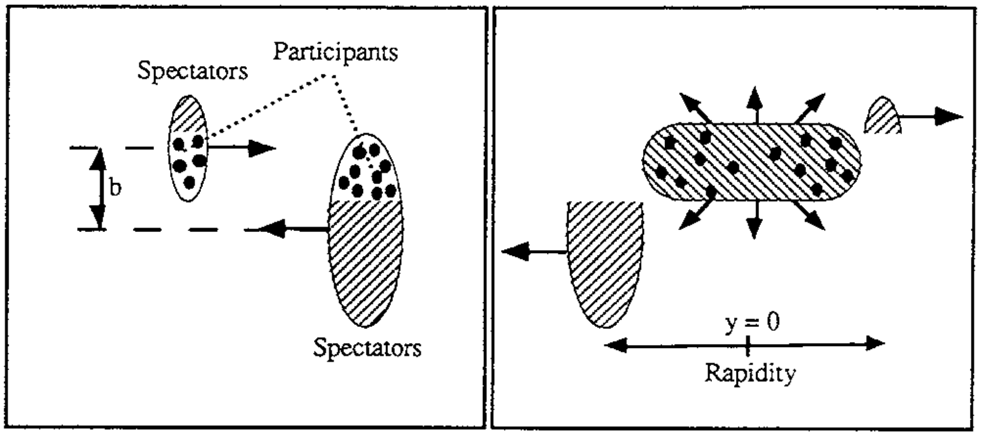

Fig.3: Schematic representation of a heavy-ion collision at impact parameter b, assuming straight-line geometry.

To use the language of *thermodynamics*, the system has to be in (or near) equilibrium, i.e. its lifetime has to be larger than the relaxation times ($\tau >> 1$ fm/c). Equilibrium can be reached and maintained throughout the expansion only in a sufficiently interacting system; therefore the number of collisions per particle has to be larger than one.

The *energy densities* ε needed for QGP formation are predicted by QCD to be of the order of 1–3 GeV/fm^3, equivalent to a temperature $T_c \approx 150$–200 MeV or a baryon density $\rho \approx 5$–10 times the nuclear matter density. It has to be verified that these energy densities can indeed be reached in heavy-ion collisions.

Because of the rapid evolution, *experimental observables* will, in general, correspond to an integral over the complete space–time history of the reaction from the first nucleon–nucleon collision until freeze-out, and disentangling the various contributions to a signal from the different phases indeed presents a formidable challenge. Furthermore, a system evolving in equilibrium by definition erases its memory of preceding stages. As in Big Bang cosmology, it is necessary to identify observables that decouple at different times from the expansion and are more sensitive to the early and hot stages of the matter.

Experimental facilities

The Alternating Gradient Synchroton (AGS) at Brookhaven was transformed into a heavy-ion accelerator in 1986; it has been running since then on a regular basis several weeks per year with beams up to ^{28}Si at 14.5 GeV/A (c.m. energy in the nucleon–nucleon system $\sqrt{s} \approx 5$ GeV/A). There are four large experiments and some smaller ones, with a total of 350 users, coming roughly in equal parts from high-energy and nuclear physics. The Super Proton Synchroton (SPS) at CERN accelerated ^{16}O at 60 ($\sqrt{s} \approx 10$ GeV/A) and 200 GeV/A ($\sqrt{s} \approx 20$ GeV/A) in 1986 and ^{32}S at 200 GeV/A in 1987. After the initial short runs of two weeks each, a new, long-term programmme of heavy-ion physics was established at CERN starting in 1990 with several weeks of ^{32}S beams. There are six big electronic detectors and also a number of smaller experiments with a total of 550 users, again half of them coming from nuclear physics.

The early, so-called 'exploratory' phase of heavy-ion collisions (1986–1990) was characterized by the fact that no dedicated machines were used, but rather existing accelerators were upgraded at modest financial expense. Likewise, the experiments made extensive reuse of existing HEP/NP equipment (> 80% at CERN).

RESULTS

Transverse energy E_t and energy density ε

The crucial quantity linking the observed event characteristics with the conjectured formation of a quark–gluon plasma is the energy density ε (energy / volume) achieved in heavy-ion reactions. The corresponding experimental observables are either the number and average momentum of final-state particles created or the transverse energy E_t ($E_t = E \cdot \sin\theta$) emitted perpendicular to the beam direction. As a typical example of the latter, the cross-section $d\sigma/dE_t$ is shown in Fig. 4 for ^{32}S on various targets at 200 GeV/*A* [3]. The cross-section is integrated in the angular region $96° < \theta_{lab} < 0.5°$, equivalent to essentially 4π in the c.m. system. The absolute amount of E_t released in central collisions of the heaviest systems studied to date (S-U) is indeed remarkable: 450 GeV and about 600 charged particles, exceeding by about two orders of magnitude the values obtained in p–p reactions at the same beam energy.

The shape of the distribution — rapidly falling at low E_t, a rather long and flat region in the middle ('plateau'), followed by an abrupt break and a steep decline ('tail') — is typical for asymmetric A–B reactions (A < B). It is governed by geometry and essentially reflects the number of primary nucleon–nucleon collisions that increases smoothly when going from peripheral ($b >> 0$, low E_t) to central ($b \approx 0$, high E_t) reactions. Even subtle geometrical effects such as nuclear deformations are borne out by the data. Based on the geometrical picture, the E_t of central collisions between spherical nuclei should grow roughly proportionally with the thickness of the target, i.e. $A_t^{1/3}$. Compared with the only slightly smaller ^{208}Pb target, much larger E_t values are observed for ^{238}U, reflecting the large quadrupole deformation of ^{238}U. High E_t in this case selects reactions where the cigar-shaped U nucleus is preferably aligned with its longer axis parallel to the beam, in this way increasing the effective amount of nuclear matter to the equivalent of a spherical nucleus with mass 400 !

As no direct observation of the initial energy released or of the initial size of the reaction volume exists, geometrical and kinematical assumptions have to be made in order to convert the measured final energy into an energy density at the very beginning of the reaction. The resulting energy densities are estimated to be of the order of 1 GeV/fm^3 at the AGS and 2–4 GeV/fm^3 at CERN, corresponding to temperatures of 150–210 MeV. Despite their somewhat qualitative nature, it is reassuring that these numbers are not only large, about twenty times the energy density of ground-state nuclear matter and still five times larger than the energy density inside a hadron, but indeed of the order of the critical value needed for the phase transition.

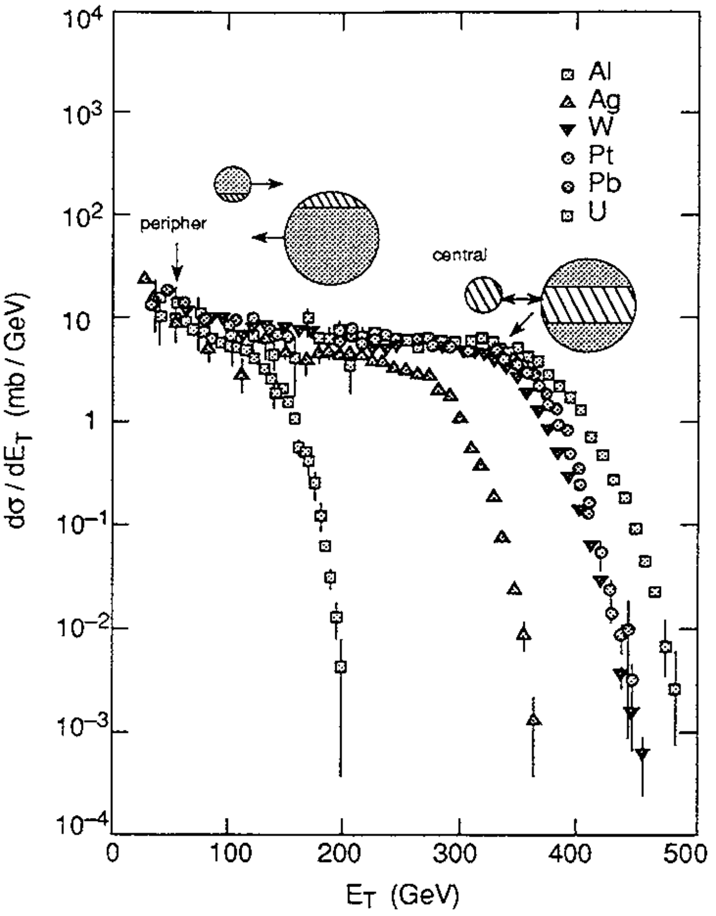

Fig. 4: Cross-section for transverse energy production in ^{32}S collisions with a number of different targets (NA34) at 200 GeV/A. The inset shows the reaction geometry corresponding roughly to the different regions in E_t.

Volumes and lifetimes

The space–time extent of sources emitting radiation or particles can, in principle, be measured via intensity interferometry. Identical particles obey the rules of quantum statistics; the (anti) symmetrization of their wave function leads to correlations in momentum–energy space, which in turn are related, via a Fourier transformation, to the source distribution in space–time. This method, originally introduced by Hanbury-Brown and Twiss (HBT) in 1953 to determine the radii of stars, is now regularly used in particle physics to measure the freeze-out volume (surface of last rescattering). In p–p and e^+e^- reactions, the transverse radii r_t extracted with this method are of the order of 1 fm (size of strings or hadrons). In low-energy nuclear reactions, the sizes correspond precisely to the geometrical interaction region (i.e. to the size of the smaller of the colliding nuclei). The coherence parameter λ which measures the strength of the correlation at zero 4-momentum difference ($\lambda = 1$ for completely chaotic emission) is, however, found in all cases to be significantly smaller than one, a fact that is sometimes attributed to experimental cuts or resonance decays.

The NA35 Collaboration have measured the correlation function with negative pions in a number of nuclear collisions [4]. They find a rather large coherence parameter ($\lambda \approx 1$) and transverse radii between 5 and 6 fm, i.e. values which exceed the projectile size by a factor of about two and indicate a very large and chaotic source which collectively expands from an initial size of 3 fm to a final size of ≈ 6 fm. This expansion leads in addition to a lower limit on the lifetime of $\tau > 3$ fm/c. Combining a number of results from p–p and A–B reactions, the freeze-out radius seems to scale with the particle density like $r_t \approx (dN/dy)^{1/3}$, i.e. it always occurs at roughly the same final matter density.

Thermal equilibrium

The momentum distribution of particles in thermal equilibrium is given by a Boltzmann law with the average momentum proportional to the temperature. In ultra-relativistic collisions, the longitudinal components (p_l) of the momentum vectors cannot be easily thermalized because of the large asymmetry in the initial state ($p_t = 0$, p_l = beam momentum). Therefore usually only the transverse components (p_t) are considered. They could, in principle, provide a direct measure of the temperature of the system, reveal collective particle flows ('viscosity' of the hadron gas/fluid), and ideally even signal the presence of a phase transition.

The general characteristics of p_t distributions in p–A and A–A reactions can be extracted from Fig. 5, where the cross-section $d\sigma/dp_t^2$ is shown for negative particles (mostly pions) in p–W, O–W and S–W central collisions as measured by NA34 [5].

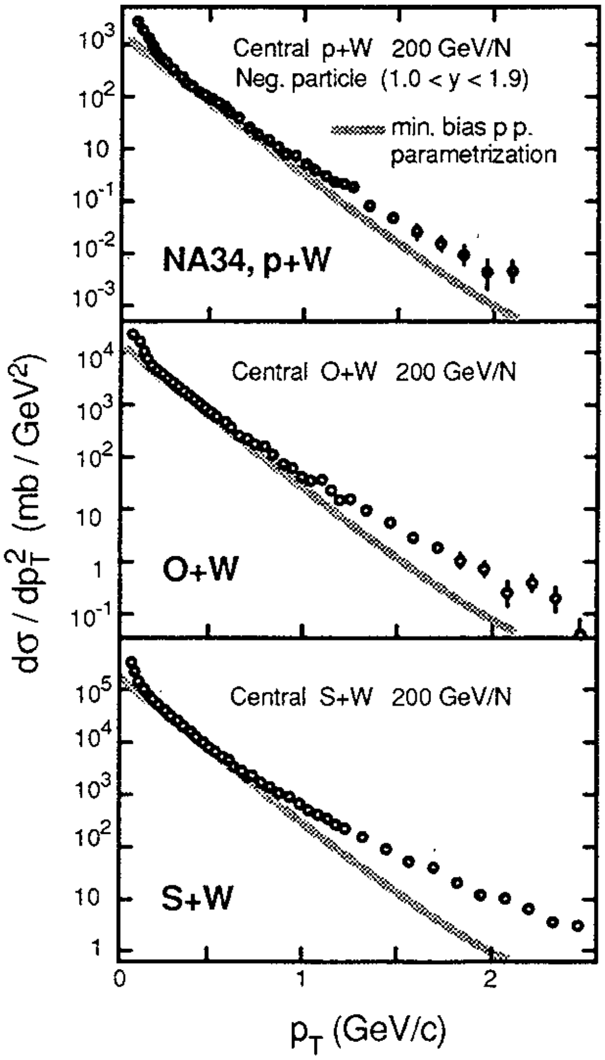

Fig. 5: Negative-particle distribution from NA34 for central collisions of p, O, S, (a, b, c) with a W target. For comparison a parametrization of p–p data is shown as a solid line.

The distributions differ substantially from the ones measured in p–p (solid line in Fig. 5); they show a strong enhancement both at high p_t (> 1 GeV/c) and at low p_t (< 250 MeV/c). Both the high p_t, usually referred to as 'Cronin' effect, as well as the low p_t rise were actually already observed in the mid 1970s at Fermilab in p–A reactions. The theoretical interest in these deviations has been considerable. The high p_t part can be interpreted in a thermal model with a substantial amount of collective flow, the low p_t part could be the result of some exotic processes, e.g. an approach to pion condensation or the remnant of supercooled QGP droplets. However, more mundane explanations are also possible and even likely, because they naturally describe some systematic trends observed in the data. Resonance decays, in particular of the Δ baryon, could be the source of low p_t pions, and multiple, small-momentum parton scattering inside the nuclei might be responsible for the high p_t enhancement.

Chemical equilibrium

In 'chemical' equilibrium, the abundance of particle species (hadrons/quarks) is again governed by Boltzmann factors, i.e. essentially by the temperature, the respective masses, and a chemical potential. The production of strange quarks is favoured in a QGP because there the mass of the strange quark is reduced to a value comparable to the temperature (chiral symmetry restoration). In addition, the creation of light u and d quarks is hindered by the large number of valence quarks already present in the colliding nuclei (Pauli blocking), leading to a large chemical potential for these quarks that favours $s\bar{s}$ over $u\bar{u}$ and $d\bar{d}$ production.

Results on enhanced strangeness production were already reported shortly after the first data were taken in 1986 [6]. Many experiments have now measured the yield of several particle species containing one or two strange quarks (K^+, K^0, Λ, Ξ and their anti-particles). In all of the cases, their production relative to pions is larger in nucleus–nucleus collisions compared to p–p by a factor of two to five. Like particles with open strangeness, the production of ϕ mesons (s, $\bar{s}$) is strongly enhanced in nuclear collisions. However, the question of 'strangeness as a signal for the QGP' has undergone a rapid development since the first predictions were made. It is now clear that the dynamical evolution through the phase transition and the unavoidable hadron-gas phase can change the strangeness content of matter and readjust the particle ratios to the respective equilibrium values at various stages (which is indeed the very definition of a system evolving in equilibrium!). Strangeness enhancement, in general, is now seen more as a characteristic feature of a system approaching chemical equilibrium rather than as a unique signal for QGP formation. Depending on the assumptions made about the space–time development, the equilibrium values predicted for many strange particles can be very similar in QGP and hadron-gas models. In addition, some of the systematic features of K^+ and Λ production are well described by non-equilibrium rescattering, which is particularly strong in this channel (e.g. π+n -> K+Λ). On the other hand, no unconventional explanation has so far been put forward for the observed increase of anti-hyperons ($\bar{\Lambda}$, Ξ^-).

Signals from the QGP

Weakly interacting probes, which decouple at early times, are the only direct means of gaining information on the plasma phase. Direct photons and lepton pairs (virtual photons) are such observables and should emerge as thermal radiation from the heated matter without being altered by final-state effects. Their strong temperature-dependence assures that the thermal radiation is sensitive mainly to the first and hottest stages of the evolution. Unfortunately, they have to be measured in the presence of an immense background of photons and leptons arising from ordinary hadronic decays or hard-QCD processes. So far, this primordial 'background' radiation has not been observed, but the present experimental upper limits ($\gamma/\pi^0 < 10$–15%) are not yet sensitive enough to measure the predicted yields.

Signals originating from hard-scattering processes at the very beginning of the reaction, such as J/ψ production, are not directly connected to plasma formation; they are nevertheless important as tools to probe the state of the surrounding QCD matter. The original idea [7] that the formation of the J/ψ should be suppressed in a QGP relies on a mechanism analogous to the Debye screening effective during an insulator–conductor Mott transition in QED. The J/ψ is produced during primary nucleon–nucleon collisions mainly via gluon fusion. The confining strong force, which would normally bind the newly created charm quarks within a small, but finite time (formation time) into a J/ψ is, however, screened in the QGP. If the screening radius (Debye radius), which is inversely proportional to the density of colour charges and therefore to the energy density, is smaller than the size of the J/ψ (≈ 0.5 fm), a bound state cannot be formed. The charmed quarks dissolve and separate in space to appear later, after hadronization, as two mesons with open charm. Because of the finite formation time, high-p_t (i.e. 'fast') charm pairs can escape the QGP unaffected, yielding a characteristic, p_t-dependent suppression pattern. This 'melting' process is specific only for the deconfined state of QGP and would therefore qualify as an unambiguous signal; however, the J/ψ is not weakly interacting and final-state rescattering of the J/ψ (absorption) will complicate the situation.

In heavy-ion reactions J/ψ suppression has indeed been observed by the NA38 experiment [8]. Figure 6 shows the dimuon mass spectrum measured in O–U for low-E_t and high-E_t collisions. The two data sets are normalized to the muon pair continuum ('Drell–Yan') outside the resonance region and show a clear suppression of J/ψs by a factor of about two in central collisions compared with peripheral ones. From the p_t spectra of J/ψs it seems that the suppression is indeed most effective at low transverse momentum. The pattern and the absolute magnitude of the effect are exactly as predicted for a QGP; nevertheless, a number of 'conventional' models are able to describe the data in terms of absorption in a hadron-gas and initial-state parton scattering. In these models, rescattering of the J/ψs in the surrounding medium provides the suppression (e.g. via $J/\psi+\pi \rightarrow D+\overline{D}+X$), and initial-state parton scattering prior to the gluon fusion shifts the p_t of the surviving J/ψs to larger values (see high-p_t enhancement of pions earlier). Both effects, which certainly occur at some level, seem to conspire in such a way as to fake a signal predicted as unambiguous for the QGP. Eventually, however, hadronic and QGP models should be distinguishable because their predictions differ at higher p_t and for heavier charmonium states.

In dense matter, hadronic resonances will change their characteristics (mass, width, branching ratios) as a consequence of chiral symmetry restoration. If a decay into weakly interacting particles (e.g. lepton pairs) happens inside the medium, we might be able to observe such resonance modifications. These measurements are amongst the most difficult to perform, because of large combinatorial backgrounds and the excellent mass resolution required, and only recently have the first experiments able to address some of these points started to take data.

In addition, there are speculations about a number of 'exotic' signals, such as massive photons, stable strange matter ('strangelets'), or free quarks, which, if observed, could be a spectacular sign of

QGP formation. Free quarks have already been searched for (with negative results), and some strangelet experiments are under consideration at the moment.

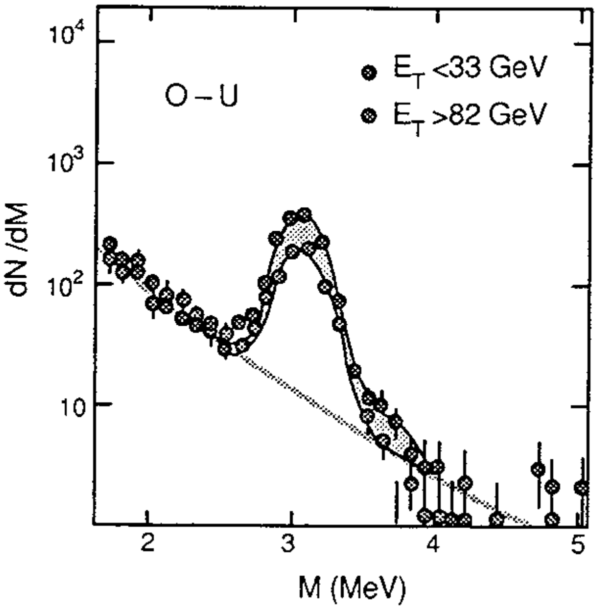

Fig. 6: Dimuon mass spectra observed in O–U collisions for low-and high-E_t events. The data are normalized with respect to each other in the continuum region above and below the J/ψ, the solid lines represent fits.

CONCLUSIONS AND OUTLOOK

An impressive amount of data have been collected and analysed in the first five years of accelerator-based ultra-relativistic heavy-ion physics at Brookhaven and CERN. The initial phase, often based on preliminary and sometimes rapidly changing data, was characterized by interpretations ranging from extremely pessimistic ('trivial superposition of p–p collision + geometry') to extremely optimistic ('clear signals of the QGP') views. The field is now becoming mature, the data are consolidating and more-balanced interpretations are emerging. No convincing evidence for the creation of a Quark–Gluon Plasma at present energies and with the (light) heavy ions available to date has been found. Nevertheless, a number of important milestones have been passed that established some necessary pre-requisites vital for the study of dense and strongly interacting matter by means of heavy-ion collisions.

Energy density: The study of global-event features (E_t and multiplicity distributions) has shown that the energy deposited in the reaction volume in the course of a nucleus–nucleus collision is as large as could have optimistically been expected; indeed, in present experiments, the energy density might already be close to or even above the threshold predicted for QGP formation.

Size and lifetime: The transverse size of the reaction zone at freeze-out, as measured by pion interferometry, is increasing by a factor of about two from the initial size; this is possible only in an expanding system with truly collective behaviour of its constituents. The observed large radii therefore constitute the first and unambiguous sign that an extended, strongly interacting system has been created, containing hundreds of particles per unit of rapidity in a final volume approaching 1000 fm^3. These spatial dimensions are certainly large by the standards of particle physics and QCD, and correspondingly macroscopic and statistical concepts should be applicable in the description of ultra-relativistic heavy-ion collisions. In contrast, the lifetime, which is estimated to be only of the order of a few fm/c, is probably at best marginal at present.

Equilibrium: The question of equilibrium and applicability of (QCD) thermodynamics remains unanswered so far. The interpretation of transverse-momentum spectra, which ideally would measure the temperature of a system in thermal equilibrium, and the interpretation of particle ratios, which signal the degree of chemical equilibrium attained in the collision, are complicated by the dynamical evolution from the (possible) QGP state through the phase transition and the unavoidable hadron-gas phase. However, the mere presence of significant differences in the inclusive spectra (both in p_t distributions and particle ratios) between p–p and nucleus–nucleus implies, even in the most conservative (non-equilibrium rescattering) models, at least the presence of extended, dense, and strongly interacting matter which, by means of rescattering between its constituents, must evolve towards equilibrium distributions. A quantitative analysis of the data, and in particular a search for surviving signals from the QGP, will depend to a large extent on further progress in understanding the hadronization process and the time scales available in the various phases.

Sensitive signals: From the number of experimental observables that are most sensitive to the earliest and hottest stages of the matter only two have been investigated so far: direct photons and J/ψ production. For photons, the experimental accuracy achieved at present is not expected to be sensitive to the thermal radiation of a QGP in the reactions studied so far. On the other hand, J/ψ suppression has been observed with the characteristics predicted for a QGP. For some time, Debye screening in the plasma has been the only explanation that could, with reasonable assumptions, describe the particular E_t- and p_t-dependent suppression pattern. To date, based partially on new results for J/ψ and Drell–Yan production in p–A reactions, it seems likely that a combination of initial-state parton scattering and final-state absorption in the dense reaction zone is sufficient to explain the nucleus–nucleus data.

Taking all evidence together, the first round of 'survey' experiments has shown that an extended and very dense system with collective features has been formed that differs in many aspects from the more elementary hadron–hadron reactions investigated in the past. The first important result is, therefore, that heavy-ion collisions indeed seem to be an appropriate and promising tool for creating and studying the properties of strongly interacting bulk matter. However, it has also become clear that the quest for the QGP will not be a quick or easy task. It requires a systematic and comprehensive search for deviations from theoretical expectations or from smooth extrapolations of existing p–p and p–A data. Only if several such anomalies are found in different observables that cannot be accounted for within a reasonable margin of flexibility, could they provide a basis for a serious claim that the QGP or some other 'new physics' has been discovered. A number of such 'anomalies' have indeed been observed, but conventional theoretical models have been improved from a (partially 'naive') pre-data stage to a level of agreement that does not require radically new physics. This better understanding of conventional physics constitutes the second major achievement attained so far.

We can now consider the 'exploratory' phase in the still very young field of ultra-relativistic heavy-ion collisions to be essentially completed. Falling short of striking discoveries, this phase has nevertheless provided a 'principle proof of feasibility' and has even substantiated the expectation that with the next generation of experimentation we shall reach a new and uncharted territory. Approved programmes with real 'heavy' ions foresee ^{197}Au beams at the AGS (11.5 GeV/A) in 1992 and ^{208}Pb beams at the SPS (160 GeV/A) in 1994. Based on our current understanding of the data, these upcoming experiments should lead to matter densities very close to the maximum possible in any laboratory experiment, reaching or even exceeding the ones in the centre of a neutron star. The larger volume, the (slightly) higher energy density, and, most important, the increased lifetime of the reaction zone will all independently help in driving the system further towards equilibrium, whether or not its internal degrees of freedom are of hadronic or of partonic nature.

By the end of the century, a different regime of very high energy density but low baryon density matter will be accessible at new machines. The Relativistic Heavy-ion Collider (RICH), capable of colliding Au on Au at $\sqrt{s}= 200$ GeV/A, is now under construction at BNL and should start operation around 1997. Heavy-ion physics will also play an important rôle in the initial experimental programme of the Large Hadron Collider (LHC) planned at CERN for 1998. In particular, the LHC will be the ultimate machine in this field for the foreseeable future. With Pb on Pb at 6.3 TeV/A, corresponding to a total centre-of-mass energy of more than 1200 TeV, we expect particle densities of several thousand per unit of rapidity, a freeze-out volume approaching 100 000 fm^3, and an initial energy density 50 to 100 times larger than the one of normal nuclear matter. Even if, for some reason, no equilibrated QGP were formed at these energies, a hadronic description in terms of individual particles makes no sense either in a system where several dozen hadrons would be piled up on top of each other (>> 10 pions/fm^3). 'New physics' of one kind or another seems therefore bound to appear somewhere along the road towards the Quark–Gluon Plasma.

REFERENCES

[1] Recent reviews of the field:
W.M. Geist, Int. J. Mod. Phys. A4 (1989) 3717J. Bartke, Int. J. Mod. Phys. A4 (1989) 1319M.J. Tannenbaum, Int. J. Mod. Phys. A4 (1989) 3377 H.R. Schmidt and J. Schukraft, to be publ. in J. Phys. G (1992) and preprint CERN-PPE/92 42 H. Gutbrod and H. Stöcker, Scientific American, November 1991J. Gribbin, New Scientist, 17 August 1991, 31

[2] Original references can be found in the proceedings of the recent Quark-Matter Conferences 'Quark Matter 87', Proc. 6th Int. Conf. on Ultra-Relativistic Nucleus–Nucleus collisions, Nordkirchen, FRG, Aug. 24–28 1987, Z. Phys C38 (1988) 'Quark Matter 88', Proc. 7th Int. Conf. on Ultra-Relativistic Nucleus–Nucleus collisions, Lennox, MA, USA, Sept. 26–30 1988, Nucl. Phys. A498 (1989) 'Quark Matter 90', Proc. 8th Int. Conf. on Ultra-Relativistic Nucleus–Nucleus collisions, Menton, France, May 7–11 1990, Nucl. Phys. A525 (1991) 'Quark Matter 91', Proc. 9th Int. Conf. on Ultra-Relativistic Nucleus–Nucleus collisions, Gatlinburg, TE, USA, Nov. 11–15 1991, to appear in Nucl. Phys. A (1992)

[3] T. Åkesson et al , NA34 Collaboration, Nuc. Phys. B353 (1991) 1

[4] A. Bamberger et al., NA35 Collaboration, Phys. Lett. B203 (1988) 320

[5] T. Åkesson et al., NA34 Collaboration, Z. Phys. C46 (1990) 369

[6] Y. Miake et al., E802 Collaboration, Z. Phys. C38 (1988) 135

[7] T. Matui and H. Satz, Phys. Lett. B178 (1986) 416

[8] C. Baglin et al., NA38 Collaboration, Phys. Lett. B220 (1989) 471, B251 (1990) 465 and 472