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**ULTRA-RELATIVISTIC HEAVY-ION COLLISIONS OR
THE QUEST FOR THE QUARK-GLUON PLASMA**

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ABSTRACT

The physics of ultra-relativistic heavy ions is presented, with particular emphasis on the basic concepts used in interpreting the data and on the principal problems encountered in this new and rapidly evolving field. A number of selected results from experiments at CERN and BNL are reviewed and compared qualitatively with models based on hadronic scenarios as well as models including quark-gluon plasma (QGP) formation. No unambiguous evidence for QGP formation has emerged from the data so far, but a number of large and significant effects have been observed which clearly show that nucleus-nucleus collisions cannot be described as a straightforward superposition of independent nucleon-nucleon reactions. Results from a number of different observables (p_T distributions, strangeness abundances, J/ψ suppression) indicate the existence of an extended and strongly interacting system. The first 'exploratory' phase of experimentation seems therefore to confirm that ultra-relativistic heavy-ion collisions are a promising tool to study the properties of bulk hadronic matter under extreme conditions.

1. INTRODUCTION

1.1 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 physics¹⁻⁵. In combining methods and concepts from both areas, the study of heavy-ion reactions at very high energies ($E/m \gg 1$) 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 the nuclear-physics scale, the strong interaction is shielded and can therefore 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 language to be used in this field would ideally be the language of thermodynamics, where complex multiparticle states are described in terms of a few macroscopic variables (temperature, density, entropy, etc.). The energy scale is given by Λ_{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).

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

Fig. 1 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 supernova explosions, Big Bang evolution, and possibly in heavy-ion reactions at present and future accelerators.

force into colourless objects, the hadrons (confinement). In addition, the quarks acquire a large effective mass ($m_u \approx m_d \approx 300 \text{ MeV}$, $m_s \approx 500 \text{ MeV}$) 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 ($m_u \approx m_d \approx 5 \text{ MeV}$, $m_s \approx 150 \text{ MeV}$).

In the context of the Standard Model, the study of this phase diagram of strongly interacting matter (Fig. 1) is not only of interest to study and test QCD on its natural scale, 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 Universe⁶. In astrophysics, the dynamics of supernova explosions and the stability of neutron stars [$\rho \approx 10\rho(\text{nucleus})$] depends on the compressibility and therefore the equation of state of nuclear matter⁷, 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 of different fields of physics.

1.2 Experimental facilities

Tables 1 and 2 provide an overview of existing and planned heavy-ion accelerators and some information on the corresponding scope of the scientific programmes. The Alternating Gradient Synchrotron (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 . There are four large experiments and a number of smaller ones, with a total of 350 users, coming roughly in equal parts from high-energy and nuclear physics. The Super Proton Synchrotron (SPS) at CERN has been accelerating ^{16}O at 60 and 200 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 programme of heavy-ion physics has been established at CERN starting in 1990 with several weeks of ^{32}S beams. There are six big electronic detectors and a large number of smaller (typically emulsion-type) 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 high-energy physics/nuclear physics equipment ($> 80\%$ at CERN) and only now, the first completely new and dedicated experiments are coming into operation at CERN.

Approved programmes foresee ^{197}Au beams at the AGS (11.5 GeV/A) in 1992 and ^{208}Pb at the SPS in 1994. Then for the first time there will be really 'heavy' ions available, providing a significant increase in volume and lifetime of the reaction zone and probably also a larger

Table 1. Existing and future heavy ion accelerators (some entries approximate only)

Machine	AGS	SPS	AGS+Au	SPS+Pb	RHIC	LHC	GSI	KEK
Commissioning date	1986	1986	1992	1994	1997	> 1998	?	?
A_{max}	^{28}Si	^{32}S	^{197}Au	^{208}Pb	^{197}Au	^{208}Pb	^{238}U	^{197}Au
E_{max} (Lab.) [GeV/n]	14.5	200	11.5	160	21×10^3	21×10^6	≈ 3000	≈ 50
$(\sqrt{s})^{\text{nn}} - 2m_n$ [GeV]	3.5	17.5	3	15.5	200	6300	50-100	≈ 10
$(\sqrt{s})^{\text{AA}} - 2Am_n$ [GeV]	98	560	580	3200	40000	1.3×10^6	≈ 18000	≈ 2000
Rapidity range Δy	± 1.7	± 3	± 1.6	± 2.9	± 5.5	± 8.8	± 4.3	± 2.3
$(\frac{dn}{dy})^{\text{nn}} \approx 0.8 \ln \sqrt{s}$ (1)	1.4	2.4	1.3	2.3	4.3	7.0	3.5	2.0
$(\frac{dn}{dy})^{\text{AA}} \approx A^{1.05} (\frac{dn}{dy})^{\text{nn}}$ (2)	45	90	300	600	1100	1900	1100	500
L [$\text{cm}^{-2}\text{s}^{-1}$] (3)	$(10^9) \approx 10^{11}$	$(10^7) \approx 2 \times 10^{28}$	$(10^9) \approx 7 \times 10^{30}$	$(3 \times 10^8) \approx 4 \times 10^{28}$	$2 \times 10^{26} - 10^{27}$	2×10^{27}	$> 10^{26}$	$> 10^{25}$
Operation [weeks/year]	4-6	0-6	8-10	> 6	≈ 40	≈ 4	≈ 40	?
Users (4)	300+80	350+200	≈ 380	≈ 400	≈ 300	?	?	?
Experiments (5)	4+2+10	6+8+12	1 big new	4-6 big	2-3 big	1	2	1-2
Cost for ion part [M\$]	25	5	30	30	300	?	?	≈ 50

(1) Rapidity density (charged + neutral) for nucleon-nucleon collisions at $y = 0$.

(2) Estimate of the rapidity density in central A-A collisions. The scaling exponent A^α is presumably in the range $\alpha \approx 1.0$ to 1.1 .

(3) The luminosity L of fixed-target machines is calculated from the number of ions/burst (number in brackets), assuming a 10% interaction length target for A-A collisions and correcting for the duty cycle.

(4) Numbers of users at AGS/SPS shown separately for electronic and other (typically emulsion) experiments.

(5) Numbers at AGS/SPS shown separately for big, small and completed experiments.

Table 2: Big active electronics experiments at CERN (WA., NA.) and BNL (E.)

Experiment	Main detector	Main physics topics
WA80	Plastic ball, e.m. calorimeter (Saphir)	π^0, γ , target fragmentation
WA85	Omega spectrometer	Strange baryons
NA34	Calorimeter, muon spectrometer	E_T low-mass dimuons
NA35	Streamer chamber	p_T , strangeness, HBT
NA36	Time projection chamber	p_T , strangeness
NA38	Muon spectrometer	High-mass dimuons
E802/E859	Spectrometer	Inclusive particle spectra, HBT
E810	Time projection chamber	Strangeness
E814	Calorimeter	Projectile fragmentation, E_T
E858	Spectrometer	Antinuclei at 0°

energy density in its core. The further development will be dominated by colliders starting with the Relativistic Heavy Ion Collider (RHIC) at BNL providing Au on Au reactions at $\sqrt{s} = 200$ GeV/A, starting around 1997. The Large Hadron Collider (LHC) planned to begin running at CERN in 1998 will be the ultimate machine in this field in the foreseeable future, since heavy-ion physics is seen as an important and integral part of the LHC programme right from the beginning with Pb on Pb at $\sqrt{s} = 6.3$ TeV/A. By the end of this century, the total available centre-of-mass energy in heavy-ion collisions might have increased by over 5 orders of magnitude in little more than 10 years, an indeed unparalleled pace even in this rapidly evolving new field of physics, made possible only by an imaginative reuse of existing facilities.

1.3 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 2 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. The use of this straight-line geometry is justified by the fact that at very high energies the size of nucleons is larger than their Compton wavelength and the nuclear radius is larger than the interaction length of ≈ 1.8 fm. Cross-sections, number of participants, and related kinematic quantities are usually calculated from simple geometrical considerations (see, for example, Ref. 8). The space-time evolution of a central ($b = 0$) Pb on Pb collision at very high energies (RHIC, LHC) is shown schematically in Fig. 3. In the first moments of the reaction, nucleon-nucleon collisions between the two highly Lorentz-contracted nuclei (with limiting thickness $r \approx$

Fig. 2 Schematic of a heavy-ion collision at impact parameter b .

Fig. 3 Space-time evolution of a Pb-Pb reaction at very high energy.

1 fm) 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 (see below), 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, and therefore lowers its temperature and reaches the critical transition temperature T_c after $\tau \approx 3\text{--}5$ fm/c. Potentially now the matter spends a long time in the mixed phase ($\tau > 10$ fm/c?), in particular if the transition is of first order. It has to rearrange the many degrees of freedom (partons) of the QGP into the smaller number available in the hadron phase, with a large associated release of latent heat. In the last and hadronic phase ('hadron gas' or 'hadron fluid', $\tau \gg 10$ fm), the still interacting system keeps expanding, possibly in an ordered motion ('flow'), to very large dimensions ($V > 10^4$ to 10^5 fm³) until 'freeze-out', when interactions cease and the particles stream freely away to be detected in the experiments. 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 ($\gg 1$ fm) and consist of 'many' particles ($\gg 1$).
- In order 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 ($\tau \gg 1$ 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. Rescattering of the produced particles (hadrons/quarks) amongst themselves and with the surrounding spectator matter is therefore of vital importance and not a trivial effect or even a nuisance. In fact, only a few (typically > 3) collisions are required, for example to equilibrate momentum distributions in low-energy nucleus-nucleus collisions⁹.
- The energy densities ϵ needed for QGP formation are predicted by QCD to be of the order of 1–3 GeV/fm³, equivalent to a temperature $T_c \approx 150\text{--}200$ MeV or a baryon density $\rho_c \approx 5\text{--}10 \times$ 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 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 or are more sensitive to the early and hot stages of matter.

The following discussion of the experimental results achieved in the first 5 years of ultra-relativistic heavy-ion physics will be oriented along these points, trying in each case to see how far we have come along the road towards the QGP.

2. GLOBAL EVENT FEATURES

2.1 Transverse-energy and multiplicity distributions

As an important part of the early experimental programme, most collaborations have measured E_T and/or multiplicities over a large part of the phase space. Consequently, the wealth of data is impressive, ranging¹⁰ from $^{28}\text{Si} + ^{12}\text{C}$ at 14.5 GeV/A to $^{32}\text{S} + ^{238}\text{U}$ at 200 GeV/A. Two representative examples^{11,12} are shown in Fig. 4. In spite of the vast range of different reactions, they clearly exhibit a distinct and common shape: large cross-sections at low E_T (the 'neck'), a rather long and flat region ('plateau') followed by an abrupt break ('knee'), and a steep decline ('tail'). Owing to the linear relation between E_T and charged-particle multiplicity N_{ch} ,

Si + Al, Cu, Ag, Au at 14.6 GeV/c per Nucleon

Fig. 4 Cross-section measurement $d\sigma/dE_T$ from (a) E802 (Ref. 11) ($1.3 < \eta < 2.5$) and (b) NA34 (Ref. 12) (200 GeV/A ^{32}S beam, $-0.1 < \eta < 5.5$).

this feature is borne out equally well in $d\sigma/dE_T$ and $d\sigma/dN_{ch}$. The shape of the cross-section is governed by the geometry of asymmetric nucleus-nucleus (A-B) collisions; it reflects the number of participants calculated from the overlap integral of the two extended nuclei as a function of their relative distance (impact parameter b)¹³. The *peripheral* collisions with fast growing geometrical overlap are responsible for the ‘neck’; the number of nucleon-nucleon encounters ν then rises steadily with decreasing impact parameter in the ‘plateau’ region up to a maximum average value for *central* collisions at about the ‘knee’, from where on fluctuations produce the ‘tail’ of the cross-section.

The decisive influence of nuclear geometry has dominated the discussion of many results in the early years, and indeed even subtle effects such as the deformation of ^{238}U are important and borne out by the data^{10,12,14}. By now, the analysis of E_T distributions is sufficiently advanced to allow a deeper and quantitative description of how nuclei actually lose energy when passing through each other, and to study the underlying collision dynamics. In a ‘wounded-nucleon’ inspired model, the basic nucleon-nucleon reaction is characterized by colour exchange, and therefore E_T production is proportional to the total number of participants (each nucleon can be ‘coloured’ only once). In a ‘collision-type’ model, momentum is exchanged in every reaction and therefore E_T would be proportional to the total number of nucleon-nucleon encounters. Recent results^{15,16} show that, within the present systematic and statistical accuracy of $\approx 10\%$, E_T is strictly proportional to the number of participants. This is compatible with what is known from p-A reactions¹⁷, where however the lever arm is significantly smaller. At higher energies (RHIC, LHC) it is predicted¹⁸ (see also Xin-Nian Wang in these proceedings) that semi-hard binary parton-parton collisions (‘mini-jets’) will play an increasing, even dominating, role in particle production, leading to energy densities much larger than the ones extrapolated from the present results.

On closer inspection, the shapes of the cross-section vary considerably between the different experiments¹⁰, which can be attributed largely to the different rapidity coverage of the various detectors. As a matter of fact, the fraction of total transverse energy falling into a given rapidity window changes essentially with all parameters at hand: projectile and target mass, beam energy,

Fig. 5 Charged-particle pseudorapidity distribution $dN_{ch}/d\eta$ for three different windows in E_T ($-0.1 < \eta < 2.9$) in O-nucleus reactions at 200 GeV/A (Ref. 19). The lines indicate predictions from the IRIS Monte Carlo.

and E_T (impact parameter b) itself. This can be clearly observed in the rapidity distribution $dN_{ch}/d\eta$ of charged particles¹⁹ in Fig. 5. The maximum, and even more the centroid, of the distributions shifts towards backward rapidities with increasing target mass and, for a given target, with increasing E_T , whereas the width of $dN_{ch}/d\eta$ shrinks with increasing E_T . As a consequence of the steady change of shape, the increase of particle multiplicity is almost exclusively accomplished in the backward hemisphere, whereas the particle density changes very little for $\eta > 3.5$, going from the average central collision into the extreme tails of E_T . Earlier results^{20, 21} from the AGS, indicating that particle production ceases to rise beyond a certain target mass, had been taken as evidence for complete stopping of a ^{28}Si projectile already in $A \approx 100$ target nuclei at $\sqrt{s} = 14.5$ GeV/A; they are however now recognized as largely being caused by a limited acceptance in rapidity²². The issue of stopping, i.e. the question of how much of the incident beam energy can be transferred into transverse degrees of freedom, is still very much confused, with different authors reaching opposite conclusions²³. It is, however, largely a qualitative one, depending on model assumptions and expectations, and will hopefully be replaced by quantitative results such as the E_T production per participant or per collision, or the rapidity shift of the nucleons (see below).

The large dispersion in the E_T cross-section introduced by the changing number of participants is somewhat of a disappointment, because fluctuations selected in the extreme tails of E_T are more of a trivial geometric than of an interesting dynamical nature ('pushing' E_T means pushing 'geometry' rather than pushing 'physics'). On the other hand, the strong correlation between E_T (N_{ch}) and b provides a useful and practical way for the experiments to select — or trigger on — central collisions, for example. An alternative approach to measuring the centrality of a collision is explored in several experiments by using so-called 'Zero-Degree Calorimeters' (ZDCs): small-aperture devices centred around 0° to cover the region $\eta \approx \eta(\text{beam})$ of the almost unperturbed forward-going non-interacting beam nucleons ('spectator' matter). The energy in a ZDC is strongly (anti)correlated with E_T and therefore also with b .

2.2 Energy and baryon density

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. As no direct observation exists of the initial energy released or of the initial size of the reaction volume, geometrical and kinematical assumptions have to be made, which are however not unique. Unfortunately, the SPS energy range is furthermore in between the two extremes of 'complete stopping', where the 'fireball' recipe could be applicable, and the 'ultra-relativistic' regime of the Bjorken model²⁴. In the former case, the measured E_T is compared with the maximum observable E_T generated by isotropic emission in the participant c.m.s. and using the Lorentz-contracted cylindrical overlap volume. In the latter, the energy density is estimated to be $\varepsilon_{Bj} = (dE_T/d\eta)/(F_{proj} \cdot c\tau)$, where the area of projectiles is $F_{proj} = \pi r_0^2 \cdot A^{2/3}$, and τ is the formation time. The concept of a 'formation time' τ is well established in high-energy physics, for example, from p-A reactions, where it is found that most of the produced particles do not reinteract inside the nucleus. Its value, usually taken on dimensional

grounds to be of the order of 1 fm/c, seems reasonable in the light of results from lepton–nucleon scattering²⁵ or particle interferometry (IIBT) in hadron–hadron reactions ($r \approx 1$ fm, see below). However, it is certainly not known to better than a factor of 2, in particular if the finite thickness of the nuclei is taken into account, and the resulting delayed buildup of energy density in the course of the collision.

The inferred energy densities are of the order of 1 GeV/fm³ at the AGS, and of order 2–3 GeV/fm³ at CERN for central O + Au collisions¹⁰ using the Bjorken prescription (somewhat larger in the fireball model). In view of the assumptions and uncertainties involved in the calculation of ϵ , these numbers can only be regarded as a rough estimate. It is nevertheless reassuring that the energy densities are not only large, ≈ 20 times the energy density of ground-state nuclear matter and still 5 times larger than the energy density inside a hadron, but also of the order of the critical value needed for the phase transition.

Much less information is available concerning the second coordinate, the baryon density ρ , in our phase diagram of nuclear matter (Fig. 1). An estimate²⁶, based on the rapidity shift of the beam nucleon in p–Pb reactions ($\Delta y \approx 2.5$) would lead to a compression factor of the order of 10. Microscopical Monte Carlo calculations, at present available only for the AGS, predict similar high values for the baryon density²⁷. However, one crucial input for these calculations, the rapidity distributions of baryons, is mainly measured in the target fragmentation region⁸. The only data available over a significant part of phase space are for S + S reactions²⁸ and are shown in Fig. 6. Considering the light system, the spectrum is remarkably flat and indeed cannot be described by models based on independent nucleon–nucleon collisions (e.g. FRITIOF). Rescattering, as implemented in some versions of VENUS and the RQMD, leads to an increased rapidity loss and could explain the high baryon densities observed even at midrapidity. If this trend continues to be present also for Pb on Pb, it might well be that the maximum attainable baryon density may only be reached at, or even above, SPS energies and not, as has been previously assumed, somewhere around the AGS range. In any case, the notion of a baryon-free ($\rho = 0$) region is certainly no longer justified at present machines and will have to await the future colliders.

Fig. 6 Rapidity distribution of protons from NA35 (Ref. 28).

2.3 Volumes and lifetimes

The space–time extent of sources emitting radiation or particles can, in principle, be measured via intensity interferometry²⁹ (see also contributions to the parallel session on IIBT in these proceedings). 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 is related, via a Fourier transformation, to the source distribution in space–time. This method, originally introduced by Hanbury-Brown and Twiss (IIBT!) in 1953 to determine the radii of stars is now regularly used in particle physics to measure freeze-out volumes (surface of last rescattering). The interpretation of the measured correlation functions is complicated by secondary effects such as Coulomb repulsion or limited acceptance, which have to be corrected for, but even more

so by ‘philosophical’ problems, such as the non-static character of the source (both in space and time), the Lorentz-frame dependence, and resonance decays. Experimentally, however, the results seem to be very reasonable. In p - p and e^+e^- reactions, the transverse radii r_T extracted are of the order of 1 fm (size of strings, hadrons, formation time). The longitudinal dimensions r_L , again of roughly 1 fm, are interpreted as a coherence length, because (as in cosmology) the rapid longitudinal expansion separates the phase space into a number of causally disconnected pieces with a ‘length’ of the order of one unit in rapidity (inside-outside cascade picture, see Fig. 2). In low-energy nuclear reactions, the sizes correspond precisely to the expected interaction region (e.g. the size of the smaller of the two nuclei), and are therefore obviously related to a geometrical dimension. 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 1, 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 reactions³⁰. In $O + Au$, the rapidity averaged results, $r_T = 4.1 \pm 0.4$, $r_L = 3.1 \pm 0.3$, $\lambda = 0.31 \pm 0.05$ in $1 < y < 4$, are roughly in line with low-energy nuclear data [$r(^{16}O) \approx 3$ fm]. At midrapidity ($2 < y < 3$), however, they find $r_T = 8.1 \pm 1.6$, $r_L = 5.6 \pm 1.0$, $\lambda = 0.77 \pm 0.2$, i.e. a value for r_T which exceeds the projectile size by almost a factor of 3 and indicates a very large and chaotic ($\lambda \approx 1$) source with a volume at freeze-out exceeding 1000 fm³! Similar (preliminary) results were obtained in $S + Au$ and $S + Ag$, whereas, at the AGS, E802 find³¹ $r_L \approx r_T \approx 3.5$ fm and $\lambda \approx 0.7 \pm 0.1$, in $Si + Au$ and $Si + Al$. These surprising results can be consistently interpreted if one assumes that the freeze-out volume depends on the particle density as shown in Fig. 7³²: r_T could be proportional either to $(dN/dy)^{1/3}$ (solid line, decoupling at constant particle density) or to $(dN/dy)^{1/2}$ (dashed line, decoupling when mean free path comparable to system size).

Fig. 7 Freeze-out radii versus charged-particle density at $y_{cm} = 0$ for hadron-hadron and nucleus-nucleus collisions from Ref. 32.

The observed large expansion at midrapidity (from 3 to 8 fm) leads to a limit on the lifetime of $\tau \geq 5$ fm/c. In principle, with high statistics and good momentum resolution the lifetime could be inferred directly from the correlation function and might even be sensitive to the occurrence of a first-order phase transition, which keeps the system frozen in the mixed phase for a very long time. Correlations with different particle species (K , $\bar{p}$) and p_T dependences are still an uncharted territory, and several new experiments are planned to exploit the potential of this method.

Summarizing the main results on global event characteristics, we have seen that very large energy and baryon densities can be created, which are already in the region of what is required for QGP formation at present accelerators and with rather light ion beams. The reaction zone, containing hundreds of particles in a volume exceeding 1000 fm³, is certainly ‘macroscopic’ by the standards of particle physics and QCD. In addition, first insight has been gained into the underlying collision dynamics in nucleus-nucleus reactions, a field interesting in its own right and a prerequisite for extrapolations to heavier projectiles and higher energies. The study of global event characteristics has therefore provided us with a good basis from where we can start looking for new phenomena.

3. TRANSVERSE-MOMENTUM SPECTRA AND THERMAL EQUILIBRIUM

3.1 Global features of p_T spectra

Ever since the discovery of hard scattering at the CERN ISR in 1973, the measurement of inclusive p_T distributions has been a valuable tool in the study of high-energy hadronic reactions. The deviation of the p_T spectra from the exponential fall-off has added strong experimental support to the then-emerging picture of the partonic substructure of hadrons. A similar striking change in the p_T of produced particles seemed to emerge from early cosmic-ray experiments studying ultra-relativistic nucleus-nucleus collisions³³. The data suggested a rapid increase of $\langle p_T \rangle$ from $\langle p_T \rangle \approx 0.34\text{--}0.4$ GeV/c, as typically found at hadron colliders (ISR, SPS $p\bar{p}$), to $\langle p_T \rangle \geq 1$ GeV/c, once the energy density exceeds a critical value of about $2\text{--}3$ GeV/fm³. According to a conjecture of Van Hove³⁴, the dramatic increase of $\langle p_T \rangle$ could be a signal of the phase transition between normal hadronic matter and the QGP. However, a thermal interpretation of p_T distributions, as implied in this picture, is and has always been disputed. The spectral form, which follows a thermal shape $f(p_T) \propto \exp(-m_T/T)$, ($m_T = \sqrt{p_T^2 + m^2}$) for $p_T \leq 0.8\text{--}1$ GeV to a very good approximation, as well as the fact that the inverse slope T is experimentally found to be similar for different particle species (m_T scaling)³⁵, has led to the speculation that the low- p_T particles are emitted from an equilibrated source of temperature T . This 'temperature' rises smoothly with $\sqrt{s}$ from low-energy A-A and p-p reactions^{9,36} up to the limiting 'Hagedorn' value of $T \approx 150$ MeV at ISR energies (the source is 'heated' up). The notion of an equilibrated system seems indeed defensible for BEVALAC A-A reactions, where it was verified with microscopical Monte Carlo calculations that the number of collisions per particle is of the order of a few ($\nu > 3$)⁹. However, there is no established mechanism that could thermalize the reaction system in p-p with the small number of particles involved ($N_{ch} < 5\text{--}10$). In addition, several other known effects will, in general, influence and disturb the shape of spectra³⁵ (resonance decays, phase-space limits, hard scattering).

3.2 Negative particle spectra

The general characteristics of p_T distributions in p-A and A-A reactions can be extracted from Fig. 8, where $d^2\sigma/dp_T^2$ is shown for negative particles (mostly pions) in p-W, O-W, and S-W central collisions as measured³⁷ by NA34 in the rapidity range $y = 1\text{--}1.9$ (for original references and a detailed discussion of p_T distributions, see Ref. 35). The distributions can no longer be described with a single exponential in p_T or m_T as was the case in p-p; they show a strong enhancement at high p_T (> 1 GeV/c) and at low p_T (< 250 MeV/c) when compared with a parametrization of minimum-bias p-p data at the corresponding $\sqrt{s}$ and y (full line in Fig. 8a). Whereas the high- p_T enhancement has been seen by all experiments at CERN, the size of the low- p_T increase is still controversial. Both the high- p_T rise, usually referred to as the 'Cronin' effect, and the low- p_T rise were actually observed already in the mid-1970's at Fermilab in p-A reactions^{38,39}.

The high- p_T excess increases both with target mass and with projectile mass; it is weaker, but still significant, in central S-S (with at most a few spectator nucleons) than in central O-Au. The effect is most pronounced when comparing p-p and p-W, which corresponds also to the largest change in atomic mass number, but it has been shown^{37,40} that the target and projectile dependence are in fact similar when parametrized by a power law in atomic mass.

The systematic behaviour of the low- p_T region is decisively different from the high- p_T excess. The projectile dependence is much weaker than the one on the target and the excess seems not to change with b (or E_T). On the other hand, a strong increase is visible as a function of rapidity in the data of NA35⁴¹. The number of low- p_T particles increases by almost a factor of 5 in O-Au, when going backward in rapidity from $\langle y \rangle = 2.5$ to $\langle y \rangle = 1.1$. In contrast, the excess is much smaller and at most weakly dependent on y for central S-S⁴². The size of the excess in the soft component is remarkable; it amounts to 10-40% of all pions observed both at CERN and at the AGS.

Fig. 8 Negative-particle distributions from NA34 (Ref. 37) for central collisions of p, O, S [(a), (b), (c)] with a W target. Central reactions are selected by a cut on $E_T > 10, 60$, and 80 GeV, respectively. For comparison, a parametrization of p-p data (see text) is shown as a full line.

3.3 Spectra of identified particles

Transverse-mass spectra of identified pions, kaons, and protons have been measured^{43,44} at the AGS by E802 in p-A and A-A reactions for $0.3 < p_T < 1$ GeV/c close to midrapidity ($y = 1.2-1.4$). Within the limited p_T range covered by this experiment, the spectra are consistent with a single exponential in m_T . Whereas the fitted values of T_0 for the pion spectra stay essentially constant at $T_0 \approx 150$ MeV, the inverse slope of protons and K^+ increases considerably from $T_0 \approx 150$ MeV in p-Be to $T_0 > 200$ MeV in central Si-Au, where they are significantly above the corresponding values for Λ , K^0 , and $\bar{p}$. The difference between p and $\bar{p}$ or K^+ and K^0 will be difficult to explain without additional assumptions (e.g. absorption of $\bar{p}$) with an equilibrium interpretation of the distributions. On the other hand, the data are measured close to target rapidity in an asymmetric system, and therefore ‘acceleration’ of the target nucleons, the equivalent to ‘stopping’ of the projectile, by primary collisions as well as ‘heating’ of the spectator matter by rescattering (e.g. pion + nucleon $\rightarrow \Lambda + K^+$) could be the reason for the hardening of p and K^+ spectra.

Transverse-mass distributions of identified particles have been measured by NA35⁴⁵ in p-Au, O-Au and S-S reactions, and in S-W by NA34⁴⁶. As was the case at the AGS, the spectra can be described with a single exponential in m_T within the limited statistics and range in p_T available. It is quite conceivable, however, that these distributions will also reveal a more complicated structure once better data become available. With the exception of K^- from NA34, all values are consistent with a common slope $T_0 \approx 200$ MeV both in p-A and A-A reactions. This could be somewhat fortuitous, because the data are taken in different rapidity intervals and p_T regions: essentially at high p_T (> 800 MeV/c) by NA35 and WA85, where the Cronin effect might influence the spectra of mesons, and at $p_T < 800$ MeV/c by NA34 where the lowest points are well inside the regime of the low- p_T enhancement observed for h^- . Taken at face value, the spectra are less steep than for comparable p-p data, in particular Λ 's^{45,47} and protons²⁸, possibly again a consequence of stopping and rescattering. The similarity of the m_T slopes (including now h^-) can also be interpreted in terms of thermodynamical variables, e.g. temperature and collective transverse flow. A quantitative calculation⁴⁸ of this kind is compared in Fig. 9 (solid line) with S-S results of NA35. The fit describes the spectra reasonably well with a temperature of $T = 112$ MeV and a rather large flow velocity of $\beta = 0.43$.

Fig. 9 Global fit with a thermal model (Ref. 48) including radial collective flow to the data of NA35 (Ref. 45). The various particle spectra are normalized to each other at $m_T = m$.

3.4 Interpretation of the p_T distributions

Explanation of the high- p_T enhancement in terms of rescattering of charged particles in the surrounding target matter seem unlikely, because one would expect a strong rapidity dependence. Likewise, collective final-state interactions (collective flow, increased ‘temperature’) will probably have a more pronounced dependence on E_T than indicated by the data. A mechanism, which could be consistent with the experimental systematics, is multiple low-momentum scattering of partons inside the nuclear matter^{49,50}. As an initial-state process, originally put forward to describe the Cronin effect, it is equivalent to increasing the average p_T of partons above their intrinsic p_T . Quantitative QCD calculations have been carried out so far only for p-A interactions⁵⁰; they are in reasonable agreement with the data and even describe some subtle differences observed between K^+ and K^- . The same mechanism is made responsible for the broadening of dimuon p_T observed in p-A Drell-Yan and J/ψ production (see S. Gavin in these proceedings).

The interest in the low- p_T enhancement has been considerable, and a number of (mostly qualitative) explanations, briefly listed below, have been proposed: i) resonance decays (in particular Δ and N^*)^{51, 52}, ii) rescattering and cascading of produced particles in the target nucleus, iii) collective transverse flow^{48, 53}, iv) modification of the pion dispersion relation⁵⁴, and v) supercooled droplets of QGP⁵⁵.

The (related) explanations (i) and (ii), which in any case will contribute to the low- p_T excess at some level, seem even to be sufficient to describe the data at the AGS. They do naturally predict the observed target and rapidity dependence, but whereas the number of nucleons available for cascading and Δ production is similar at AGS and SPS, the absolute number of excess pions is considerably larger (for $y > 1-1.5$ only) at the higher energy. The other models will probably have difficulties in describing the systematic features, in particular the prominent effect visible already in minimum-bias p-A reactions.

In spite of the large energy densities and final-state particle multiplicities reached in ultra-relativistic heavy-ion reactions, no qualitatively new or striking phenomena have emerged so far. However, the data are by now of sufficient quality to study in detail the subtle variations that appear as a function of target, projectile, rapidity, p_T and $\sqrt{s}$. On the theoretical side, a fair number of models are at hand to interpret the p_T spectra observed in A-A collisions. However, many of them have not been confronted in a quantitative way with the rich set of data now available. Most likely, no single one will be able to explain all systematic trends and detailed

structures, and a thorough exclusion of more mundane processes will be necessary before we can conclude whether or not new physics may still be hidden in the transverse momentum observable. In any case, the rather large effects observed in A-A collisions are a clear deviation from a simple superposition of independent nucleon-nucleon collisions. Their explanation requires at least strong initial and final-state rescattering, which is exactly what is needed to approach (thermal) equilibrium.

4. STRANGENESS PRODUCTION AND CHEMICAL EQUILIBRIUM

An increased abundance of strange particles in heavy-ion reactions has been one of the predicted signals for a QGP from the very beginning⁵⁶. In ‘chemical’ equilibrium, the abundance of particle species (hadrons/quarks) are governed by Boltzman factors, i.e. essentially by the temperature, the respective masses, and a chemical potential μ . Compared with hadronic processes, the production of strange quarks is favoured in a QGP because there the mass of the strange quark is reduced from ≈ 500 MeV to ≈ 150 MeV (chiral symmetry restoration), i.e. a value comparable with the critical temperature. In addition, in a baryon-rich region 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 in favour of s and $\bar{s}$ production. However, it has been realized since that the dynamical evolution through the phase transition and the unavoidable hadron gas phase can dilute the strangeness content of matter and readjust the particle ratios to the respective equilibrium values at the various stages (which is indeed the very definition of a system evolving in equilibrium!). The interpretation of the strangeness content will therefore depend to a large extent on our understanding of the hadronization scenarios and on the time scales and relaxation times which are available for equilibration in the various phases.

4.1 Results from the AGS

The first results on enhanced strangeness production were reported from the AGS already shortly after the first data had been taken in 1986⁵⁷. As can be seen from the rapidity distribution of charged particles⁵⁸ in Fig. 10, the yield of charged kaons per incident beam nucleon increases gradually from p + Be to p + Au to central Si + Au, whereas the number of charged pions stays essentially constant. The resulting K^+/π^+ ratios, integrated over $1.2 < y < 1.4$ ⁵⁸, vary smoothly from p + Be to p + Au to central Si + Au ($K^+/\pi^+ = 7.8 \pm 0.4, 12.5 \pm 0.6$, and $18.2 \pm 0.9\%$ respectively), whereas K^-/π^- increases only little, from 2% to 3%. The p + Be data are comparable with p-p results at corresponding energies⁵⁸ ($K^+/\pi^+ = 4$ to 8%, $K^-/\pi^- = 2$ to 5%), whereas the K^+/π^+ ratio is larger by more than a factor of 2 in central Si + Au. The increase in K^-/π^- is seemingly less, 50% only, but with a large statistical error. As can be seen from Fig. 10, these ratios are rapidity-dependent and range in Si + Au, for example, from $K^+/\pi^+ \approx 16\%$ at $y = 1.7$ to 25% at $y = 0.9$. The different rapidity distributions of K^+ , K^- , and pions probably reflect a different production mechanism: K^- are more centrally produced, in particular in p-Be collisions, whereas the K^+ behave similarly to the protons and shift clearly backwards with increasing target mass. An enhancement of K^+ production (K^+ ‘distillation’)

Fig. 10 Rapidity distributions dn/dy for pions, kaons, and protons in p + Be, p + Au, and central Si + Au collisions at 14.6 GeV/A (Ref. 58). The Si + Au data are divided by 28 for comparison.

has been predicted to occur in very baryon-dense matter⁵⁹ or in the case of QGP formation⁶⁰, where the effect would indeed be most pronounced in the target fragmentation region (highest baryon density). However, the gradual increase in K^+ production from p-p to p- Λ to Λ - Λ together with the change in slope of the p_T spectra suggests that rescattering effects of produced particles amongst themselves and with the surrounding cold spectator matter are responsible for the large K/π ratios. Microscopical, non-equilibrium calculations including rescattering (in particular π - $\pi \rightarrow K$ - K and π - $n \rightarrow K$ - Λ) can reproduce quantitatively the observed K/π ratios and the p_T spectra⁶¹. Because of strangeness conservation, the large kaon yields have to be balanced by an increase in Λ production. Absolute numbers are not available so far, but E810 has been measuring K_S^0 and Λ in the forward hemisphere as a function of centrality⁶². No dependence on impact parameter is found, in contrast with the slight increase in K/π ratios seen by E802⁶³, and the inverse slopes of K_S^0 , Λ , and π are identical ($T_0 \approx 150$ MeV/c).

4.2 Results from the SPS

Charged kaons were measured in the external spectrometer of the NA34 experiment⁴⁶ in p-W and S-W for low p_T in the target fragmentation region ($0.8 < y < 1.3$). The K/π ratios show the same trend as that observed at the lower AGS energy: a gradual increase of up to a factor of 2 in the K^+/π^+ ratio when going from p-p to p-W and S-W, a K^-/π^- ratio which stays approximately constant, and a different p_T slope for K^+ and K^- . These similarities might be indicative of a common underlying mechanism (e.g. associated $K^+\Lambda$ production), particularly since both experiments are carrying out measurements in a baryon-rich region of phase space. It is intriguing, however, that the K^+/π^+ ratio reaches about the same level at CERN and AGS, i.e. $\approx 25\%$ when integrated over p_T . This number happens to be close to the one predicted for chemical equilibrium, which is equivalent to a K/π ratio of the order of 1 when plotted⁴⁶ as a function of m_T instead of p_T .

Neutral strange particle production (K_S^0 , Λ , $\bar{\Lambda}$) has been measured by NA35 in O-Au backward from midrapidity, $\langle y \rangle \approx 2$, and in S-S reactions in $1 < y < 3$, which is equivalent to most of the phase space owing to the reflection symmetry around $y = 3$ in the symmetric S-S system^{64, 65}. In O-Au, no change in the K_S^0 and $\bar{\Lambda}$ yield, normalized to negative particles, was seen compared with p-Au or the FRITIOF Monte Carlo code (FRITIOF $\approx$ p-p), whereas Λ 's are again produced about two times more frequently with the heavy target (both in p-Au and O-Au) than predicted by FRITIOF⁶⁴. In the S-S system, however, all neutral strange particles seem to be enhanced by a factor of about 2 in central collisions as compared with p-p reactions⁶⁵. The following numbers, extrapolated to full phase space ($1 < y < 5$, $p_T > 0$), were obtained for the relative yields in central S-S over p-p: $h^- = 36 \pm 1.5$, $\Lambda/h^- = 2.4 \pm 0.2$, $\bar{\Lambda}/h^- = 3.2 \pm 0.9$, $K_S^0/h^- = 1.8 \pm 0.4$. [The published errors are a linear sum of statistical and extrapolation errors and were reduced by $1/\sqrt{2}$ (R. Brockmann, private communication).] The rapidity distribution⁶⁵ of K_S^0 and $\bar{\Lambda}$ are peaked at $y = 3$ (central production), whereas the Λ 's are more spread out in y and probably trace to some extent the proton distribution²⁸, when proper care is taken about the effect of the limited p_T acceptance. In Fig. 11, the multiplicity of neutral strange particles normalized to the total multiplicity $\langle N_{h^-} \rangle$ is shown as a function of $\langle N_{h^-} \rangle$ for peripheral, intermediate, and central collisions. In addition to the previously mentioned enhanced strangeness yield in central S-S compared with p-p (open circles) and, somewhat smaller, with p-S (open squares), there is a weak indication of a further dependence on centrality.

The apparently different behaviour of K_S^0 and $\bar{\Lambda}$ in O-Au and S-S, if not simply due to the limited statistics, has no straightforward explanation. It might be caused by the different rapidity acceptance of the two data sets, reflecting different strangeness enhancement mechanisms in the dense and baryon-rich target fragmentation region of the O-Au reaction as compared to the lighter S-S system, where K_S^0 and $\bar{\Lambda}$ production is dominantly central.

Multistrange (anti)baryons are expected to be a particularly sensitive probe of strangeness enhancement from the QGP, because their thermal production depends on a high power of the

Fig. 11 Ratio of the mean multiplicities of Λ , K_S^0 and $\bar{\Lambda}$ observed in the NA35 acceptance to the total negative particle multiplicity (h^-) as a function of the event multiplicity. Also shown are p-p data (open circles), p-S minimum-bias data (open squares) and the FRITIOF prediction (dashed line) (Ref. 65).

strangeness density, whereas the non-equilibrium production in the hadron-gas phase is expected to be suppressed owing to the large mass. The WA85 experiment, optimized to measure strange baryon decays in $2.3 < y < 3.0$ and $p_T > 1$ GeV/c, has obtained the following results⁶⁶ in S-W reactions at 200 GeV/A for $m_T > 1.72$ GeV (numbers in brackets for $1 < p_T < 2$ GeV/c): $\bar{\Lambda}/\Lambda = 0.13 \pm 0.03$, $\bar{\Xi}/\Xi = 0.39 \pm 0.07$, $\Xi/\Lambda = 0.20 \pm 0.04$ (0.11 ± 0.02), $\bar{\Xi}/\bar{\Lambda} = 0.60 \pm 0.20$ (0.33 ± 0.11). The Λ sample includes Λ 's from Σ^0 , whereas the contamination arising from cascade decays has been corrected for. Production of both Λ and $\bar{\Lambda}$ increases by $\approx 70\%$ when going from p-W to S-W, leaving the $\bar{\Lambda}/\Lambda$ ratio essentially constant (Fig. 12). Whereas the Ξ/Λ ratio is compatible with results from p-p and e^+e^- reactions⁶⁶, the $\bar{\Xi}/\bar{\Lambda}$ ratio is about five times greater than the one measured at the ISR, albeit with very large statistical errors. For the reasons mentioned above, a strong overall increase in antibaryon production will be difficult to explain in non-QGP models^{67,68} (see also J. Rafelski in these proceedings). However, in the high- p_T region accessible to WA85, nuclear effects similar to the one discussed in connection with p_T distribution ('Cronin effect') or different A-dependences for soft and hard processes could alter particle ratios significantly, with little influence on the integrated yields.

Fig. 12 Transverse-mass spectra of negative particles Λ and $\bar{\Lambda}$ in S-W and p-W reactions. The dashed lines with an exponential slope of 4.3 are drawn to guide the eye (Ref. 66).

Fig. 13 Ratio of $(\phi/\rho + \omega)$ as a function of E_T in O + U and S + U reactions, normalized to p + U events (from Ref. 71). The full line is a fit with a hadronic enhancement model.

Similarly to particles with open strangeness, the production of ϕ mesons is strongly enhanced in nuclear collisions. The ratio of ϕ , normalized to $\rho + \omega$, is shown in Fig. 13 as a function of scaled E_T (E_T divided by transverse area $F \propto A^{2/3}$, which is proportional to energy density) as measured by NA38⁶⁹ in the dimuon channel for $p_T > 1.3$ GeV, $y_{cm} \approx 0.6$. The increased number of ϕ mesons, up to a factor of 3 at the highest E_T compared with p-p, has been predicted for the case of QGP formation⁷⁰, but hadronic-gas models are able to describe the data equally well (full lines in Fig. 13)⁷¹.

4.3 Interpretation of strangeness production

As is the case with many of the observables measured in ultra-relativistic heavy-ion collisions, the question of ‘strangeness as a signal for the QGP’ has undergone a rapid development in the recent past. On the experimental side, a significant enhancement of strange-particle production has been observed in most channels, both at the AGS and at the SPS, when comparing p-p and A-A reactions, with p-A results in many cases in between. The pattern is, however, far from being simple, depending on particle species, rapidity, p_T , and probably a number of other reaction parameters as well. In many cases, the data suffer severely from a lack of statistics or limited acceptance (particularly at low p_T); but experimental clarification on some issues is expected in the near future from a new generation of upgraded heavy-ion experiments now being planned or under way. On the theoretical side, strangeness enhancement, in general, is seen now more as a characteristic feature of a system approaching thermal (and 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 (all?) 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. On the other hand, no unconventional explanation has so far been put forward for the observed increase of anti-hyperons ($\bar{\Lambda}$, $\bar{\Xi}$).

Again, as in the case of p_T distributions, strong nuclear effects have been observed. Even in the most conservative models, their explanation requires an extended, strongly interacting system evolving towards (chemical) equilibrium.

5. SIGNALS FROM THE QGP

Weakly interacting probes, which decouple at early times from the evolving matter, or signals that are characteristic only for the QGP phase, can give us direct and hopefully unambiguous information on the state created in the first moment of the reaction. The two best-known examples, J/ψ suppression and thermal radiation, are discussed in turn.

5.1 J/ψ suppression

The original idea⁷² that the formation of 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 $g + g \rightarrow c + \bar{c}$. 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 charm quarks dissolve and separate in space to later appear 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 characteristic 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 been observed by the NA38 experiment; it was indeed amongst the first results and was later confirmed with different beams and targets by the same collaboration⁷³. Figure 14 shows the invariant dimuon mass spectrum measured in O + U for low- E_T and high- E_T collisions. The two data sets are normalized to the Drell-Yan continuum outside the resonance region and show a clear suppression of J/ψ by a factor of about 2 in central collisions compared with peripheral ones. The number of J/ψ 's relative to the number of events in the continuum underneath the peak decreases smoothly with the scaled E_T (energy density) (Fig. 15). The ratio of p_T spectra from J/ψ created in high- E_T reactions to J/ψ 's created in low- E_T reactions show furthermore that the suppression is most effective at low transverse momentum (Fig. 16). 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 (see Ref. 74 and references therein). In these models, which typically involve a number of uncertain parameters and assumptions, rescattering of the J/ψ 's in the surrounding medium provides the

Fig. 14 Dimuon mass spectrum 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 .

Fig. 15 J/ψ suppression factor (number of J/ψ events divided by number of continuum events below the peak) plotted against scaled E_T (see text) in p-U, O-U, and S-U reactions at 200 GeV/A.

Fig. 16 Ratio $R(p_T)$ of the p_T distributions of J/ψ at high and low E_T . The data are normalized to the continuum events in the same E_T intervals.

suppression (e.g. via $J/\psi + \pi \rightarrow D\bar{D} X$), and initial-state parton scattering prior to the gluon fusion shifts the p_T of the surviving J/ψ 's to larger values (see Cronin effect earlier on and S. Gavin in these proceedings). Both effects 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 states⁷⁴.

5.2 Thermal photons

Direct photons and lepton pairs (virtual photons) are weakly interacting observables and should emerge as thermal radiation from the heated matter without being altered by final-state effects⁷⁵. They are, however, not at all unique for a QGP, because their shape and amount are given by the classical laws of black-body radiation and contains information only about the temperature and the space-time volume of the emitting source and nothing about its constituents. On the other hand, the emission is strongly temperature-dependent and their observation might be the only way to gather direct information on the first and hottest stages of the evolution. Background from hadronic decays and direct hard photons from QCD Compton scattering or lepton pairs from Drell-Yan limit the accessible p_T range to $1 < p_T < 3$ GeV. The sensitivity of present experiments is not yet sufficient to reach the predicted level of thermal radiation for temperatures below 250 MeV, and only upper limits ($\gamma/\pi < 15\%$ – 20%) have been published⁷⁶.

6. CONCLUSIONS

An impressive list of observables has been measured and analysed in the first five years of experimental heavy-ion physics. Macroscopic systems (by the standards of QCD) are created in these reactions with energy and particle densities of the order of magnitude required for QGP formation. A number of significant deviations from straightforward extrapolations of hadron-hadron reactions have been found, many of them indeed consistent with QGP formation. But so far, no clean 'smoking gun' has been identified as unambiguous evidence, and alternative hadronic explanations are always possible, in some cases even likely. However, even the most conservative models involve a large amount of rescattering amongst the produced particles and therefore imply strongly interacting hadronic matter on its way to thermal and chemical equilibrium. Significant improvements in all relevant parameters (energy density, volume, lifetime) can be expected from 'real' heavy ions that will be available in the near future at AGS and SPS, and later from the larger energies at RHIC and the LHC. As far as one can tell at present from the data, heavy-ion reactions seem indeed to be an appropriate and promising tool to study the properties of strongly interacting hadronic bulk matter and prove the existence of the quark-gluon plasma.

REFERENCES

1. Quark Matter '87, Proc. 6th Int. Conf. on Ultra Relativistic Nucleus-Nucleus Collisions, Nordkirchen, Fed. Rep. Germany, 1987 [Z. Phys. C38 (1988)].
2. Quark Matter '88, Proc. 7th Int. Conf. on Ultra Relativistic Nucleus-Nucleus Collisions, Lennox, Mass., USA, 1988 [Nucl. Phys. A498 (1989)].
3. Quark Matter '90, Proc. 8th Int. Conf. on Ultra Relativistic Nucleus-Nucleus Collisions, Menton, France, 1990 [Nucl. Phys. A525 (1991)].
4. Proc. Workshop on Heavy Ion Physics at the AGS (HIPAG), Brookhaven, NY, USA, 1990 [report BNL-44911].
5. Proc. 'Hadronic Matter in Collision 1988', Tucson, Ariz., USA, 1988 (World Scientific, Singapore, 1989).
6. D. Schramm, Proc. 2nd ESO-CERN Symposium, Garching, 1986, p. 269.
7. N.K. Glendennig et al., Berkeley preprints LBL-30645 and LBL-30296 (1991).
8. H.R. Schmidt and J. Schukraft, The physics of highly relativistic heavy-ion collisions, to be published in J. Phys. G (1991).
9. S. Nagamiya et al., Phys. Rev. C24 (1981) 971.
10. J. Schukraft, preprint CERN-EP/88-141 and Proc. 19th Int. Symp. on Multiparticle Dynamics, Arles, 1988 (World Scientific, Singapore, 1988), p. 537.
11. F. Videbaek, in Ref. 4, p. 38.
12. T. Akesson et al., Nucl. Phys. B353 (1991) 1.
J. Schukraft, in Ref. 2, p. 79c.
13. G. Baum, P. Braun Munzinger and V. Ruuskanen, Phys. Lett. B190 (1987) 29.
14. T. Akesson et al., Z. Phys. C38 (1988) 383 and Phys. Lett. B214 (1988) 295.
15. J. Baechler et al., submitted to Z. Phys. C (1991).
16. R. Albrecht et al., submitted to Phys. Rev. C (1991).
17. W. Busya and R. Ledoux, Annu. Rev. Nucl. Part. Sci. 38 (1988) 119.
18. A. Capella, C. Merino and J. Tran Thanh Van, Orsay preprint LPTHE 91-27 (1991).
19. T. Akesson et al., Z. Phys. C38 (1988) 59 and Nucl. Phys. B333 (1990) 48.
20. B. Bassalek et al., Z. Phys. C38 (1988) 45.
21. T. Abbott et al., Phys. Lett. B197 (1987) 285.
22. See R. Hall (E814) and M. Tannenbaum (E802) in Ref. 4, p. 16 and p. 44, respectively.
23. A. von Keitz et al., Univ. Frankfurt preprint UFTP 255/1991.
S. Chapman and M. Gyulassy, Berkeley preprint LBL-30644 (1991).
24. J.D. Bjorken, Phys. Rev. D27 (1983) 140.
25. M. Gyulassy and M. Pluemer, Nucl. Phys. B 346 (1990) 1.
26. R. Anishetty, P. Koehler and M. McLarren, Phys. Rev. D22 (1980) 2793.
27. H. Sorge et al., Univ. Frankfurt preprint UFTP 243/1990.
28. H. Stroebele and R. Stock, in Ref. 3, p. 59c and p. 221c, respectively.
29. D. Boal, C. Gelbke and B. Jennings, Rev. Mod. Phys. 62 (1990) 553.
W. Zajz in Ref. 4, p. 411, and Ref. 3, p. 315c.
30. R. Bamberger et al., Phys. Lett. B203 (1988) 320 and Ref. 3, p. 327c.
P. Seyboth, in Ref. 4, p. 261.
31. R.J. Morse, in Ref. 4, p. 402.
32. R. Stock, Frankfurt preprint OKF 90-3 (1990).
33. T.H. Burnett et al., Phys. Rev. Lett. 57 (1986) 3249.
34. L. Van Hove, Phys. Lett. 118B (1982) 138.
E.V. Shuryak and O.V. Zhirov, Phys. Lett. 89B (1980) 253 and 171B (1986) 99.
35. J. Schukraft, preprint CERN-PPE/91-04, talk given at the Int. Workshop on Quark Gluon Plasma Signatures, Strasbourg, France, 1990.
36. R. Hagedorn, Riv. Nuovo Cim. 6 (1983) 1.
37. T. Akesson et al., Z. Phys. C46 (1990) 361.
38. J.W. Cronin et al., Phys. Rev. D11 (1975) 3105.
D. Antreasyan et al., Phys. Rev. D19 (1979) 764.
L. Kluberg et al., Phys. Rev. Lett. 38 (1977) 670.
39. D.A. Garbutt et al., Phys. Lett. B67 (1977) 355.
D. Chaney et al., Phys. Rev. D19 (1979) 3210.

40. A. Drees (NA34), Thesis, Univ. Heidelberg (1989).
41. H. Stroebele et al., Z. Phys. C38 (1988) 89 and private communication.
42. S. Wenig (NA35), Thesis, Univ. Frankfurt (1990).
43. T. Abbott et al., Phys. Rev. Lett. 64 (1990) 847.
Y. Miake (E802), in Ref. 4, p. 240, and Ref. 3, p. 231c.
S.G. Steadman (E802), in ref. 5, p. 607.
44. J.B. Costales (E802), in ref. 3 and ref. 4.
45. G. Odyniec (NA35), Brookhaven preprint LBL-27926 and G. Pugh (NA35), preprint LBL-27833.
46. H. Van Hecke (NA34) in Ref. 3, p. 227c.
47. I. Derado (NA35), in ref. 5, p. 636.
J. Bartke et al., Z. Phys. C48 (1990) 191.
48. K. Lee, U. Heinz and E. Schnedermann, Z. Phys. C48 (1990) 525.
49. M.J. Longo, Nucl. Phys. B134 (1978) 82.
A. Krzywicki et al., Phys. Lett. 85 (1979) 407.
50. M. Lev and B. Petersson, Z. Phys. C21 (1983) 155.
51. J. Stachel, Talk given at the XII Int. Conf. on Particles and Nuclei in Collision (PANIC), Cambridge, Mass., USA, 1990.
52. G.E. Brown, J. Stachel and G.M. Welke, submitted to Phys. Lett. B. (1991).
53. T.W. Atwater, P.S. Freyer and J.I. Kapusta, Phys. Lett. B199 (1978) 30.
54. E.V. Shuryak, in L. Van Hove Festschrift (World Scientific Publishing, Singapore, 1989), in Ref. 3, p. 3c, and Phys. Rev. 42 (1990) 1764.
55. L. Van Hove, Ann. Phys. 192 (1989) 66.
56. P. Koch, B. Mueller and J. Rafelski, Phys. Rep. 142 (1986) 167.
P. Koch, Prog. Part. Nucl. Phys. 26 (1991) 253.
57. Y. Miake et al., in Ref. 1, p. 135.
58. T. Abbott et al., Phys. Rev. Lett. 64 (1990) 847 and 66 (1991) 1567.
59. C. Greiner et al., Phys. Rev. D38 (1988) 2797 and ref. 5, p. 750.
U. Heinz et al., Mod. Phys. Lett. A2 (1987) 153.
60. J. Rafelski, Nucl. Phys. A418 (1984) 215c.
J. Rafelski and B. Mueller, Phys. Rev. Lett. 48 (1982) 1066.
61. R. Matiello et al., Phys. Rev. Lett. 63 (1989) 1459 and Phys. Lett. B243 (1990) 7.
H. Sorge et al., Univ. Frankfurt preprint UFTP 263/1991.
62. S.E. Eisman et al., Phys. Lett. B248 (1990) 254.
63. J. Costales (E802) in Ref. 3, p. 455c.
64. A. Bamberger et al., Z. Phys. C43 (1989) 25.
65. A. Bamberger et al., Z. Phys. C48 (1990) 191.
66. S. Abatzis et al., Phys. Lett. B244 (1990) 130.
D. Evans and J.L. Narjoux, in Ref. 3, p. 441c and 445c, respectively.
S. Abatzis et al., submitted to Phys. Lett. B.
67. N.S. Amelin et al., submitted to Phys. Rev. D (1991).
68. J. Rafelski, Univ. Arizona preprint AZPH-TII-91-11 (1991), submitted to Phys. Lett. B.
69. J.P. Guillaud, in Ref. 3, p. 449c.
70. A. Shor, Phys. Rev. Lett. C54 (1985) 1122.
71. P. Koch and U. Heinz, in Ref. 3, p. 293c.
72. T. Matsui and H. Satz, Phys. Lett. B178 (1986) 416.
F. Karsch and R. Petronzio, Phys. Lett. B193 (1987) 105.
73. A. Bussière et al., Z. Phys. C38 (1988) 117.
C. Baglin et al., Phys. Lett. B220 (1989) 471.
R. Varela, in Ref. 3, p. 275c.
74. H. Satz, Phys. Lett. B242 (1990) 107 and preprint CERN TH.5900/90 (1990).
75. P.V. Ruuskaenen, in Ref. 3, p. 255c.
76. T. Akesson et al., Z. Phys. C46 (1990) 369.
R. Albrecht et al., preprint CERN-PPE/91-01, submitted to Z. Phys. C (1991).