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THE PHYSICS OF ULTRA-RELATIVISTIC HEAVY-ION COLLISIONS

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ABSTRACT

The physics of ultra-relativistic heavy-ion collisions is presented with particular emphasis on experimental results, the basic concepts used in interpreting the data, and some 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 this formation has emerged from the data so far, but some 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 independent observables ($p_{\perp}$ distributions, strangeness abundances, J/ψ suppression, particle interferometry) 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.

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1. INTRODUCTION

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. 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 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. Unifying 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 , Λ , etc.) 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 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).

In the context of the Standard Model, the study of this phase diagram of strongly interacting matter (Fig. 1.1) is not only of interest to explore 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^{-6} – 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 [Sch86]. In astrophysics, the dynamics of supernova explosions and the stability of neutron stars ($\rho/\rho_{\text{nuc}} \approx 10$) depends on the compressibility and therefore the equation of the state of nuclear matter [Gle91], 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.

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

- i) In order to use macroscopic variables, the system created has to be 'big', i.e. its dimensions ought to be much larger than the typical scale of strong interactions ($\gg 1$ fm) and it should consist of 'many' particles ($\gg 1$).
- ii) 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 typical relaxation times ($\tau \gg 1$ fm/c). Thermodynamical concepts are frequently applied in the description of heavy-ion collisions, but their applicability has to be verified and checked with microscopical, non-equilibrium calculations. 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 nuclear 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 collisions [Nag81].
- iii) The energy densities ϵ needed for QGP formation are predicted by QCD to be of the order of $1\text{--}3$ GeV/fm³, equivalent to a temperature $T_c \approx 150\text{--}200$ MeV or a baryon density $\rho_c \approx 5\text{--}10 \times$ nuclear matter density. It has to be verified that these energy densities can indeed be reached in heavy-ion collisions.
- iv) Because the created system is not static but rather rapidly evolving, 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 shown in Fig. 1.1 presents indeed 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.

The discussion of the experimental results collected 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 QGP¹. The article is organized as follows. Section 2 gives a brief sketch of the basic concepts of the deconfinement phase transition and its predicted experimental signatures. Section 3 describes the major heavy-ion experiments and their capabilities. Section 4 reviews results from these experiments and Section 5 contains conclusions and the outlook.

¹ Further reviews can be found in Refs [Tan89, Gei89, Spe89, Sch89a, Sch91, Sal89, Sat91]

2. CONCEPTS OF HEAVY-ION COLLISIONS AND QGP FORMATION

This section introduces some basic concepts used in the context of heavy-ion physics and QGP formation. After a brief theoretical review², the space-time evolution of heavy-ion collisions and the corresponding experimental observables are summarized. A thorough understanding of soft-physics appears to be mandatory if plasma signatures are to be separated from 'conventional' background. Therefore a number of Monte Carlo models, which attempt to simulate the non-plasma features, are described in some detail.

2.1. The Deconfinement Phase Transition

Owing to the nature of strong interaction, quarks are confined within a nucleon. However, if the quarks are embedded in sufficiently dense matter, gluons will screen the colour force between quarks, and the effective strong coupling constant vanishes, i.e. the quarks are allowed to move freely. This mechanism has an analogy in atomic matter, where it is known as Debye screening. In the presence of many other electric charges the Coulomb potential which binds an electron to an ion is modified as $e^2/r \rightarrow (e^2/r) \cdot \exp(-r/r_D)$, where the screening radius r_D is proportional to the overall charge density of the system. The higher the charge density the shorter becomes the range of the force between the two charges. Finally the electron is liberated from the ion binding potential. This is known as Mott-transition from a charge insulator to a charge conductor [Mot68].

An estimate of the required density for the transition from a *colour* insulator to a *colour* conductor, i.e. a QGP, can be obtained from QCD calculations. These calculations are, in the non-perturbative regime, only possible via Monte Carlo calculations on the lattice [Sat85, Kar88, Eng89]. In fact, early lattice QCD calculations [Cel83] found a sharp discontinuity in the temperature (T/T_c) as a function of energy density (ϵ/T^4) diagram as shown in Fig. 2.1. This phenomenon had been associated with a first-order deconfinement transition from an (ideal) hadron gas to an (ideal) QGP at a temperature of 150–200 MeV and demonstrated that a phase transition is within the reach of present accelerators. More recent calculations [Got87a, Eng90] have, however, shown that the system deviates considerably from ideal behaviour around the transition temperature, indicated by a sizeable difference of the energy density (ϵ/T^4) and the pressure ($3P/T^4$) as shown in Fig. 2.1. Moreover, the 'first order' nature of the phase transition is questionable. Whilst calculations both with static ($m_q \approx \infty$) and dynamical ($m_q \approx 0$) fermions render first-order phase transitions, the use of realistic quark masses ($m_{u,d} \approx 10$ MeV, $m_s \approx 200$ MeV, open circle) seems to yield a second-order phase change only [Bro90b]. This is illustrated in Fig. 2.2, which represents the 'state-of-the-art' knowledge about the order of the phase transition: two regions of first-order phase transitions around infinite ('static fermions'), and zero mass quarks ('dynamical fermions'), are separated by a region of second-order phase transitions corresponding to finite masses.

² More complete theoretical reviews can be found in Refs. [Sat85, Mül85, McL86, Wer90, Kaj87].

2.2. Space-Time Evolution of Heavy-Ion Collisions

Nuclei are extended objects, and therefore their geometry plays an important role in heavy-ion collisions. Fig. 2.3 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. 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 Section 4.5).

The space–time evolution of a central ($b = 0$) collision at very high energies [RHIC (Relativistic Heavy-Ion Collider), LHC (Large Hadron Collider)] is shown schematically in Fig. 2.4. In the first moments of the reaction, hard scattering processes on the parton level may occur with a (small) probability given by structure functions and perturbative QCD cross-sections. In addition, soft nucleon–nucleon collisions (large cross-section) between the two highly Lorentz-contracted nuclei (with limiting thickness $r \approx 1$ fm) [Bjo75] 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 $1 \text{ fm}/c$ ('formation time'), partons materialize out of the highly excited QCD field. Thermal equilibrium may now be approached via individual parton–parton or, equivalently, string–string interactions. Calculations of the mean free path of quarks in QCD matter give a value of $\lambda \approx 0.5 \text{ fm}$ at energy densities $\epsilon = 2 \text{ GeV}/\text{fm}^3$ [Hos85, Dan85], thus indicating that equilibrium may indeed be reached in collisions of heavy nuclei, where the transverse radii, and therefore the initial dimensions, are clearly larger than λ .

However, the system expands rapidly, mainly along the longitudinal direction, and therefore lowers its temperature and reaches the critical transition temperature T_c after $\tau \approx 3\text{--}5 \text{ fm}$ [Sat91]. Potentially the matter now spends a long time in the mixed phase ($\tau > 10 \text{ fm}/c$), in particular if the transition is of first order [Hwa85]. 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', $\tau \gg 10 \text{ fm}$), the still interacting system keeps expanding, possibly in an ordered motion ('flow'). It may expand to very large dimensions ($V > 10^4\text{--}10^5 \text{ fm}^3$) until 'freeze-out', when interactions cease and the particles stream freely away to be detected in the experiments.

The various signals that can be observed by experiments and associated (to some extent) with the different stages of the evolution, are summarized below:

INITIAL CONDITIONS: The measurement of global event features is necessary to specify the initial conditions given in a heavy-ion reaction. From baryon distributions, transverse energy, and particle production, one can derive, in a more or less model-dependent way, the impact parameter, the initial volume, and the energy density reached on an event-by-event basis.

QUARK-GLUON PLASMA: Weakly interacting probes, which decouple at early times, are the only direct means to gain information on the plasma phase. Direct photons and lepton pairs (virtual photons) are such observables [Kaj81, McL85] and should emerge as thermal radiation from the heated matter without being altered by final-state effects. Unfortunately, they are not a unique signal of the QGP, because their shape and amount are given by the laws of black-body radiation, and contain information only about the temperature and the space-time volume of the emitting source, and nothing about the nature of its constituents. The strong temperature dependence, however, ensures that the thermal radiation is sensitive mainly to the first and hottest stages of the evolution. Signals originating from hard scattering processes at the very beginning of the reaction are not directly connected with plasma formation. They are nevertheless important as tools to probe the state of the surrounding QCD matter. The suppression ('melting') of heavy quarkonium resonances (J/ψ , ψ') via Debye screening is characteristic only for the deconfined state of QCD [Mat86], and the energy loss of jets might be different in a QGP, and in hadronic matter ('jet quenching') [Gyu90a]. In addition, there are speculations about a number of 'exotic' signals, such as massive photons [Wel90], stable strange matter ('strangelets') [Gre87, Gre88a, Gre88b] or free quarks, which, if observed, might be an unambiguous sign of QGP formation.

PHASE TRANSITION: Strange quarks are abundantly produced in the plasma [Raf81, Koc86, Egg90], but the final number observed in strange hadrons will depend upon the details of the hadronization phase transition and, to some extent, on the following expansion [Lee89]. The presence of the transition could also be signalled by long-range fluctuations in multiplicity [VHo84, Gyu84b, Hwa88a] or by intermittency patterns [Bia86]. The long lifetime associated with a first-order phase transition might reflect itself in Bose-Einstein correlations of identical particles (HBT) [Pra86, Ber88b]. Ideally, the presence of a phase transition (i.e. constant temperature over a range of energy densities) would reveal itself in a characteristic dependence of the average $p_{\perp}$ on energy density [VHo82].

HADRON GAS: The evolution and cooling of the system is usually described in terms of a hydrodynamic expansion. The collective motion alters the otherwise thermal spectra of produced particles. Thus, the investigation of $p_{\perp}$ or $m_{\perp}$ spectra could, in principle, yield information on the expansion process. The dynamics of the evolution, in particular the longitudinal expansion of the source, introduces a strong correlation of the position and momentum coordinates of particles, which could, in principle, also be measured via two-particle correlations [Pra84, Pra86]. In dense matter, hadronic resonances are predicted to change their characteristics (mass, width, branching ratios) as a consequence of chiral symmetry restoration [Shu91, Gal91, Fur90]. If a decay into weakly interacting particles (e.g. lepton pairs) happens inside the medium, we might be able to observe such resonance modifications. Finally, once the system has reached a certain size and density, collisions among the particles cease, and the final hadron distribution freezes out. The corresponding freeze-out radius is accessible via two-particle correlations [Lor89, Boa90, Bow90].

2.3. Relativistic Microscopic Models

Because Monte Carlo codes based on string models are widely used by experimentalists, the basic ideas of string formation and fragmentation will be discussed in some detail. The

relativistic microscopic models, VENUS [Wer89a], MCFM [Ran89], FRITIOF [And87], IRIS [Pa87], ATTILA [Gyu87a], QGSM [Ame89], RQMD [Sor89, Sor90b], HIJET [Sho89] and HIJING [Wan90], are altogether non-plasma models, which have string formation and fragmentation as an important ingredient. They attempt to describe the phenomenology of heavy-ion collisions based on extrapolations from known regions of high-energy interactions. They might thus be used to discriminate 'new physics' from the 'background' of conventional physics.

2.3.1. Collision geometry

The *geometry* of the collision is treated in most models in a very similar fashion: the nucleons of the projectile and target nuclei move through each other on straight line trajectories. Interactions between two nucleons occur whenever they come closer than some minimal distance, e.g. $d < \sqrt{\sigma_{NN}/\pi}$. The result of the interaction is a longitudinally-oriented object called a 'string'. A string can be conceived as a quark–antiquark or quark–diquark pair which stretches an attractive 'colour field' of 'flux tube' between them.

2.3.2. String formation

The detailed mechanism of *string formation* is different in the various models. HIJET employs the ISAJET [Pai86] formalism, VENUS, IRIS, QGSM, and MCFM form strings via *colour exchange* [Cap80], while FRITIOF, ATTILA, HIJING, and RQMD create them via *momentum exchange* (longitudinal excitation). The latter two mechanisms are shown schematically in Fig. 2.5a–d. In the case of colour exchange, a target parton is linked to a projectile diquark and vice versa. Neither a particle nor momentum has been exchanged, just a colour exchange has formed two new strings which have acquired large (longitudinal) masses because of the large momentum difference of the newly combined partons. In the case of *longitudinal excitation* the strings are stretched between the original partons of the projectile or target nucleon. The required excitation of the string comes from a longitudinal momentum transfer between the hadrons. Despite the differences in their formation, the resulting strings are quite similar; measurable differences are provided only by the different flavour content of the strings. It has been demonstrated by Werner [Wer89b] that the inclusion of anti-quark colour exchange and diquark breakup increases the baryon content in the central region. No transverse momentum transfer is considered at this stage of the reaction. This is in accord with the 'soft' character (only a few hundred MeV transverse momentum is carried by the final hadrons) of the hadron–hadron interactions the models are made for.

2.3.3. String fragmentation

Transverse momentum and mass is assigned to string pieces or hadrons at *string fragmentation*. Again, there are different prescriptions on how a string breaks up into smaller string pieces or hadrons. VENUS employs the Atru–Mennessier formalism [Atr74, Got87b] for string fragmentation; IRIS, FRITIOF, ATTILA, and RQMD use the LUND formalism [And83]; QGSM, MCFM, HIJET, and earlier versions of VENUS use the Field-Feynman

model [Fie78] for fragmentation. The differences between the fragmentation models are mainly of a technical nature, e.g. how to determine the location of the breakpoints on the string surface.

2.3.4. *Rescattering and the Concept of a Formation Time*

Owing to the similarities of the employed formalisms, the calculated observables from the various model are very similar [Awe89]. Considerable differences emerge if rescattering of secondary particles is included in the models. Two aspects of rescattering are particularly important: the excitation of the target spectator and the modification of particle yields. At present, VENUS, QGSM, RQMD, HIJET, and MCFM have implemented reinteractions of produced particles. The interaction of produced particles is closely tied to the concept of a 'formation time' [Lan53, Sto75] of secondary particles. The formation time cannot be calculated in QCD, because hadronization is a soft process, belonging to the non-perturbative sector. MCFM, QGSM, and HIJET treat secondary particle production as a black box, as far as the formation time is concerned: the hadrons are created with a certain spectral distribution at a space-time point (x, t) (= the collision point) and from then on, propagate freely to the point $(x', t + \tau)$, where they become observables (on mass-shell states). During this formation time τ , the preformed hadron does not reinteract with the surrounding hadronic matter. The proper formation time τ_0 is given by

$$\tau = E/m\tau_0 . \quad (2.1)$$

In principle, τ_0 is now a parameter which has to be determined by comparison with experimental data. Within the string picture, Bialas and Gyulassy [Bia87] have introduced a constituent and a yoyo-formation time, τ_c and τ_y , respectively. τ_c is the time when the string breaks, i.e. new constituents are created; τ_y is the time when the 'yoyo-state' is formed. Both VENUS and RQMD contain interactions of constituent (di)quarks with hadrons which occur for times $\tau_c < t < \tau_y$. Leading (di)quarks may also interact for times $t < \tau_c$. Thereafter one has hadron-hadron interactions.

For simplicity, VENUS assumes the cross-section for (di)quark-hadron and hadron-hadron interactions to be identical. They are parametrized in terms of a unique interaction radius r_0 . Again, r_0 can, in principle, be determined from comparison with experimental data.

In the RQMD [Sor90b] model the interaction distance is, where known, defined by the experimentally measured cross-sections of each individual hadron-hadron collision. Otherwise, hadronic interaction models, such as the Additive Quark Model, boson exchange, the Breit-Wigner formalism or the Regge phenomenology are employed. The result of an interaction are either strings (depending on the energy), or resonances as they are defined in experimental tables with their measured lifetimes, branching ratios, and masses.

Thus, most models are similar in the respect that they parametrize the 'strength' of rescattering with a single parameter, which could be determined from comparison with experimental data. An exception is the RQMD model which includes, as far as possible, measured cross-sections and decay probabilities. Furthermore, MCFM and HIJET treat only interactions of secondary particles with cold spectator matter, whilst VENUS, QGSM, and RQMD include rescattering of *all* particles.

3. EXPERIMENTAL FACILITIES

3.1. Accelerators

Table 3.1 summarizes existing and planned heavy-ion accelerators and provides 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 three active large experiments and a number of smaller ones, with a total of 350 users, coming roughly in equal numbers from high-energy and nuclear physics.

Initiated by a proposal of Stock and Gutbrod in 1982 [Ang82], the Super Proton Synchrotron (SPS) at CERN was 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 was 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 re-use of existing high-energy 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 energy density in its core. The further development will be dominated by colliders starting with the RHIC at BNL providing Au on Au reactions at $\sqrt{s} = 200$ GeV/A, starting around 1997. Heavy-ion physics will also play an important rôle already in the initial experimental programme of the LHC planned to start running at CERN in 1998. With Pb on Pb at $\sqrt{s} = 6.3$ TeV/A, the LHC will be the ultimate machine in this field for the foreseeable future.

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 re-use of existing facilities (Fig 3.1).

3.2. Experiments

When at CERN the first ^{16}O beam became available in 1986, four major experiments were ready to take data at CERN: WA80 [Alb85, Sor87], NA34 (HELIOS) [Gor84], NA35 [Kar85, San87], and NA38 [Bag85, Bus88b]. In 1987, with a ^{32}S beam, the NA36 [Gru87,

Nel89] experiment became operational and the Ω spectrometer group (WA85) [Apo84] joined. For the 1990/91 running periods, two further experiments, NA44 and NA45, were set up. In addition, several smaller experiments [CER87] were running parasitically: EMU01-08 (emulsion/plastic stacks, measuring projectile fragmentation and Coulomb cross-sections, $dN/d\eta$), NA40 (γ -ray spectroscopy, measuring electromagnetic dissociation), NA41 (silicon telescopes, measuring multifragmentation), WA87 (plastic stacks, measuring electromagnetic dissociation, free quark search). Emulsion or plastic stack experiments exhibit an extremely high spatial resolution of tracks [typically $\sigma(\vartheta) \approx 3 \times 10^{-5}$ rad] and therefore give the most accurate information on charge-particle tracking and are the only means of measuring the fragmentation or dissociation of the projectile.

At present, three large detectors E802/E858 [Abb90a], E810 [Lov90], and E814 [Bar90a, Bar90b], and several small set-ups are installed to take data at the AGS [Tru91].

3.3. Global Observables and Triggering

All experiments are able to measure the centrality of the reaction, which is most clearly reflected by global observables, such as the transverse or forward energy, or the charged-particle flux.

Whilst NA36, NA38, WA85, and E802 use these measurements mainly for trigger purposes, NA34, NA35, WA80, and E814 have studied the global aspects of the reaction, i.e. the energy flow $dE_{\perp}/d\eta$ and particle densities in great detail. Table 3.2 contains the coverage of the latter three experiments for the global observables forward energy flow, transverse energy flow, and charged-particle multiplicity.

3.4. Dedicated Detectors

Besides 4π calorimetry, the NA34 (Fig. 3.2) experiment employs a magnetic spectrometer for particle identification, and a dimuon spectrometer. The external spectrometer looks at the target through a narrow slit (of 10 cm height) in the calorimeter wall. The coverage in pseudorapidity is $1.0 < \eta < 1.9$; in the azimuthal angle the coverage is 2.1% at $\eta \approx 1.9$, and 0.75% at $\eta = 1.0$. A magnet with a momentum kick of ≈ 80 MeV/c and two high-resolution drift chambers determine the momentum of charged particles. An iron converter with a thickness of 5.7% ($= 1$ mm) radiation length is placed directly in front of the first drift chamber. This enables the measurement of photons by their conversion into e^+e^- pairs. Particle identification is provided by time-of-flight (TOF) walls behind the second drift chamber with a flight path of 5 m.

The dimuon spectrometer is composed of a 4.2 T·m superconducting dipole magnet, several multiwire proportional chambers (MWPCs) (PC0-PC6) for tracking, and scintillator hodoscopes (H2,H3) for triggering. The mass resolution and vertex reconstruction of the spectrometer is limited by the non-optimized material of the absorber, i.e. the U-calorimeters, which introduces large multiple scattering of muons. In addition, dimuons produced in the dump are a severe source of background. For the 1990 running period the U-calorimeter

absorber was replaced by Al_2O_3 , which should remedy the above problems to some extent. [Gal88].

The heart of the NA35 experiment (Fig. 3.3) is a $2 \times 1.2 \times 0.72 \text{ m}^3$ streamer chamber in a 1.5 T magnetic field of a superconducting vertex magnet for particle momentum analysis. The ionization tracks are viewed by three cameras equipped with image intensifiers for three-dimensional track reconstruction. Even though a streamer chamber is an intrinsically slow detector, its large acceptance yields, for central $^{16}\text{O} + \text{Au}$ events, about 80 negative tracks which gives more than 2×10^5 pions pairs for $1 < y < 4$ in each event. Streamer chambers, or their electronic counterparts, time projection chambers (TPCs), are thus ideally suited for HBT measurements. For the 1990 running period a downstream TPC was added to the experiment which covers essentially the region $y_{\text{lab}} > 3$, which had, owing to the high-track density, not been accessible with the streamer chamber. For the 1991/92 runs NA35 has added a forward TPC, as shown in Fig. 3.2.

The NA36 collaboration (Fig. 3.4) employs a TPC for three dimensional tracking. It operates in a magnetic field of 2.7 T and is positioned 1 m away from the target and 1.5 cm above the beam. There are no dE/dx measurements for particle identification. The rather high track density in the TPC (up to 200 tracks) requires an unexpectedly involved data analysis, delaying the outcome of physics results from this experiment. The NA36 experiment is finished with the 1990 run.

The NA38 experiment is dedicated to the study of dimuon pairs. The experimental apparatus for these measurements is shown in Fig. 3.5. The dimuon spectrometer has already been used in the NA10 experiment [And84]. A carbon absorber filters the muons from the other reaction products. The beam is dumped in a central uranium core. Behind the dump, the muons are measured by two sets of MWPCs, located in front and behind a toroidal magnet. For the J/ψ , the mass resolution σ/E is $\approx 5\%$ and the acceptance is $\approx 7\%$.

The WA80 group (Fig. 3.6) surrounds the target with the Plastic Ball spectrometer. This detector consists of 655 ΔE - E telescopes and identifies low- $p_{\perp}$ target fragments (p, d, t, ^3He). In addition, positive pions are identified via ΔE - E and the delayed emission of positrons coming from stopped pions via the decay chain $\pi^+ \rightarrow \mu^+ \rightarrow e^+$. This restricts pion identification to kinetic energies below 120 MeV. Photons and π^0 's in mid-rapidity are measured with a 1278 element lead-glass [Bau90] array positioned at a distance of 3.42 m from the target. The energy resolution of the detector is $\sigma/E = 0.4\% + 6\%/\sqrt{E/\text{GeV}}$. The size of a module is 3.5 by 3.5 by 46 cm^3 , equivalent to 18 radiation lengths. For the 1990 run, the number of lead-glass modules was tripled, resulting in a much improved acceptance for π^0 and η reconstruction. The Plastic Ball has been removed from the set-up. The WA93 group is the successor of WA80 and has complemented the experiment by a charged-particle tracking part. Data taking is foreseen for the 1991/92 heavy-ion runs.

The core of the WA85 experiment (Fig. 3.7) is a set of MWPCs for tracking charged particles. Seven are placed inside the field of the Ω -magnet, whilst four of them are positioned outside. The trigger hodoscopes are matched to the butterfly shape of the events, such that only particles with $p_{\perp} \geq 0.6 \text{ GeV}/c$ and $2.2 \leq y_{\text{lab}} < 3.2$ are recorded [Beu86].

The E802 experiment (Fig. 3.8) utilizes a single-arm magnetic spectrometer for particle identification. The spectrometer has two sections: a large solid angle (25 msr) section consisting of a dipole magnet, tracking chambers (T1–T4), a 96-segment aerogel Cherenkov threshold counter (AEROC), and a 160 segment TOF wall with excellent time resolution ($\sigma \approx 75$ ps). The second, small, solid-angle section (1 msr), consists of sets of Cherenkov, tracking (T5–T7) and timing (S1, S2) counters. Whilst the first section identifies tracks from $p \approx 0.5$ to 4.7 GeV/c, the second section extends the particle identification up to 15 GeV/c. The whole spectrometer is rotatable from 5° to 58° and thus provides good coverage of the central region. The successor of E802 is E858.

The E810 (Fig. 3.9) experiment is a set of three TPC modules inside a magnetic field of 5 kG. The TPC modules are solely read out by short anode wires and no dE/dx information for particle identification is available. The trigger and a crude event characterization is obtained from a set of scintillation counters (S9–S11).

Besides the nearly 4π multiplicity and calorimeter coverage, a unique feature of the E814 experiment is its forward spectrometer (Fig. 3.10): a set of two dipole magnets separates spatially charged from neutral particles which go through an aperture of $5 \times 5 \text{ cm}^2 (\approx 0.8^\circ)$. The energy of forward-going neutrons and protons is measured in calorimeters. The absence or presence of charge in the forward scintillator, together with the energy information from the calorimeters, allows protons and neutrons to be identified. Three tracking chambers measure the position in two dimensions and provide the momentum measurement. The momentum measurement permits the discrimination of small-angle charged pions which are predominantly of less than 10 GeV/c.

Table 3.3 contains a list which summarizes the acceptance and dedication of the detectors described above.

4. EXPERIMENTAL RESULTS

4.1. Global Features of Nuclear Interactions

The study of the transverse or forward-energy flux and of the multiplicity distributions has revealed the dominant geometrical character of ultra-relativistic nucleus–nucleus collisions. The global features are satisfactorily explained by a linear superposition of independent NN collisions. The energy densities reached are close to the critical value required for the phase transition. The investigation of the target fragmentation region yields a sizeable contribution of target rapidity particles to the total transverse energy. Whilst a simple, leading order cascade cannot reproduce the baryon yield at backward rapidities, Monte Carlo simulations including a full intra-nuclear cascade are in better agreement with the data.

4.1.1. Introduction

Before embarking on the ambitious goal of detecting new or rare phenomena in ultra-relativistic heavy-ion collisions, a thorough investigation of the gross features and of the basic

reaction dynamics in AA collisions seems a necessary prerequisite for the selection and interpretation of more specific signals. Accordingly, in the first round of 'survey' experiments, a significant part of the effort was spent on investigating global event characteristics, i.e. total cross-sections, energy distributions, and particle production. In very general terms, the questions of what happens to nuclei when passing through each other at very high energies ('nuclear stopping') and what happens to the energy lost by the projectile ('energy and particle flow') are the subjects of this section.

High-energy nuclear reactions can be divided into two distinct classes: distant collisions, where the electromagnetic interaction between the colliding nuclei leads to the breakup of the target or the projectile; and close encounters, where the strong force gives rise to inelastic reactions with a major redistribution of the initial beam energy and abundant particle production. The distribution of transverse energy and particles observed in the final state determine the character, i.e. the 'violence' of the interaction. The global experimental observables $E_{\perp}$ and N_{ch} ³ therefore provide a crucial link between the initial state created and the macroscopic statistical variables such as temperature and energy density. These entities are commonly used to characterize the excited system formed in the course of the reaction. The systematic study of these observables provides the basis for our understanding of the reaction mechanism in ultra-relativistic nucleus–nucleus collisions.

4.1.2. Total cross-section and electromagnetic dissociation

The interaction between colliding nuclei is dominantly electromagnetic for impact parameters b exceeding the size of projectile and target radii, $b > R_t + R_p$. According to the classical model of Weizsacker and Williams [Wei34, Wil34, Jac75], the strong and rapidly time varying field of a point charge Z_t is seen by a passing charge as a flux of virtual photons with an intensity $\propto Z_t^2$ and an energy spectrum $\propto 1/E_{\gamma}$ up to a maximum energy $E_{\gamma}(\max) = \hbar\gamma c/b_{\min}$, where γ is the Lorentz factor of the projectile. With $b_{\min} = R_t + R_p$, the maximum energy is of the order of $E_{\gamma}(\max) = 5\text{--}10$ GeV for typical experiments at CERN. Absorption of one or several of these photons via photonuclear reactions, which are most effective in the region of the giant dipole resonance $10 < E_{\gamma} < 40$ MeV, or via production of baryon resonances at higher E_{γ} , leads to excitation and possibly breakup of the passing nucleus. This process is referred to as electromagnetic dissociation (EMD) and is well-known from studies at lower energies [Ols81]. At CERN, σ_{emd} has been measured with O and S beams on a number of target nuclei in an inclusive manner by comparing the charge changing cross-section, where at least one proton has been removed from the projectile, with the total nuclear inelastic cross-section σ_{in} [Hil88, Bre88a, Bre88b, Pri88, And89], and exclusively by

³ The transverse energy $E_{\perp}$ is usually defined as $E_{\perp} = \sum E_i \sin \vartheta_i$, summed over all particles i , where E_i is pragmatically defined as the energy deposited in a total absorption calorimeter. E_i is equal to the total energy for mesons, and total energy (plus) minus the rest mass for (anti)baryons. The multiplicity of particles is usually measured in the charged final states. The fraction of charged particles is approximately 1/2 for baryons and 2/3 for mesons, determined by the proton-to-neutron ratio in the colliding nuclei and the isospin invariance of the strong force.

identification of individual channels (e.g. $S \rightarrow \text{Al} + \alpha + p$) in emulsion stacks [Ard88, Bar90]. In general, the agreement between measurements and quantitative theoretical predictions of EMD processes is satisfactory [Bre88a, Bre88b, Pri88, Ard88, Bar90]. The cross-section σ_{emd} for projectile breakup rises with energy, projectile, and target charge, roughly as $\ln(E)$, Z_p , and Z_t^2 , respectively, and reaches values of several barns in 200 GeV/A S-Pb, which is comparable to σ_{in} .

At still higher energies, electromagnetic processes will completely dominate the total cross-section. For example, $\sigma_{\text{emd}} = 60 \text{ b} = 10\sigma_{\text{in}}$ has been calculated for a single channel ($^{197}\text{Au} \rightarrow ^{196}\text{Au} + n$) for colliding gold beams at 100 GeV/A [Hil88]. This severely limits the lifetime of stored beams in future heavy-ion colliders (RHIC or LHC). It is even speculated that the by then, abundant $\gamma\gamma$ reactions could be used as a means for exotic particle production [Abr90a].

Some measurements of the total nuclear cross-section σ_{in} are shown in Fig. 4.1 for different target-projectile combinations and energies [And89]. σ_{in} is essentially equal to the sum of the areas of the colliding nuclei

$$\sigma_{\text{in}} = \pi r_0^2 (A_a^{1/3} + A_b^{1/3} - \delta)^2 \quad \text{with } r_0 \approx 1.35 \text{ and } \delta \approx 1.1 \text{ (fm)} \quad (4.1)$$

(see Ref. [Bar88b] for different parametrizations). The linear, energy-independent relation between inelastic cross-section and transverse nuclear dimension is a direct consequence of the fact that nuclei are extended objects, i.e. 'large' compared with the range of the strong interaction and the Compton wavelength of the colliding nucleons, and 'thick' compared with the mean free path of hadrons in nuclear matter ($\approx 1.8 \text{ fm}$). Consequently, straight-line trajectories and simple geometrical concepts are remarkably successful in describing some of the global features of nuclear interactions.

4.1.3. Differential cross-sections $d\sigma/dE_\perp$, $d\sigma/dN_{\text{ch}}$

In the initial part of the experimental programme, most collaborations have measured $E_\perp$ and/or multiplicities over a large fraction of the phase space. Consequently, the wealth of data is impressing, ranging from $^{28}\text{Si} + ^{12}\text{C}$ at 14.5 GeV/A, to $^{32}\text{S} + ^{238}\text{U}$ at 200 GeV/A; a small selection of cross-section measurements is collected in Fig. 4.2a–c. In spite of the vast range of different reactions, they clearly exhibit a distinct and common shape: large cross-sections at low $E_\perp$ (the 'neck')⁴, a rather long and flat region ('plateau'), followed by an abrupt break ('knee'), and a steep decline ('tail'). Owing to the linear relation between $E_\perp$ and charged-particle multiplicity N_{ch} (see below), this feature is borne out equally well in $d\sigma/dE_\perp$ (Fig. 4.2 b, c) and $d\sigma/dN_{\text{ch}}$ (Fig. 4.2 a). The shape of this cross-section is governed by the geometry of asymmetric nucleus–nucleus collisions; it reflects the probability distribution of the number of possible nucleon–nucleon interactions which can be calculated from the overlap integral of the two extended nuclei as a function of their relative distance (impact parameter b) [Bay87, Jac87]. As shown in the inset of Fig. 4.3, the *peripheral* collisions with fast-growing geometrical

⁴ In some spectra, the 'neck' region is less pronounced owing to a trigger bias at low $E_\perp$.

overlap are responsible for the 'neck'; the number of nucleon–nucleon encounters v then rises steadily with decreasing impact parameter in the 'plateau' up to a maximum average value for *central* collisions at about the 'knee', from whereon upward fluctuations in v produce the 'tail' of the cross-section. On closer inspection, the shapes of the cross-section in Fig. 4.2 vary considerably between the different experiments. As will become clear later when discussing rapidity distributions, a large part of this difference can be attributed 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, and $E_{\perp}$ (impact parameter b) itself. Therefore one always has to take into account the possible effects of a limited angular acceptance for all but the most qualitative comparisons.

These characteristic features of AA reactions were indeed predicted [Cap87] and constitute the basic ingredient in the growing number of 'geometrical' models. The decisive influence of nuclear geometry dominated the discussion of many results in the early years, and indeed, even subtle effects such as nuclear deformations are borne out by the data, as demonstrated in Fig. 4.2 c. Based on the geometrical picture, the $E_{\perp}$ of central collisions between spherical nuclei should grow approximately proportionally with the thickness of the target, i.e. $A_t^{1/3}$. Compared with the only slightly smaller ^{208}Pb target, a large excess is observed in Fig. 4.2 c for ^{238}U , reflecting the large quadrupole deformation of ^{238}U . High $E_{\perp}$ in this case does select reactions where the cigar-shaped U nucleus (axis ratio 1:1.27) 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 !

The large dispersion introduced into the $E_{\perp}$ cross-section by the changing number of nucleon–nucleon interactions is somewhat of a disappointment, because fluctuations selected in the extreme tails of $E_{\perp}$ are more of a trivial geometric than of an interesting dynamical nature ('pushing' $E_{\perp}$ means pushing 'geometry' rather than pushing 'physics'). If new phenomena are present only at low cross-sections (i.e. in rare events), it seems we need to explore other directions than $E_{\perp}$. On the other hand, the strong correlation between $E_{\perp}$ (N_{ch}) and the impact parameter provides a useful and practical way for the experiments to select — or trigger on — central collisions, for example. Indeed, one of the lessons learned in the first round of experiments is that a very modest quality $E_{\perp}$ (alternatively N_{ch} or E_{ZDC} , see below) measurement over a limited region of phase space will already provide sufficiently accurate information for impact-parameter tagging. There is to date no universally employed definition for 'peripheral' or 'central' collisions, and different collaborations use different scales, all of them monotonic in impact parameter, but not necessarily linear with respect to each other: $E_{\perp}$, $dN_{\text{ch}}/d\eta$, entropy density, number of participants, fraction of cross-section, etc. In Fig. 4.3 some of them are compared for a specific reaction with the help of a geometrical $E_{\perp}$ parametrization, as used by NA34 [Åke88]. An alternative approach of measuring the centrality of a collision is explored in several experiments (NA35, WA80, E802) 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). As shown in Fig. 4.4 [Sor88, Alb87] the energy in a ZDC is strongly (anti)correlated with $E_{\perp}$ and therefore the impact parameter. Notice, however, that the correlation becomes non linear for large $E_{\perp}$, i.e. central collisions. All of the 'tail' is strongly

compressed in a small region around $E_{ZDC} \approx 0$, because for asymmetric target-projectile combinations, the projectile has already full overlap for a range of $b \neq 0$ collisions.

A straightforward interpretation of E_{ZDC} is further complicated owing to the energy carried away by leading particles at small angles. In pp, typically 80% of the beam energy is found in the projectile region ($\eta_{\text{beam}} - \eta < 2$, and still as much as 60% in central p + Pb collisions [Bus88a]. Therefore, the acceptance of ZDCs has to be chosen such as to minimize the effect of leading particles without losing spectators via the Fermi motion [Sor88, Alb87].

The information content of $E_{\perp}$ and multiplicity distributions is very similar owing to the large number of particles produced in heavy-ion collisions, which keeps the correlation narrow even on an event-by-event basis. Combining the two quantities, we obtain access to a new observable, which is $E_{\perp}$ per charged particle. The value of $E_{\perp}/N_{\text{ch}}$ is related to a 'global' transverse momentum ' $p_{\perp}$ ', averaged over all particle species, via the ratio of charged to neutral transverse energy. The absolute value of $p_{\perp}$ is difficult to extract because of the unknown particle composition and the contribution from isospin-breaking decays, which can considerably change the canonical value of 2/3 for $E_{\perp}(\text{charged})/E_{\perp}(\text{total})$. However, strong variations of $p_{\perp}$ with energy density were reported from cosmic-ray research [Bur85] and predicted as a possible sign of the quark-gluon plasma; it is therefore already interesting to study relative variations of $E_{\perp}/N_{\text{ch}}$. Two results are available from NA34 [Sch88b, Åke90c] and WA80 [Lun88, Alb88b]. They are plotted together in Fig. 4.5, where the NA34 data are measured as a function of $E_{\perp}$ (and therefore not linear in the abscissa E_{ZDC}) and thus only indicate the observed trend. One can hardly avoid suspecting some systematic change of $E_{\perp}/N_{\text{ch}}$ with centrality in Fig. 4.5, but allowing for systematic errors both experiments prefer to stress the constancy of ' $p_{\perp}$ ', which is better than about 10%. The same conclusions, except for some variations at very high and very low $p_{\perp}$, can be drawn from the measurement of inclusive particle spectra (see subsection 4.2).

4.1.4. Transverse energy production in the target region

In the mostly asymmetric collision systems studied so far, the target fragmentation region consists of target spectators and target participants which could occupy the same region in phase space. It is therefore interesting to investigate how strongly the participants do couple to the surrounding spectators. Whilst FRITIOF completely ignores all particles outside the primary reaction zone, an opposite point of view is taken by hydrodynamical calculations, where the projectile interacts with the target as a whole [Str89a], and no distinction between target spectators and participants is preconceived. A kind of intermediate position is taken by string models which have incorporated rescattering: there the coupling to the target spectator is mediated by cascading of secondaries in the target spectator matter. In addition, in an early paper by Anishetty, Koehler and McLerran [Ani80] it was argued that a QGP might be formed in the compressed and baryon-rich fragmentation regions of very energetic, central AA collisions.

Transverse-energy production in the target fragmentation region is measured by the NA34 [Åke88a, Åke88b] and the WA80 experiments [Alb90b]. Whilst NA34 has calorimeter coverage back to $\eta = -0.1$, the WA80 Plastic Ball covers the target region in the range $-0.7 \leq \eta \leq 1.3$. Below $\eta \leq 0.6$ the Plastic Ball is capable of identifying particles, thus the

WA80 data can be split into $E_{\perp}$ generated by pions and baryons. The mean values for the respective transverse energies are shown in Tables 4.1a) and b) for 60 and 200 GeV/A bombarding energy, respectively, and for several targets. The observed values at backward rapidities amount to roughly 20% of the E_t measured in the range $2.4 \leq \eta \leq 5.5$ [Alb87]. This relatively large value clearly indicates that non-linear effects, i.e. rescattering or cascading, may not be neglected as is done, for example, in the FRITIOF event generator. It can also be seen that, in contrast with mid-rapidity data, there is no great difference between 60 and 200 GeV/A. This observation is also known from multiplicity measurements of grey tracks in emulsion experiments [Fre87] and has been called 'limiting fragmentation'.

The correlation of $\langle E_{\perp} \rangle$ with the number of target *spectator* nucleons is shown in Fig. 4.6. The slope parameter for the baryonic $E_{\perp}$ is $\alpha = 1.06$, whilst that for the pionic $E_{\perp}$ is 0.62. From these observations one might conclude that the whole target nucleus becomes excited during the passage of the projectile, whilst pion production is at best partly related to the target spectator volume.

4.1.5 Pseudoapidity distributions $dE_{\perp}/d\eta$, $dN_{ch}/d\eta$

Turning our attention now to rapidity distributions, we will concentrate more on the measurement of the charged-particle flow rather than $E_{\perp}$. In general, the information contained in $E_{\perp}$ and N_{ch} tends to be very similar in heavy-ion reactions. However, granularity and acceptance in practically all of the present experiments are better for the N_{ch} data. The most precise results, concerning resolution and η coverage, were obtained in emulsion exposures; one example of $dN_{ch}/d\eta$ for O + AgBr [Hol87] at 200 GeV/A is shown in Fig. 4.7. The distribution has even less of a central plateau than pp at the same energy [DMa82]; it is more bell-shaped with the maximum around $\eta \approx 2.6$, somewhat below the average value of $y = 3$ expected for symmetric pp collisions. Again, a simple geometrical model seems to give a qualitative estimate of the observed rapidity shift. If we assume a collision of two objects with mass $N_p m$ and $N_t m$, where m = the nucleon mass, N_p = the number of projectile nucleons, and N_t = the number of participating target nucleons in the cylinder mapped out by the cross-section of the projectile (see Fig. 4.3), we find for central collisions ($b = 0$) of two nuclei with mass number A and B ($B > A$), the following kinematical relations:

$$N_p = A \quad \text{and} \quad N_t = B - A[(B/A)^{2/3} - 1]^{3/2} \quad (4.2)$$

$$\nu = 0.28 R_0^4 \left[(A^{2/3} + B^{2/3}) A^{1/3} B^{1/3} + 0.5 (B^{2/3} - A^{2/3})^2 \ln \left(\frac{B^{1/3} - A^{1/3}}{B^{1/3} + A^{1/3}} \right) \right] \quad (4.3)$$

$$\sqrt{s} = [(N_p m)^2 + (N_t m)^2 + 2 E_{beam} N_t m]^{1/2} \quad (4.4)$$

$$y_{cm} = \ln[\sqrt{s}/(N_t m)] \quad (4.5)$$

Here ν is the number of nucleon-nucleon collisions, R_0 the nuclear radius parameter (≈ 1.16 fm), $\sqrt{s}$ the c.m. energy and y_{cm} the c.m. rapidity of the participant system. For ^{16}O on ^{108}Ag ($N_p = 16$, $N_t = 42$), the mid-rapidity in the '16 + 42' c.m. system is $y_{cm} = 2.55$,

in remarkable agreement with the value observed in Fig. 4.7. However, a detailed investigation by WA80 [Alb91b] shows significant deviations from this purely kinematic picture, revealing that the centroid and shape of the rapidity distribution is not only of kinematic, but also of (probably complex) dynamical origin.

When looking at negative particles only (Fig. 4.8), the width of $d\sigma/dN_{ch}$ (FWHM = 3.1) is considerably smaller than in comparable pA reactions, and even somewhat smaller than in pp (FWHM = 3.5) [Hec88]. However, it is still significantly wider than the distribution of particles emitted isotropically from a hot fireball at rest in the combined N_p+N_t system, as defined above (FWHM = 1.8).

The Lund Monte Carlo code FRITIOF seems to reproduce the rapidity distribution in Fig. 4.7 fairly well. This is clearly in contrast with the findings of WA80 (Fig. 4.9), where the data exceed the prediction of the very same model in the central region by about 30–40% (both in minimum-bias data and central events [Lun88, Alb88b]). In order to compare the shapes of the emulsion and the electronic measurements the data of Fig. 4.7 are plotted in Fig. 4.9, rescaled⁵ to the same height. The distributions are in agreement for $\eta > 1.5$, whereas a clear excess is seen in the counter data for $\eta < 1$. The most likely cause of this excess are target fragments and other slow (non-minimum-ionizing) particles, which are removed from the emulsion sample by a cut on dE/dx corresponding to $v/c > 0.7$. Whether these 'grey' and 'black' tracks are indeed the only source of discrepancy seen, in general, between emulsion and electronic experiments, has, however, not been shown quantitatively up to now.

The dependence of $dN_{ch}/d\eta$ on centrality and target mass can be seen in Fig. 4.10 [Sch88b, Åke90c] for CERN, and in Fig. 4.11 [Vid90] for AGS energies:

- The maximum and, especially, the centroid of the distributions shifts towards backward rapidities with increasing target mass and, for a given target, with increasing $E_\perp$.
- The width of $dN_{ch}/d\eta$ shrinks with increasing $E_\perp$.
- The asymmetry around the maximum is more pronounced for the heavy target, indicating once more the importance of target fragments and possibly reinteractions of produced particles inside heavy target nuclei (cascading).

A remarkable consequence of the steady change of $dN_{ch}/d\eta$ with $E_\perp$ is clearly visible in Fig. 4.10. 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 $E_\perp$. This feature manifests itself again in the shape of $d\sigma/dE_\perp(N_{ch})$, which has a steeper slope when measured at forward rapidities (cf. Fig. 4.2 b and c).

⁵ Absolute values are a sensitive function of the data sample selected, for example the experimental definition of a minimum-bias trigger.

4.1.6. Baryon rapidity distributions

The knowledge of baryon rapidity distributions is of great importance in order to assess, the amount of stopping (i.e. the slowing down of participants) in nuclear collisions, and to estimate the baryon content of the reaction zone. However, none of the CERN experiments is really capable of measuring the baryon distribution with complete coverage. The Plastic Ball of the WA80 experiment identifies protons around target rapidity. The NA34 Collaboration measures protons in a small portion of phase space by covering $0.9 \leq \eta \leq 2.0$ with a slit spectrometer. The NA35 Collaboration measures an excess of positive over negative tracks ('+-' procedure) for $y < y_{cm}$ which is, for symmetric collisions, attributed to protons. This method suffers: a) from the fact that two large numbers have to be subtracted from each other in order to extract the excess positive charge, and b) because the final-state positive excess charge has to be corrected in a model-dependent fashion, e.g. by using FRITIOF results, for the K^+ over K^- excess.

The result of the '+-' procedure is shown in Fig. 4.12 for the reaction $^{32}\text{S}+\text{S}$ [Str89b, Str91]. The distribution for $y > y_{cm}$ is mirrored at y_{cm} . The above assumption (b) has been verified using events generated by FRITIOF. These results are so far the only experimental indication that much more baryon stopping occurs in ultra-relativistic AA collisions than expected from FRITIOF simulations, which show a distinct minimum at mid-rapidity. The data are, on the other hand, described by VENUS 3 [Wer89b] and RQMD [Sor91b] simulations, which include, in contradiction with FRITIOF, diquark breakup and rescattering. An important consequence of this result is that 'realistic' QGP models have to reconsider the assumption of a baryon-free plasma at CERN SPS energies. If the same trend is also present in Pb-Pb reactions, it might well be that the maximum attainable baryon density may only be reached at, or even be above, SPS energies, and not, as has been previously assumed, somewhere around the AGS energy range.

Baryon pseudorapidity distributions in the target region are shown in Fig. 4.13 for the reactions $^{16}\text{O} + \text{Cu}, \text{Ag}, \text{Au}$ at 60 and 200 GeV/A bombarding energy. These distributions are compared with calculations using the MCFM [Ran89]. As outlined above, this model is equipped with a leading-order cascade of secondary particles in the target spectator matter. The amount of cascading is governed by a formation-time parameter τ_0 ⁶. As can be seen, the number of baryons in the target rapidity region is not sufficiently accounted for in a leading-order cascade. In particular, at backward angles the discrepancy is large. Even for the very small formation-time parameter $\tau_0 = 5 \text{ fm}/c$ (corresponding to a proper formation time τ_s of a pion of $0.7 \text{ fm}/c$) the yield of baryons is not described by the model. A more recent version of the MCFM, now equipped with a full cascade, is reported to reproduce the backward baryon yield satisfactorily [Ran91]. Similarly, the RQMD and VENUS models, since they also both have a full cascade, *do* reproduce the baryon yields [Sor90b, Sor91b, Wer91].

⁶ In the most recent version of the MCFM [Ran89] the formation-time parameter τ_0 is defined by $\tau_{lab} = \gamma_s \tau_s$, where $\tau_s = \tau_0 * m_s^2 / m_t^2$. Here m_s and m_{ts} are the mass and the transverse mass of the secondary particle, respectively. The factor m_s^2 / m_{ts}^2 is 7.3 for a pion of transverse mass $m_{ts} = 375 \text{ MeV}$.

Analogous results for angular distributions of grey tracks have been obtained by the EMU01 Collaboration [Ada89, Ada90c]. Grey prongs are believed to belong mainly to protons with kinetic energies in the range from 26.2 to 375 MeV, which corresponds to the energy range also covered by the Plastic Ball spectrometer. The results (Fig. 4.14) of a comparison of the data with the MCFM are similar to the Plastic Ball results: the angular distribution of 'protons' is not sufficiently described by a simple, leading-order cascading mechanism. In addition, FRITIOF results are shown which yield, owing to the complete lack of cascading, very little protons at backward angles.

4.1.7. Energy density, baryon density, and scaling behaviour

One of the crucial quantities linking the measured $E_{\perp}$ distributions with the conjectured formation of a quark–gluon plasma is the energy density ε 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 in between the two extremes of 'full stopping'—where the 'fireball' recipe could be applicable—and the 'ultra-relativistic' regime of the Bjorken model [Bjo83]. In the latter case, the energy density is estimated to be

$$\varepsilon_{BJ} = \frac{1}{F_p c \tau_0} \frac{dE_{\perp}}{dy} \approx \frac{dE_{\perp}/d\eta}{F_p c \tau_0} \quad (4.6)$$

where $F_p = \pi R_0^2 A^{2/3}$ (area of the projectile), $dy c \tau_0 =$ 'length of the reaction zone', and $\tau_0 =$ formation time. As has been mentioned earlier, the concept of a formation time is well established in high-energy physics, for example from p–A reactions, where it is found that most of the particles produced do not reinteract inside the nucleus. Its value, usually taken to be of the order of 1 fm/c on dimensional grounds, seems reasonable in the light of results from lepton–nucleon scattering [Gyu90b] or particle interferometry (see below). However, it is certainly not known to better than a factor of 2. If, in addition, one takes into account the finite thickness (≈ 1 fm) of the nuclei, the build-up of energy density will be distributed over a time of at least 2 fm/c in the course of the collision [Zhu91, Sei91].

In the fireball model, the measured $E_{\perp}$ is compared with the maximum observable $E_{\perp}$, generated by isotropic emission in the participant c.m.s. Using the Lorentz contracted cylindrical overlap volume of central collisions and the definitions in Eqs. (4.2)–(4.5), the fireball energy density ε_{FB} is calculated as follows:

$$E^{\max} = \sqrt{s} - m(N_p + N_t), \quad (4.7)$$

corresponding to c.m. energy minus the nucleon rest mass (i.e. the energy observed in a calorimeter)

$$E_{\perp}^{\max} = \frac{\pi}{4} E^{\max} \quad (4.8)$$

$$V_{cyl} = 4\pi/3 R_0^3 N_t \approx \pi R_0^2 A^{2/3} 2R_0 B^{1/3}. \quad (4.9)$$

Assuming linear scaling of the energy density with $E_{\perp}$, we get

$$\varepsilon_{FB} = \varepsilon_{FB}^{\max} E_{\perp}^{\exp} / E_{\perp}^{\max}, \quad (4.10)$$

where γ is the Lorentz contraction factor, and $E_{\perp}^{\text{exp}}$ is the maximum $E_{\perp}$ measured in an experiment.

It is reassuring that all groups and both recipes agree that the energy density is of the order of a few (2–3) GeV/fm³ in both ¹⁶O and ³²S induced central collisions with heavy targets. This number compares favourably with the lattice QCD-based guideline of $\epsilon_c \approx 1\text{--}3$ GeV/fm³ required for the phase transition [Sat91]. However, in view of the assumptions and uncertainties involved in the calculation of ϵ , we should consider the above relations to be only an educated guess, and to date no solid information exists, whether the critical energy density could indeed be reached in present experiments—even if ϵ_c were as low as 1 GeV/fm³. In addition, in order to be effective (or even only to speak about energy density in a thermodynamical sense), some degree of thermal equilibrium has to be attained—a question that will be considered below.

The conclusion can therefore only be qualitative, namely that the energy densities achieved in the first round of heavy-ion experiments at CERN are certainly large, i.e. about 10–20 times the energy density of ground-state nuclear matter, and possibly already sufficient to see the first glimpses of the quark–gluon plasma.

Much less experimental information and theoretical guidelines are available concerning the second coordinate in the phase diagram of nuclear matter (Fig. 1.1), i.e. the baryon density ρ . An estimate [Ani80], based on the rapidity shift Δy of the participants, and the corresponding change in the Lorentz contraction factor, would lead to a compression of

$$\rho/\rho_0 = 1/[\Delta\gamma - \sqrt{(\Delta\gamma^2 - 1)}], \Delta\gamma = \cosh \Delta y. \quad (4.11)$$

Using $\Delta y \approx 2.5$, as observed in central p–Pb reactions [Bus88a], the density would be an order of magnitude above ground-state nuclear density ($\rho/\rho_0 \approx 10$). Microscopical Monte Carlo calculations [Sor90c, Sor91b, Kei91] lead to similarly high values.

The numerous projectile–target–energy combinations investigated up to now allow a rather detailed study of scaling behaviour. As stressed repeatedly, a comparison of different reactions will, in general, lead to answers that will depend upon the part of the rapidity space used. This can be seen very nicely in Fig. 4.15, where the A-dependence of the multiplicity distribution, parametrized as $dN_{\text{ch}}/d\eta \propto A^{\alpha}$ is plotted as a function of pseudorapidity [Lun88, Alb88b]. The exponent α varies from ≈ 0 in the projectile fragmentation region, i.e. from no target dependence, to $\alpha \approx 0.8$ at $\eta < 0$, i.e. to almost linear increase of the particle density with target mass. The scaling of $E_{\perp}$ production reported by the NA35 and NA34 experiments, $E_{\perp} \propto A^{0.2}$ [Åke88] and $E_{\perp} \propto A^{0.5}$ [Hec88] respectively, fits perfectly into the observed trend when plotted at the appropriate η range. Therefore, the scaling should, in general only be investigated with observables that are independent of the acceptance, i.e. with the total production in 4π , or with the value at the maximum of the rapidity distribution ($dE_{\perp}/d\eta|_{\text{max}}$, $dN_{\text{ch}}/d\eta|_{\text{max}}$). From such a systematic comparison, which was carried out by Stachel [Sta91], the following trends emerge.

- i) *Energy dependence:* The width as well as the height of $dN_{\text{ch}}/d\eta$ increase approximately linearly with $\ln\sqrt{s}$, and therefore the total multiplicity is proportional to $(\ln\sqrt{s})^2$, similar to what is known from p–p reactions.

- ii) *Target dependence:* Both the maximum of the rapidity distribution and the total $E_{\perp}$ scale with target mass of the order of $A^{0.4}$, with little dependence on projectile and $\sqrt{s}$. This scaling is significantly larger than what is expected from a superposition of independent nucleon–nucleon collisions ($A^{1/3}$) and indicates the presence of collective effects, probably via rescattering of the produced particles amongst themselves and with the surrounding spectator matter. It is interesting to note that the same scaling up to the largest target masses is observed also at the AGS (cf. Fig. 4.2a and Fig. 4.11). Earlier results [Bas88, Abb87], that particle production ceases to rise beyond a certain target mass⁷ ($A \approx 100$), were largely caused by a limited acceptance in rapidity [Hal90, Tan90].
- iii) *Projectile dependence:* When going from O + W to S + W, the total $E_{\perp}$ increases by a factor of 1.65 for central collisions at 200 GeV/A [Åke90b, Sch89b]. This is less than the factor of 2 in the projectile mass, but close to the increase in the total available centre-of-mass energy in the participant system (1.77), as calculated according to Eq. (4.4) above. Therefore the energy of the ^{32}S nucleus is still distributed very effectively into the transverse degrees of freedom. Because the transverse size grows with $\approx A_p^{2/3}$, the energy density is roughly the same in both cases. However, the reaction volume is larger with heavier projectiles and therefore the conditions to create a thermalized and long-life system will be more favourable.

The various systematic trends allow a deeper and quantitative analysis 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 n–n reaction is characterized by colour exchange, and therefore $E_{\perp}$ production would be proportional to the number of participants (each nucleon can be coloured only once). In a 'collision-type' model, momentum is exchanged in every binary collision and correspondingly $E_{\perp}$ is proportional to the total number of n–n encounters. Recent results from NA35 [Bäc91] and WA80 [Alb87, You89, Alb91b] show that, within the present systematic and statistical accuracy of $\approx 10\%$, $E_{\perp}$ in the central region is strictly proportional to the number of participants. This is compatible with what is known from p–A [Bus88a], where, however, the lever arm is significantly smaller. At higher energies (RHIC, LHC), the situation is predicted to be very different [Lan90, Esk90, Cap91, Wan90]. Semi-hard 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 present results.

4.1.8. Summary

The study of $E_{\perp}$ and particle production have provided us with some promising insight into the reaction dynamics of heavy-ion collisions. Even with the 'light' heavy-ions at the present accelerators, the sufficiently large 'nuclear stopping power' has enabled us to reach energy densities close to the critical value needed for the phase transition. These results therefore constitute the necessary basis from whereon we can start looking for new phenomena.

⁷ These measurements had been taken as an indication for complete stopping of the ^{28}Si projectile already in a medium heavy target nuclei at $\sqrt{s} = 14.5$ GeV/n.

On the other hand, it seems that the global event features measured with $E_{\perp}$ and N_{ch} distributions can be described reasonably well simply in terms of a superposition of independent nucleon–nucleon collisions. Obvious additions, such as including nuclear deformation and reinteraction of produced secondaries in the target nucleus (cascading), will further improve the agreement between data and model predictions. The main conclusion from the data in the target fragmentation region is that rescattering is a non-negligible process, since a sizeable amount (15–20%) of the total $E_{\perp}$ is found at pseudorapidities $\eta \leq 1$. However, a simple, leading-order cascade cannot, by far, account for the observed $dN_{baryon}/d\eta$ distributions or for $\langle E_{\perp} \rangle$. Preliminary comparisons with models having a full cascade [Ran91, Wer91, Sor90b, Sor91b] yield a better description of the target fragmentation data.

As emphasized by Shuryak [Shu87], the seemingly 'trivial' results can by no means be taken as evidence against the formation of a quark–gluon plasma. After all, thermalization and hadronization could obscure the information contained in the global final-state observables $E_{\perp}$ and N_{ch} , and therefore other, more sensitive, tests and observables are needed in addition to probe the interesting early stages of relativistic heavy-ion reactions.

4.2. Transverse-momentum distributions

The $p_{\perp}$ distributions, in particular of pions and baryons, are found to be markedly different from the ones measured in p–p interactions at comparable energies. Systematic trends, which are extracted by comparing the results of different experiments and collision systems, strongly constrain the large number of theoretical models invoked to explain the low- and high- $p_{\perp}$ enhancement observed for negative particles. The data do not seem to require novel physics, but rather might yield new information on how transverse-momentum spectra can be modified in the presence of nuclear matter by initial- and final-state interactions.

Ever since the discovery of hard scattering at the CERN ISR in 1973 [Alp73, Ban73, Bus73], the measurement of inclusive transverse momentum distributions has been a valuable tool in the study of high-energy hadronic reactions⁸. The deviation of the $p_{\perp}$ spectra above $p_{\perp} \approx 1\text{--}2$ GeV/c from the exponential fall-off $1/p_{\perp} d\sigma/dp_{\perp} \propto \exp^{-6p_{\perp}}$, characteristic for lower $p_{\perp}$ added strong experimental support to the then-emerging picture of the partonic substructure of hadrons. A similar striking change in the $p_{\perp}$ of produced particles seemed to emerge from early cosmic-ray experiments studying ultra-relativistic nucleus–nucleus collisions. Fig.4.16a shows the average transverse momentum $\langle p_{\perp} \rangle$ of charged secondaries as measured in individual events by the JACEE Collaboration with nuclear emulsions exposed to cosmic rays [Bur86]. The data suggest a rapid increase of $\langle p_{\perp} \rangle$ from $\langle p_{\perp} \rangle \approx 0.34\text{--}0.4$ GeV/c as typically found at hadron colliders (ISR, SPS $p\bar{p}$), to $\langle p_{\perp} \rangle \geq 1$ GeV/c, once the energy density, which is estimated from the observed multiplicity density $dN/d\eta$, exceeds a critical value of about $2\text{--}3$ GeV/fm³. According to a conjecture of Van Hove [VHo82, Shu80, Shu86] the dramatic increase of $\langle p_{\perp} \rangle$ could be a sign of the phase transition between normal hadronic matter and the QGP, as schematically indicated in Fig. 4.16b).

⁸ For recent reviews on the subject see for example Refs. [Tan89, Sch90, Jac91].

Although energy densities comparable to the ones in cosmic-ray events have been achieved in the accelerator-based experiments with oxygen and sulphur beams up to 200 GeV/A [Sch88a], no such striking change in the $p_{\perp}$ spectra has been observed so far. Furthermore, more recent hydrodynamical calculations predict only a modest increase of $\langle p_{\perp} \rangle$ for inclusive charged particles even in the case of QGP formation [Kat86, Bla86, vGe87]. However, the $p_{\perp}$ distributions of different particle species exhibit a rich variety of A + A collisions. Their careful study can help to unravel the complex dynamics of high-energy nucleus–nucleus reactions, as well as the properties of the extended and dense state of strongly interacting matter which is formed in these collisions.

4.2.1. $p_{\perp}$ distributions in hadron–hadron collisions

a) Global features

Transverse momentum spectra are usually presented in terms of the invariant cross-section

$$E \frac{d^3\sigma}{dp^3} \sim \frac{1}{p_{\perp}} \frac{d^2\sigma}{dp_{\perp} dy} \sim \frac{1}{m_{\perp}} \frac{d^2\sigma}{dm_{\perp} dy} \quad (4.12)$$

The use of the transverse mass $m_{\perp} = \sqrt{p_{\perp}^2 + m^2}$ is suggested by the experimental fact that the cross-section $1/p_{\perp} d\sigma/dp_{\perp}$ of a given particle species is better described by an exponential in $m_{\perp}$ rather than in $p_{\perp}$, i.e. $f(p_{\perp}) \approx e^{-m_{\perp}/T}$ [Gue76]. Whereas in the central region the average $p_{\perp}$ of particles increases with their mass and therefore particle ratios vary strongly with $p_{\perp}$, the spectral shape and, to some extent, even the absolute cross-section of different mass particles (see Fig. 4.17) is similar when plotted instead as a function of $m_{\perp}$ [Bar77, Bou75, Bou76, Cra78]. This observation leads to the notion of $m_{\perp}$ scaling which seems to be valid even for random combinations of multipion systems [Sti77, Deu76]. A number of theoretical explanations have been proposed for the $m_{\perp}$ scaling [Mic79, Hag83, Tar85], often assuming a local thermal equilibrium and therefore linking the inverse slope T to a temperature⁹. This 'temperature' rises smoothly with $\sqrt{s}$ from low-energy p–p and A–A reactions [Nag81, Hag83, Stö86] up to the limiting 'Hagedorn' temperature of $T \approx 150$ MeV at ISR energies. The notion of an equilibrated system does indeed seem defensible for BEVALAC A–A reactions, where it was verified, with microscopical Monte Carlo calculations, that the number of collisions per nucleon is of the order of a few (> 2), sufficient to approach a thermal distribution to a good approximation (see references in [Nag81]). However, there is no established mechanism that could thermalize the reaction system in p–p with the small number of particles involved ($N_{\text{ch}} < 5-10$).

The momentum distribution of a thermalized system at fixed rapidity is given by [Hag83]:

⁹ Non-equilibrium models exhibit $m_{\perp}$ scaling as well, e.g. the LUND physics Monte Carlo generators do so because of the quantum mechanical tunnelling process that generates $p_{\perp}$.

$$\frac{1}{p_{\perp}} \frac{dN}{dp_{\perp}} \sim \frac{m_{\perp}}{T} K\left(\frac{p_{\perp}}{T}\right) \quad (4.13)$$

$$\frac{1}{p_{\perp}} \frac{dN}{dp_{\perp}} \approx \frac{1}{T} \sqrt{m_{\perp}} \exp\left(-\frac{p_{\perp}}{T}\right) \quad \text{for} \quad \frac{m_{\perp}}{T} \gg 1 \quad (4.14)$$

where K_1 is the modified Bessel function. The exact expression [Eq. (4.13)] and the approximation [Eq. (4.14)] are plotted in Fig. 4.18 for pions, together with $\exp^{-6p_{\perp}}$ and $\exp^{-6m_{\perp}}$, all functions being normalized to each other at $p_{\perp} = 1$ GeV/c. The differences at low $p_{\perp}$ are substantial and have to be kept in mind when data are extrapolated beyond the region of experimental acceptance in order to extract the average $p_{\perp}$. Furthermore, with the onset of QCD (semi)hard scattering above $p_{\perp} > 1-2$ GeV/c, the spectral shape is better described by a power law :

$$\frac{1}{p_{\perp}} \frac{dN}{dp_{\perp}} \sim \left(\frac{p_0}{p_0 + p_{\perp}}\right)^n \quad (4.15)$$

It was therefore advocated by Hagedorn [Hag83], some time ago, that a combination of Eq. 4.13 and Eq. 4.15 should be used to fit the experimental data and check their thermal character.

For practical purposes the following parametrization [Sch90, Boe90] of pion $p_{\perp}$ spectra, which is based on data up to ISR energies, might be used to estimate the rapidity and $\sqrt{s}$ dependence :

$$\frac{1}{\sigma} \frac{d^2\sigma}{dp_{\perp} dy} = \frac{f(p_{\perp})}{g(y)} \quad (4.16)$$

where

$$f(p_{\perp}) = \begin{cases} 105 p_{\perp} \exp^{-6.73p_{\perp}} \left(\frac{p_0}{31.5}\right)^{0.3}, & p_{\perp} \leq 0.42 \text{ GeV}/c \\ 5.7 (\exp^{-0.9p_{\perp}} + \exp^{-0.27p_{\perp}})^{4.45} \left(1 - \frac{p_{\perp}}{p_0}\right)^{11} \left/ \left(1 - \frac{p_{\perp}}{31.5}\right)^{11} \right., & p_{\perp} > 0.42 \text{ GeV}/c \end{cases}$$

$$g(y) = 1 + \exp^{2.5(y-y_0-y_{\max})}$$

and

$$p_0 = \sqrt{s}/2, \quad y_0 = 1.8 + 1.2 \ln(p_0/31.5), \quad y_{\max} = \ln(\sqrt{s}/m_{\perp}).$$

The rather simple shape of $p_{\perp}$ distributions is somewhat surprising because the majority of the observed final-state particles are not produced directly in the first stage of the hadronization, but rather indirectly via the decay of heavier, short-lived resonances. The dominance of resonance production was measured quantitatively, e.g. in $\pi+\pi$ reactions at 16 GeV/c [Gra78], where it was found that $\approx 50\%$ of the inclusive pion yield can be accounted for by the decay of some of the lower mass resonances (ρ , ω , η , f) alone, and that

only 10–30% are produced directly. In this light it seems remarkable that the sum over many decay channels, each contributing differently to the $p_{\perp}$ spectrum according to the available phase space, yields a transverse momentum distribution of secondary pions that is very similar in shape to the inclusive one [Gra78], and in fact can be satisfactorily described in terms of the thermodynamical models mentioned above. In general, however, a change in the production ratio of different resonances will reflect itself in the $p_{\perp}$ distribution of final-state particles and can distort their spectra, as is shown for the case of the Δ , in Fig. 4.19 decaying into pions and nucleons.

b) $p_{\perp}$ as a function of rapidity, $\sqrt{s}$, and multiplicity

In general, $p_{\perp}$ spectra at high energies are rather insensitive to the type of reaction studied. However, a detailed investigation reveals that they do, for example, depend on the available phase-space and centre-of-mass energy. As an example for kinematical constraints, the average $p_{\perp}$ is shown in Fig. 4.20 as a function of rapidity for two different centre-of-mass energies [Bos73, Bre88]. Besides possible dynamical correlations, energy conservation alone requires that $\langle p_{\perp} \rangle$ goes to zero at the end of phase space, i.e. at $y \approx y_{\text{beam}}$ and y_{target} . Therefore rapidity and $p_{\perp}$ cannot factorize completely, and by comparing Fig. 4.20a and b it is evident that $\langle p_{\perp} \rangle$ starts to decrease from its maximum value at $y_{\text{cm}} = 0$ at the latest about 2 units away from the end of phase space. The shape of $1/p_{\perp} d\sigma/dp_{\perp}$ also evolves as a function of $\sqrt{s}$ mainly at high $p_{\perp} > 2$ GeV/c, which is reflected in the slow increase of $\langle p_{\perp} \rangle$ of inclusive charged particles from ≈ 360 MeV/c at $\sqrt{s} = 20$ GeV to $\langle p_{\perp} \rangle \approx 460$ MeV/c at $\sqrt{s} = 1.8$ TeV [Alb90c]. A similar rise of $\langle p_{\perp} \rangle$ with charged-particle multiplicity was observed at the ISR [Bre88], Sp $\bar{p}$ S [Alb90c], and the Tevatron [Ale88, Ale90]. The change in the shape of the distributions seems to be rather complex, affecting both the low- and the high- $p_{\perp}$ region [Bel85] (see below), and varies for different particle species.

4.2.2. Transverse-momentum distributions of negative particles

a) Global features

The general characteristics of $p_{\perp}$ distributions in $p + A$ and $A + A$ reactions can be extracted from Fig. 4.21, where $d^2\sigma/dp_{\perp}^2$ is shown for negative particles (mostly pions) in $p+W$, $O+W$, and $S+W$ central collisions, as measured by NA34 [Åke90a] in the rapidity range $1 < y < 1.9$. The distributions can no longer be described with a single exponential in $p_{\perp}$ or $m_{\perp}$, as was the case in $p + p$. They show a strong enhancement at high $p_{\perp}$ (> 1 GeV/c), and at low $p_{\perp}$ (< 250 MeV/c), when compared with the parametrization given in Eq. (4.16) of minimum-bias $p + p$ data at the corresponding $\sqrt{s}$ and y (full line in Fig. 4.21a). In this section we will therefore concentrate on a comparison of the *full spectral shapes* in different reactions; slope values fitted in limited regions of $p_{\perp}$ contain less information, but can be found in the original publications and in Ref. [Sal89]. Whereas the high $p_{\perp}$ enhancement has been seen by all experiments at CERN, the size of the low $p_{\perp}$ increase is still controversial, with the emulsion experiment EMU5 reporting a much smaller excess at target rapidities ($y < 2$) than NA34 and NA35 [Sch90, Str91]. Both the rise at high $p_{\perp}$, usually referred to as the 'Cronin' effect, as

well as the low $p_{\perp}$ rise have actually already been observed in the mid-1970's at Fermilab in $p + A$ reactions [Cro75, Klu77, Ant79, Gar77, Cha79], as we will discuss below.

b) The high $p_{\perp}$ enhancement

The spectral shapes of $p_{\perp}$ distributions from different reactions are compared in Figs. 4.22 and 4.23 by plotting their ratio R as a function of $p_{\perp}$. The high- $p_{\perp}$ excess increases both with target mass (Fig. 4.22a) and with projectile mass (Fig. 4.22b, c). It is weaker, but still significant in central S+S reactions (with at most a few spectator nucleons) than in central O+Au (Fig. 4.23). The effect is most pronounced in $p+W/p+p$, which also corresponds to the largest change in atomic mass number. The NA34 Collaboration [Åke90a, Dre89] has shown that the target and projectile dependence are in fact similar when parametrized by a power

$$\frac{d\sigma}{dp_{\perp}}(p + A) = A^{\alpha(p_{\perp})} \frac{d\sigma}{dp_{\perp}}(p + p) \quad (4.17)$$

and

$$\frac{d\sigma}{dp_{\perp}}(B + A) = B^{\beta(p_{\perp})} \frac{d\sigma}{dp_{\perp}}(p + A) . \quad (4.18)$$

A fit of $\alpha(p_{\perp})$ to the original Fermilab $p+A$ data [Cro75, Klu77, Ant79, Gar77, Cha79] (full line in Fig. 4.24a) also describes reasonably well the values of $\beta(p_{\perp})$, extracted from the ratios $S+W/p+W$ and $O+W/p+W$, in Fig. 4.24b. The similarity of $\alpha(p_{\perp})$ and $\beta(p_{\perp})$ can be interpreted as a dependence of the Cronin effect on the projectile mass number analogous to the one on the target.

The dependence of the high- $p_{\perp}$ enhancement seems to depend only weakly on $\sqrt{s}$ when going from 60 to 200 GeV/c [Alb90a, Pei90a]. Furthermore, there is no significant y -dependence evident when comparing the values of NA34 ($\langle y \rangle = 1.5$) and NA35 ($\langle y \rangle = 2.5$) in Fig. 4.23.

One of the first observations made in heavy-ion reactions was the near constancy of the average $p_{\perp}$ as a function of the impact parameter [Sch88c, Str88, Löh88]. A closer look at the data reveals, however, that there is a transition region from peripheral to central collisions, where $\langle p_{\perp} \rangle$ increases by some 10–20%. Figure 4.25 shows $\langle p_{\perp} \rangle$ of negative particles [Åke90a], extracted from fits to the slope above $p_{\perp} \geq 0.4$ GeV/c as a function of $E_{\perp}$ in $-0.1 < \eta < 2.9$. Figure 4.26 shows the average $p_{\perp}$ of photons ($p_{\perp} > 0.4$ GeV/c) as a function of entropy density [Pur90, Alb88a]. Taking the different scales into account (see Fig. 4.3), the increase in $p_{\perp}$ occurs essentially between glancing collisions and about the point where most of the projectile nucleons participate in the interaction. This region corresponds to $\approx 1/2$ of the total cross-section, whereas only a small fraction of the maximal observable $E_{\perp}$ is produced in these reactions.

The increase in $\langle p_{\perp} \rangle$ seems to be due to a flattening of the high- $p_{\perp}$ tail rather than an overall change in slope. This can be seen in Fig. 4.27, where the ratio of $p_{\perp}$ spectra of different $E_{\perp}$ regions [Åke90a] deviates from a constant only in the lowest $E_{\perp}$ bin and only for $p_{\perp} > 0.8$ GeV/c. This is also consistent with the results of WA80 [Pur90, Alb88a], who, for example, have measured the slope of photons above $p_{\perp}(\gamma) > 0.4$ GeV/c, $p_{\perp}(\pi^0) > 0.8$ GeV/c, and π^0 spectra, as a function of the impact parameter (Fig. 4.28).

The following is a summary of the essential properties of the high- $p_{\perp}$ enhancement:

- i) strong dependence on both target and projectile mass,
- ii) also present in reactions without cold spectator matter (central S+S),
- iii) weak (if any) rapidity dependence,
- iv) weak (if any) $\sqrt{s}$ -dependence,
- v) impact parameter dependence restricted to collisions without full overlap of target and projectile,
- vi) no further $E_{\perp}$ -dependence above point (v).

The last two observations could be a direct consequence of point (i), because the effective projectile and target masses, i.e. the number of participants, increase with decreasing impact parameter, but in a strong way only up to the point of full overlap (see Fig. 4.3).

Interpretations of the high- $p_{\perp}$ enhancement in terms of rescattering of charged particles in the surrounding target matter seem unlikely, because one would expect a stronger rapidity dependence. Likewise, collective final-state interactions (collective flow increased 'temperature') will probably have a smoother dependence on $E_{\perp}$ than indicated by points (iv) and (v) above. An explanation, which could be consistent with the experimental systematics, is multiple low-momentum scattering of partons inside the nuclear matter [Lon78, Kry79, Lev83]. As an initial-state process, originally put forward to describe the Cronin effect, it is equivalent to increasing the average $p_{\perp}$ of partons above their intrinsic value. Quantitative QCD calculations have been carried out so far only for p+A interactions [Lev83]. They are in reasonable agreement with the data and even describe some subtle differences observed between K^+ and K^- . The same mechanism is thought to be responsible for the broadening of dimuon $p_{\perp}$ distributions observed in p+A Drell-Yan and J/Ψ production (see Subsection 4.7.1)

c) The low $p_{\perp}$ enhancement

The systematic behaviour of the low $p_{\perp}$ region is decisively different from the high- $p_{\perp}$ excess discussed so far. Leaving aside, for the moment, the experimental controversy mentioned before, in Fig. 4.22 we can see that the dependence on the projectile is much weaker than the one on the target in the measured rapidity region. Furthermore, no change with impact parameter (or $E_{\perp}$) is evident from Fig. 4.27. On the other hand, a strong increase as a function of rapidity is visible in Fig. 4.29 where negative particle spectra taken at different rapidities by NA35 [Str88, Str90b] are overlaid on top of each other with arbitrary relative normalization. The number of low- $p_{\perp}$ h^- 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+S [Wen90].

To illustrate the size of the excess, the data of NA34 from Fig. 4.21 were fitted with two exponentials in $m_{\perp}$. The two contributions, with inverse slopes $T_1 = 52$ MeV and $T_2 = 180$ MeV, are shown together with the data points on a linear scale as $dN/dp_{\perp}$ ($\propto$ number of events) in Fig. 4.30; the soft component amounts to a remarkable 40% of the total number of pions observed. The same 'toy' model, which, however, should not be taken too

seriously, yields a 30% soft component for the NA35 data (O+Au, $\langle y \rangle = 1.1$) and still $\approx 8\%$ for EMU5 (S-Pb $\langle y \rangle = 3$). Very similar numbers are observed at the AGS [Sta90], for example 30% for the data of E810 [Lov91, Eis91] (Si-Au $\langle y \rangle = 2.4$). The spectral shape of the soft part is reminiscent of the momentum distribution of pions from Δ decay (c.f. Fig. 4.19), and a corresponding interpretation has been worked out [Sta90, Bro90b] for the preliminary AGS results. Let us again summarize the essential features of the low- $p_{\perp}$ excess:

- i) very strong target dependence,
- ii) weak projectile dependence,
- iii) very strong rapidity dependence,
- iv) no (or weak) impact parameter dependence,
- v) unfortunately, very strong Collaboration dependence.

The interest in the low- $p_{\perp}$ enhancement has been considerable, and a number of (mostly qualitative) explanations, listed briefly below, have been proposed:

- i) phase-space bias [Cas90], that is to say it is 'easier' to produce many particles if they have a lower $p_{\perp}$ than on average
- ii) rescattering and cascading of produced particles in the target nucleus yielding additional soft pions and resonances [Sor91a]
- iii) resonance decays, in particular Δ and N^* [Sta90, Bro91, Sol90, Orn91, Sor91a]
- iv) pion chemical potential [Ger90, Kat90, Gav91]
- v) modification of pion dispersion relation [Shu89, Shu90, Shu91]
- vi) supercooled droplets of QGP [VHo88].

Whether the (related) explanations (ii) and (iii), which in any case will contribute to the low- $p_{\perp}$ excess at some level, are sufficient to describe the data at the SPS, remains to be shown [Kus89, Hah88]. They would naturally predict the observed target and rapidity dependence, but whereas the number of nucleons available for cascading and Δ production is similar at the AGS and the 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 [Kus89]. A thermal interpretation has an additional problem; it is not easy to cool an expanding pion gas to temperatures below 100 MeV, because $\pi+\pi$ scattering is strongly momentum-dependent, and therefore the freeze-out normally already occurs at a higher temperature [Shu89, Shu90, Shu91].

d) Comparison with other reactions

Soon after the first results on $p_{\perp}$ distributions were available from heavy-ion collisions, it was pointed out [Fis88], that features very much like the ones discussed above appear when comparing different classes of p+p reactions. A compilation [Str88, Str90b] for ratios of $p_{\perp}$ spectra from p+p scattering is contained in Fig. 4.31, i.e. high over low multiplicity, high over low $\sqrt{s}$, high momentum transfer over normal double Pomeron exchange, as well as S+S over p+p. The pattern looks indeed strikingly similar in all cases, leading one to suspect a common cause for the enhancements at low and high $p_{\perp}$ in very different reactions. However, at least in p+A and A+A, we have seen that the systematic features are very different for the low- and

high- $p_{\perp}$ excess, and are therefore not likely to be caused by a single mechanism. In addition, the selection criteria applied to the p+p data push, in all cases, the reaction from 'softer' collisions towards more 'violent' ones. By selecting high multiplicity, a steepening of the $p_{\perp}$ distribution could arise via an increased bias towards (semi)hard parton-parton scattering, even if clean jets are finally only observed at the upper ISR energies, and then only for the highest $E_{\perp}$ events. Likewise, a hardening of $p_{\perp}$ with $\sqrt{s}$ is expected from QCD, and even if calculable only for $p_{\perp} \gg 1$ GeV/c, a smooth transition down to values of order 1 GeV/c is conceivable ('mini-mini-jets'). On the other hand, when going from p+p to p+A, or when varying the projectile or impact parameter in A+A, the changes are mainly geometrical in nature, effecting rather the *number* of participants and spectators than the *type* of interactions. The enhancement involving nuclear targets might therefore very well be of a completely different origin, and most of the models mentioned before are indeed not applicable for p+p reactions.

4.2.3. Transverse-momentum distributions of identified particles

a) Results from the AGS

Transverse mass spectra of identified pions, kaons, and protons have been measured at the AGS by E802 [Abb90, Mia91, Ste90, Cos91] in p+A and A+A reactions for $p_{\perp} = 0.3\text{--}1$ GeV/c close to mid-rapidity ($y = 1.2\text{--}1.4$). Within the limited $p_{\perp}$ range covered by this experiment, the spectra are consistent with a single exponential in $m_{\perp}$. The fitted slope values for p+Be, p+Au, and Si+Au are summarized in Fig. 4.32, together with preliminary results from E810 [Lov91, Eis91] on Λ and K^0 production ($\langle y \rangle \approx 2.3$). Whereas 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 reconcile without additional assumptions (e.g. absorption of $\bar{p}$), with a thermal, local equilibrium interpretation of the distributions [Jah91]. 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 [Sor91a]. New, preliminary data [Cos91], show a strong dependence of the proton slopes as a function of rapidity and target-projectile combination. The inverse slope rises up to a value of $T_0 \approx 270$ MeV in central Si+Au at $y = 1.6$, substantially higher than the one measured by NA35 in S+S ($T_0 \approx 200$ MeV, see next section) at CERN. This could be the first indication that at AGS energies some collective hydrodynamic 'sideways'-flow of nuclear matter still survives from the lower energies of the Bevalac, where this phenomenon is known to exist in A+A reactions below 2 GeV/A [Gut89, Kam89]. This flow should, however, not be confused with the 'transverse flow' claimed to be seen at CERN energies [Lee90]; the latter affects all particles and arises in a *thermalized* system with pressure differences.

b) Results from CERN

Transverse mass distributions of identified particles are shown in Fig. 4.33 for K^0 , Λ , and 'p' (positive-negative particles, corrected for the difference in K^+ and K^- contributions) measured by NA35 [Har89, Ren89, Ody89, Pug89] in p+Au, O+Au and S+S reactions, and in Fig. 4.34 for π^- , $K^\pm$, and p measured by NA34 [VHe91] in S+W. As was the case at the AGS, the spectra can be described with a single exponential in $m_\perp$: ($T_0 \approx 200$ MeV) within the limited statistics and range in $p_\perp$ available. It is quite conceivable, however, that these distributions will also reveal a more complicated structure once better data are available. The inverse slopes are summarized in Fig. 4.35 for p+A and A+A measurements. 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 $p_\perp$ regions: essentially at high $p_\perp$ (> 800 MeV/c) by NA35 and WA85, where the Cronin enhancement might steepen the spectra of mesons, and at $p_\perp < 800$ MeV/c by NA34, with the lowest points well inside the regime of the low- $p_\perp$ enhancement observed for h^- . Taken at face value, the spectra are less steep than comparable p+p data—in particular Λ 's [Ody89, Pug89, Der89, Bar90c] and protons [Str91], which is again possibly a consequence of stopping and rescattering. The similarity of the $m_\perp$ slopes (including now h^-) can also be interpreted in terms of thermodynamical variables, e.g. temperature and collective transverse flow. A quantitative calculation [Lee90] is compared in Fig. 4.36 (solid line) with the S+S results of NA35. The fit describes the spectra reasonably well with a temperature of 112 MeV and a rather large flow velocity of $\beta = 0.43$, but possible problems of thermodynamical models with the systematic features of negative particle spectra have been mentioned earlier.

4.2.4. Summary

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 from $p_\perp$ distribution. However, the data on pions are by now of sufficient quality to study in detail the subtle variations that appear as a function of target, projectile, rapidity, $p_\perp$ and $\sqrt{s}$. The same might hold for other particle species as well, once higher statistics data are available over a larger region of phase space. The following list summarizes the results on $p_\perp$ distributions that have been calculated in the previous sections:

- The pion spectra follow no simple distribution in A+A collisions; not in $p_\perp$, or in $m_\perp$, or $m_\perp^{-3/2}$, or in any other variable suggested so far. Therefore averages or slopes contain only a very limited information, and the full spectral shapes should be consulted instead.
- The low- and high- $p_\perp$ excesses show a distinct but different variation with reaction parameters; they are therefore possibly of different origin and might have nothing in common either with the similar phenomena found in p+p reactions, despite their suggestive analogue pattern.
- The lower and upper ranges in $p_\perp$ are probably influenced by initial- and final-state rescattering, which must be taken into account before drawing conclusions about global

properties of nucleus–nucleus reactions. These effects limit the region where one could hope to find evidence for thermalization and collective flow to $0.3 < p_{\perp} < 1 \text{ GeV}/c$.

- $p_{\perp}$ spectra of identified particles other than pions are well described by a single exponential in $m_{\perp}$ for the time being.
- The slopes of most particle types seem to be independent of the target and projectile at the AGS, with the exceptions (p, K^+) possibly caused by rescattering or some hydrodynamic sideways flow. There is no evidence for more thermalization in A+A, or an increase of temperature compared to p+p.
- Slopes are higher at CERN energies and, within errors, are identical for many particle species; but in fact very few data are available for a direct comparison between p+p, p+A, and A+A in identical regions of phase space.

On the theoretical side, quite a number of models are at hand to interpret the $p_{\perp}$ spectra observed in A+A collisions. However, many of them have not been confronted in a quantitative and systematic way with the rich set of data now available. Probably no single one will be able to explain all the systematic trends and detailed structures, and a thorough exclusion of mundane processes will be necessary before we can conclude whether or not new physics may still be hidden in the transverse-momentum observable. However, even the most conservative models incorporate a large amount of initial- and in particular, final-state rescattering. They therefore imply a dense and strongly-interacting system, i.e. conditions which are favourable (and necessary) to eventually reach (thermal) equilibrium.

4.3. Bose–Einstein Interferometry

A mid-rapidity transverse source size, which exceeds the geometrical dimensions of the primary reaction zone by about a factor of 2 is observed. Backward and forward of mid-rapidity the inferred transverse size is closer to the geometrical dimensions. Around target rapidity, a peculiar dependence of the invariant radius on the target nucleus is observed.

The interferometry of identical pions, performed in analogy to the well-known Hanbury-Brown and Twiss (HBT) method in astronomy [Han54], has become a common tool for analysing the space–time extent of the emitting source. To gain knowledge on the space–time distribution of a pion-emitting source appears to be particularly interesting in view of a possible transient presence of a QGP. Even though the correlation function measures the pion space–time distribution at freeze-out, i.e. the domain where the pions decouple from strong interaction, a possible phase transition to a QGP in the early expansion phase could modify the dynamics of the expansion, and thus the correlation among the pions [Pra86].

The two-pion correlation function is expressed experimentally as

$$C(P_1, P_2) = \frac{N_2(P_1, P_2)}{N_1(P_1)N_1(P_2)} \quad (4.19)$$

where the P_i are the four-momenta of the pions, and N_1 and N_2 are the single- and double-pion inclusive distribution functions, respectively. $C(P_1, P_2)$ is evaluated by correlating all pions from an event and summing over all events. A 'background' distribution is usually obtained by correlating pions from different events. The correlation function $C(P_1, P_2)$ is analysed in terms of

$$C(P_1, P_2) = 1 + \lambda |\rho(Q)|^2, \quad (4.20)$$

where λ is the incoherence or chaoticity parameter, Q is often chosen as the invariant four-momentum difference

$$Q = \sqrt{-(P_1 - P_2)^2}, \quad (4.21)$$

and $\rho(Q)$ is the Fourier transform of the freeze-out space-time density. A simple, yet common parameterization of $\rho(Q)$ is a Gaussian space-time density distribution, separable in space and time, which yields a Gaussian correlation function

$$C(Q) = 1 + \lambda e^{-(QR)^2/2}. \quad (4.22)$$

The above parametrization assumes a source with emitters fixed in space-time, i.e. no correlations in phase space between space-time and momentum coordinates of the pions. Corrections to this simplistic picture might, for instance, result from resonance decays into pions after freeze-out [Gyu88, Pad89], from the specific expansion mechanism [Pra84, Gyu82], or from a transient QGP phase [Pra86, Ber88b, Ber89]. For example, in the Landau-Bjorken picture of a (separable) longitudinal expansion of the source, there is a strong correlation of the position and momentum coordinates along the beam axis, which drastically alters the correlation function [Kol86, Gyu79, Ham88, Mak88]. At present, it appears to be a rather difficult task to analyse the experimental body of data according to these rather complex considerations. Therefore, we shall review in the following only analyses carried out employing the most simple parametrizations [as for example expressed in Eq. (4.22)] of the correlation function¹⁰.

4.3.1. Experimental Results

a) NA35 Collaboration

The NA35 Collaboration has measured negative pion correlations over a wide range of rapidity [Bam88]. They found no sensitivity of their data to the source lifetime and hence omitted the time dependence. In this case the correlation function has the form

$$C(q_\perp, q_\parallel) = 1 + \lambda e^{-(q_\perp R_\perp)^2/2} e^{-(q_\parallel R_\parallel)^2/2} \quad (4.23)$$

where $q_\perp$ and $q_\parallel$ are the transverse and parallel (with respect to the beam axis) three-momentum differences, respectively.

Figure 4.37a–e shows projections of $C(q_\perp, q_\parallel)$ on to the relative transverse-momentum axis $q_\perp$, together with Gaussian fits to the data, according to Eq. (4.23). The data are classified in different rapidity bins: $1 < y < 4$, i.e. the overall acceptance of the NA35 streamer chamber, $1 < y < 2$ corresponding to events lying backwards of mid-rapidity, and $2 < y < 3$ related to pions emitted from a '16 + 50' mid-rapidity source. A clear narrowing of

¹⁰ For a review of HBT results over a wide range of bombarding energies see Ref. [Lor89].

the width, and an increase in the height of the Gaussian can be seen when going from backward to mid-rapidity. The corresponding radii and values of the chaoticity parameter λ are shown in Table 4.2. Finally, Fig. 4.37d shows the results from an analysis of FRITIOF events, which exhibit no Bose–Einstein enhancement at low $Q_\perp$, demonstrating the absence of dynamical ‘background’ correlations.

The outstanding features of the data are the large radii and λ -parameters at mid-rapidity. For comparison, radii extracted from high-energy NN scattering [Åke85, Åke87a, Åke87b, Bor87, Alb89b] are of the order of 1 fm, but also those from the collision of relativistic heavy ions at energies of a few GeV/A do not exceed 2–5 fm, corresponding to the size of the projectile [Akh84, Zaj84, Fun78, Bea83a, Bea83b, Bea86, Lu81, Boc88, Boc89]. In the present case, the transverse radii at forward and backward rapidity are about the geometrical size of the projectile, while exceeding the geometrical formation volume (given by the projectile radius: $R_{\text{form}} = 1.2 A_{\text{proj}}^{1/3}$) at mid-rapidity by about a factor of 2.

b) E802 Collaboration

The E802 Collaboration has measured correlations of identical pions in a window $1.39 \leq \eta \leq 2.1$ [Mor90, Mor91]), employing the magnetic spectrometer. Figure 4.38 shows the correlation as a function of $q_\perp$ as projected from a slice along the $q_{||} = 10$ MeV axis. The solid line is a Gaussian fit according to Eq. (4.23). Both the Al and Au targets show a similar behaviour and give, in contrast to the NA35 result, transverse radii close to the dimensions of the projectile (see Table 4.3).

c) Interpretation

In order to understand the large transverse radii, it is necessary to recall that the observed radius is given by the dynamical evolution of the source. A corresponding explanation has recently been given by Stock [Sto90] considering the idealized case of a uniform density decrease during expansion, and an instantaneous decoupling of the hadrons from strong interaction. Starting from a mean free path $\lambda_{\pi\pi}$ (for simplicity only pions are considered) given by

$$\lambda_{\pi\pi} = \frac{\frac{4}{3}\pi R^3}{N_\pi \sigma_{\pi\pi}} \quad (4.24)$$

the freeze-out radius $R_F = \lambda_{\pi\pi}$ has to be inserted into the above equation. For simplicity, a constant value $\sigma_{\pi\pi} = 20$ mb = 2 fm² is used, which results in $R_F = 0.69 N^{1/2}$ fm. By replacing N by dN/dy and considering only charged pions we get

$$R_F^\lambda = 0.84 \sqrt{\frac{dN_{\text{charged}}}{dy}}. \quad (4.25)$$

Similarly, the freeze-out density is obtained as

$$\rho_F = \frac{1}{\lambda\sigma} \approx \frac{0.5}{R_F}. \quad (4.26)$$

Figure 4.39 shows a comparison of radii extracted from experiments at the ISR for pp collisions at $\sqrt{s} = 60$ GeV [Åke87a, Åke87b, Bre87], $p\bar{p}$ collisions at the SPS collider at $\sqrt{s}$ between 200 and 900 GeV [Alb89b], as well as (preliminary) NA35 data from central collisions

of $^{16}\text{O}+\text{Au}$, $^{32}\text{S}+^{32}\text{S}$ and $^{32}\text{S}+\text{Ag}$ at $\sqrt{s} = 19.6$ GeV/A (200 GeV/A in the laboratory). The $^{16}\text{O}+\text{Au}$ reaction is also shown for $\sqrt{s} = 10.8$ GeV/A (60 GeV/A in the laboratory). The different conventions for the various experiments, and the effects of Lorentz contraction for the extraction of a radius parameter, have been taken into account. The simple multiplicity dependence of the freeze-out radius is shown as the solid curve derived in Eqs (4.24) and (4.25), which gives a reasonably good description of the data over almost two orders of magnitude of bombarding energies. For comparison, we have drawn, as the dashed curve, the multiplicity dependence which is obtained assuming that interactions stop when the energy density has fallen to that of an ideal pion gas at $T \approx T_c = 150$ MeV [Sat90a]. This results in a cubic dependence of the freeze-out radius on the multiplicity:

$$R_F^e \approx 1.42 \sqrt[3]{\frac{dN_{\text{charged}}}{dy}}. \quad (4.27)$$

In the range of present multiplicities the data are compatible with both forms. However, already the multiplicities reached in SPS Pb + Pb collisions should permit a distinction between the two descriptions. An extrapolation to the apparent source size radii to be expected for Pb + Pb collisions gives, assuming a charged particle density dN_{ch}/dy at mid-rapidity of about 550, freeze-out radii of 10 (cubic extrapolation) to 20 fm (square root extrapolation). Experimentally, a measurement of this radius is rather demanding: a resolution of Δp better than 10 MeV/c is required.

The above considerations give at least a qualitative understanding of the expansion dynamics: whilst at low initial densities of the formation volume (given by the projectile radius) the hadrons expand without further reinteraction, the high initial density of heavy-ion collisions enforces rescattering of the produced particle. The freeze-out volume becomes independent of the formation volume, and depends only on the square (or cubic) root of the particle density.

Whether or not the first stages of the expansion proceeded via a deconfined phase still remains an open question. There are interesting suggestions how a phase transition to a QGP would modify the correlation function. Pratt [Pra86] and later Bertsch et al. [Ber88b, Ber89] showed that a phase transition changes the dynamics of the expansion significantly, resulting in quite different 'outward' and 'sideward' source dimensions. Here outward and sideward refer to the pion emission direction parallel and perpendicular to $Q_{\perp} = p_{\perp 1} + p_{\perp 2}$. At present, the limited statistics of the data do not allow meaningful projections of $R_{\perp}$ on to the 'sideward' and 'outward' directions. These detailed investigations are awaiting high-statistics data from forthcoming experiments.

d) WA80 Collaboration

Another degree of complexity for the interpretation of the data is added by investigating HBT effects in the target fragmentation region. This is because the expanding system might be altered by the surrounding target spectator matter via rescattering. Data in the target fragmentation region have been obtained by the WA80 Collaboration employing the Plastic Ball.

Reactions of 200 GeV/A oxygen with C, Cu, Ag, and Au were examined [Pei90b, Pei91]. The correlations were analysed according to Eq. (4.22). The experimental data in the

rapidity range $-1 \leq y_{\text{lab}} \leq 1$ together with Gaussian, multi-Gaussian and exponential fits (solid, dotted, and dashed lines, respectively) are shown in Fig. 4.40. For the case of $^{16}\text{O}+\text{C}$ a multi-Gaussian fit is shown, because a single Gaussian gave no stable fit to the data [Pei91]. A clear enhancement for small values of Q is visible for all cases. The most prominent feature of the data is the narrowing of the correlation function as the target mass decreases, i.e. an apparently increasing source size as the target size decreases! The numerical results of the Gaussian fits, in terms of R and λ , are shown in Table. 4.4.

It is not understood in which way the target spectator alters the pion correlation function in order to produce the above result. One could speculate that the rescattered pions come from *very* large volumes or *very* late times, and their correlation could thus be hidden at very small values of Q , hardly accessible to the experiment.

4.3.2. Summary

The observation of a large source at mid-rapidity by the NA35 Collaboration has renewed interest in HBT measurements. At present, several experiments (NA35, WA80/93, NA44) are setting up detectors for interferometry measurements with future ion beams. However, a scaling of the radii with the charged particle multiplicity can be obtained from very simple assumptions about the freeze-out density. There is thus no necessity to invoke new phenomena to 'explain' the data. The observed large radii do, however, indicate a high primordial density of particles. An improved sensitivity of the methods of analysis are at present hampered both by the limited statistics of the data, as well as by the lack of an appropriate theoretical description of the experimental correlation function. Experiments aiming at good statistics and/or particle identification (WA93, NA35, NA44), should provide further insight from investigating, for example, the $p_{\perp}$ -dependence of the HBT effect or KK correlations.

The apparent large source sizes found in the target rapidity range point toward the importance of rescattering effects, which might alter the source size and obscure a straightforward interpretation of the extracted radii.

4.4. Fluctuations and Intermittency

The results of fluctuation analyses of various emulsion experiments are compared. Intermittency signals are observed by all experiments. However, sizeable differences in the results raise the question whether background and detector effects are well enough understood.

Large, non-statistical fluctuations, e.g. of rapidity or energy density, have been proposed as a possible signature of the QGP phase transition [VHo84, VHo85, Gyu84b]. In fact, cosmic-ray experiments report events with large 'spikes' in their pseudorapidity distribution [Bur82]. However, 'interesting' non-statistical, dynamical fluctuations have to be distinguished from mere statistical or geometrical ones. Several methods have been devised in order to single out non-statistical fluctuations. It turns out that geometrical and statistical fluctuations are dominant. The weak signal of non-statistical fluctuations, sitting on top of a large 'noise', is both extremely difficult to analyse and to understand theoretically.

4.4.1. Multiplicity fluctuation analysis

A fluctation analysis according to theoretical schemes proposed by Hwa [Hwa88a, Hwa89] has been performed by EMU-NA34 [Åke90b], WA80 [Alb89a, Ber88a], and by the EMU08 experiment [Sen88]. The proposed analysis is sensitive to non-statistical, dynamical fluctuations, provided that geometrical fluctuations are minimized. Geometrical fluctuations are due to variations of the impact parameter and can be minimized by proper selection criteria for central collisions. In the proposed scheme the normalized moments of the experimental charged-particle multiplicity distributions C_i

$$C_i = \frac{\langle n^i \rangle}{\langle n \rangle^i} \quad (4.28)$$

are calculated for different bins of pseudorapidity, which are centred around mid-rapidity. The second and third moments should depend on $\langle n \rangle$ and $\langle n \rangle^2$ as follows [Hwa88b]:

$$L_2 := C_2 \langle n \rangle - 1 = S_2 \langle n \rangle \quad (4.29)$$

$$L_3 := C_3 \langle n \rangle^2 - 3C_2 \langle n \rangle + 2 = S_3 \langle n \rangle^2. \quad (4.30)$$

Both dynamical (v_i) and geometrical (μ_i) fluctuations contribute to the slope: $S_i = v_i + \mu_i$. For a fixed impact parameter μ_i is equal to unity by definition. In this case, any excess of S over unity would be a sign of dynamical fluctuations. Figure 4.4.1 shows L_2 and L_3 plotted against $\langle n \rangle$ and $\langle n \rangle^2$, respectively, from the EMU-NA34 experiment. In this experiment the impact parameter range was narrowed by triggering on central collisions, employing the NA34 calorimeter arrays. The resulting values for the slopes are close to one, i.e. no sign for large dynamical fluctuations emerged from this analysis.

From a similar analysis, Sengupta et al. [Sen88] had reported values above one. However, this can probably be attributed to a less stringent impact parameter trigger which still allows geometrical fluctuations.

A related analysis [Hwa88a, Ber88b, Alb89a] investigates the normalized variance

$$\Omega := \frac{\langle n^2 \rangle - \langle n \rangle^2}{\langle n \rangle^2} = C_2 - 1 \quad (4.31)$$

as a function of the pseudorapidity window $\Delta\eta$. It can be shown analytically [Alb89a] that, in the case of purely statistical assumptions, the local multiplicity fluctuations in a window $\Delta\eta$ at a given value of η can be related to the average multiplicity density $\rho(\eta)$ by

$$\Omega(\eta, \Delta\eta) - [\Delta\eta \cdot \rho(\eta)]^{-1} = \text{const.} \quad (4.32)$$

The corresponding function is shown in Fig. 4.42a and b, together with data and results from FRITIOF simulations, respectively. Whilst, as expected, FRITIOF and the statistical formula agree, slight deviations occur at small $\Delta\eta$ for the data. This excess might be due to two-particle correlations or to an intermittent behaviour. It has to be concluded from the above analyses that the data are dominated by purely stochastic emission of particles and no evidence for large non-statistical fluctuations has been revealed. In order to disentangle small non-statistical contributions from the stochastic background more sensitive methods are required.

4.4.2. Intermittency analysis

At present, intermittency analyses¹¹ are believed to be more receptive for non-statistical fluctuation. Intermittency is a phenomenon which can, in general terms, be defined as the appearance of structure in random media [Zel87]. It is, in some sense, the inverse of the onset of chaos from an ordered motion. Bialas and Peschanski [Bia86, Bia88a, Bia88b] have proposed a new method of searching for intermittency patterns in large multiplicity events. As already pointed out, 'interesting' fluctuations compete with ordinary statistical 'noise' owing to the finite particle number. Bialas and Peschanski have shown that the *scaled moments* of a *probability* distribution are equal to the *scaled factorial moments* of the *experimental* distribution, i.e. by considering scaled factorial moments the statistical noise is damped out to a large extent. The formalism is as follows.

The pseudorapidity range $\Delta\eta$ is divided into M bins of uniform width $\delta\eta = \Delta\eta/M$. The so-called 'horizontal' scaled factorial moments are calculated as

$$\langle F_q \rangle_{\text{horizontal}} = \frac{1}{N_{\text{events}}} \sum_{i=1}^{N_{\text{events}}} M^{q-1} \sum_{m=1}^M \frac{k_{m,i}(k_{m,i}-1)\dots(k_{m,i}-q+1)}{\langle N \rangle^q} \quad (4.33)$$

In order to be sensitive to fluctuation on all scales $\langle F_q \rangle$ is investigated as a function of the bin size $\delta\eta$, where the limit in $\delta\eta$ is given by the experimental resolution. This kind of analysis is not restricted to intervals in $\delta\eta$, but can, for example, also be performed in terms of $\delta\phi$ or $\delta\eta \cdot \delta\phi$, where ϕ is the azimuthal angle [Och88]. An event or a sample of events is called 'intermittent' if the scaled factorial moments depend on the bin size as

$$\langle F_q \rangle \propto \left(\frac{1}{\delta\eta} \right)^{\phi_i} \leftrightarrow \ln(\langle F_q \rangle) \propto -\phi_i \ln(\delta\eta). \quad (4.34)$$

The slope ϕ_i characterizes the strength of the intermittent behaviour.

e) Experimental data

Experimentally, intermittency has been found in e^+e^- reactions [Bus88c, Bra89, Beh90a, Beh90b, Abr90b], in hadron-hadron [Aji89, Aji90, Bus89a, Bus89b] and heavy-ion collisions [Ada90a, Ada90b, Hol87, Sen90, Åke90b]. A comparison between different experiments is difficult or made impossible because of the different acceptances or biases of the experiments, as well as the different normalizations of the factorial moments. The emulsion experiments, which are subjected to very similar experimental conditions, are an exception. As an example, we show in Fig. 4.43 factorial moments obtained from the EMU01 experiment. A rise of $\langle F_i \rangle$ as a function of $\delta\eta$ down to a resolution of $\delta\eta \approx 0.1$ is shown, followed by a flattening of the moments at distances $\delta\eta < 0.1$, suggesting a change of the intermittent behaviour.

Figure 4.44a-c systematically compares results from different emulsion experiments, EMU01 [Ada90a, Ada90b], EMU07 [Hol87, Hol89], EMU08 [Sen90], and EMU-NA34 [Åke90b] for various projectiles and bombarding energies. The data are evaluated down to a

¹¹ Recent reviews on intermittency can be found in Refs. [vHo89, Bus 89, Kit90, Bia89, Bia91].

resolution of $\delta\eta \approx 0.1$. The normalized slopes $\xi_i = 2\phi_i/i(i-1)$ are plotted as motivated by a scaling behaviour proposed by Bialas and Peschanski [Bia86, Bia88a].

Whilst all experiments report *qualitatively* a power-law behaviour according to Eq. (4.34), the data are *quantitatively* not consistent.

- i) As can be seen from Fig. 4.44a, the data of EMU07 and EMU08 agree at 200 GeV/A, but disagree strongly at 60 GeV. Thus, the energy dependence of the intermittency effect, namely a stronger intermittent behaviour at the lower bombarding energy, remains unsolved by these sets of data. Such a behaviour has also been claimed when looking at NA22 data (π^+p and K^+p reactions at $\sqrt{s} = 22$ GeV) [Aji89, Aji90] and UA1 data ($p\bar{p}$ reactions at $\sqrt{630}$ GeV) [Bus89a, Bus89b].
- ii) The contribution of unresolved e^+e^- pairs from γ -conversion to the slopes is controversial: whilst EMU-NA34 estimates a contribution of about $(70 \pm 30)\%$ for $S + Em$ [Åke90b], EMU01 evaluates only 20–30% [Ada90a]. The weakness of the intermittency signal carries the danger of dramatic systematical errors: it has been emphasized by Buschbeck and Lipa [Bus89a] that a double counting of tracks on the 1% level would produce intermittency signals of the same order as the experimentally observed ones.
- iii) The data do not consistently scale as suggested by the α model of intermittency [Bia88a] (see Fig. 4.44a-c). The α model represents a simple, self-similar cascade of particle production, and yields $\xi_i = \text{const.}$ as a function of the order of the moments. It should, however, be noted that all moments are correlated, i.e. the higher moments contain components from lower ones. It has been shown [Ada90b] that this forces a linear relation of the normalized slopes ξ_i as a function of the order of the moment. The 'slope' of the slopes is determined by the difference of the second and third moments. A small statistical offset at $i = 3$ will carry over to higher moments and thus produce a rather arbitrary linear dependence, or even negative slopes.

Nevertheless, the following systematic features can be extracted from the data:

- i) A slight decrease of ξ_i is found by going from ^{16}O to ^{32}S (Fig. 4.44b and c), except for the EMU08 data set.
- ii) A decrease of ξ_i is found by selecting the central collision for a given projectile (Fig. 4.44a and b).
- iii) Another scaling rule is proposed by Seibert [Sei90]. The basic idea is that two-particle correlations are mainly responsible for the intermittency effect. In this case $F_i - 1$ should scale like the inverse of the average particle density, i.e. $1/\langle\rho\rangle$. As can be seen from Fig. 4.45 the data points fall rather well on to the $1/\langle\rho\rangle$ curve, independent of the bombarding energy or centrality of the reaction. An exception from this scaling is seen for the largest systems investigated. For sulfur-induced reactions the intermittency signal, normalized to the particle density, is about a factor of 2 higher than for all other systems investigated so far. This might be an indication of the onset of collective effects [Bia89, Cap89]. Finally, it should be emphasized that, normalized to the particle density, the intermittency effect in hadron–hadron or hadron–nucleus reactions is *not* larger than in nucleus–nucleus reactions.

Whilst the physical origin of the intermittency signal in heavy-ion reactions is unclear, progress has been achieved for e^+e^- reactions. An excellent description of the factorial moments by the LUND 7.2 parton shower model has been recently reported by the CELLO Collaboration [Beh90b], leaving no room for 'new', unexplained phenomena. The intermittent behaviour can be completely attributed to the particle production scheme in LUND 7.2 and additional two-particle correlations from resonance decays (mainly the Dalitz decay of the π^0), and Bose–Einstein correlations.

In the case of heavy-ion induced reactions the intermittent behaviour is not reproduced by FRITIOF [Hol89, Ada90a, Sen90]. It should, however, be noted that the present available version of FRITIOF (1.6) is far less sophisticated than LUND 7.2. The theoretically-predicted contribution of Bose–Einstein correlations [Car89, Gyu90c] can, in principle, be tested experimentally: we would expect a stronger intermittency effect for like-sign pions as for all pions. This investigation was made in several experiments [Aji89, Hau89, Bus89a] with the conclusion that the HBT correlation is unlikely to be the main reason for intermittency.

4.4.3. Summary

It may be concluded that the present experimental data and the theoretical understanding are far away from the goal of relating intermittency to collective effects [Bia89, Cap89] and, eventually, to a phase transition [Bia91, Bia90].

4.5. Strangeness Production

A factor of 2 enhancement of the K^+/π^+ ratio compared to the one from pp or pA reactions has been measured both at the AGS and the SPS. This enhancement can, however, also be explained by rescattering processes in a purely hadronic scenario. An enhancement of neutral strange particle production is found in S + S, but not in $^{16}\text{O}+\text{Au}$. The strange antibaryon ratios are drastically enhanced at high $p_\perp$, but still have large error bars. A ϕ enhancement, found via dilepton spectroscopy, can be explained both in a QGP and a high-density hadronic scenario.

4.5.1. Strangeness a signature of the QGP ?

Strangeness as a possible signature of a QGP state was put forward almost ten years ago [Raf81]. The arguments were as follows ¹²:

- i) In a hadron gas (HG), strange mesons and baryons are made via associated production during the collision of two, typically non-strange hadrons. The threshold energy is determined by the mass of the strange hadron pair. The reaction with the lowest threshold is $p + n \rightarrow \Lambda^0 + K^+ + n$ and requires 671 MeV. The production of a $K\bar{K}$ pair requires

¹² For recent reviews on the subject see Refs. [Ody90, Koc86, Koc91, Egg91].

986 MeV. On the other hand, in a QGP the threshold for strangeness production is equal to the rest mass of the $s\bar{s}$ pair, i.e. $2m_s \approx 300$ MeV. Thus, at the experimentally measured temperatures around 200 MeV, strangeness production in a QGP is favoured over HG production.

- ii) At high baryon density, i.e. in collisions with high baryon stopping, or in the fragmentation regions, the production of $s\bar{s}$ pairs is enhanced over $u\bar{u}$ or $d\bar{d}$ pairs: the production of the light quarks has to supply the large Fermi energy (chemical potential μ_B) for the u- and d-quarks, whilst the s-quarks are not affected by μ_B and are only suppressed by their non-zero mass. As a consequence, 'K⁺ distillation' might occur: owing to the abundance of u over $\bar{u}$ quarks the K⁺ ($u\bar{s}$) is more likely to be produced than the K⁻ and, eventually, radiated off from the plasma surface. This leads to a net-strangeness enrichment of the plasma and to the production of multiple strange particles and, ultimately, to exotic objects called 'strangelets' [Gre87, Gre88a, Gre88b].

It is, however, not clear to which extent the primordial flavour distribution of a plasma survives the hadronization transition and the hadron gas phase. Furthermore, it is being argued [Lee88, Bar88a, Fri89, Cle91] that an *equilibrium* HG also shows a strangeness enhancement. The quality of strangeness as a QGP signature thus becomes a question of the time scales involved: is the strangeness equilibration process in hadron gas sufficiently fast to achieve equilibration in a hadronic scenario?

4.5.2. Experimental results on strangeness production

The production of strange particles in nucleus–nucleus collisions has been measured, essentially, with two different techniques: the long-lived charged kaons with a combination of momentum analysis (magnetic spectrometer) and particle ID [time-of-flight (TOF) and Cherenkov] by E802 and NA34, the short-lived K_s^0 and strange baryons (Λ , Ξ) via their decay pattern in large-volume tracking devices (E810, NA35, NA36) or specialized spectrometers (WA85). The different experiments and their acceptance in $p_\perp$ and rapidity have been summarized in Section 3. In addition, the NA38 experiment has measured ϕ production via its decay into two muons.

a) Results from the AGS

The first results on enhanced strangeness production were already reported from the AGS shortly after the first data had been taken in 1986 [Mia88]. As can be seen from the rapidity distribution of charged particles in Fig. 4.11 [Abb90, Abb91], the yield of charged kaons per incident beam nucleon increases gradually from p + Be to pAu to central Si + Au, whereas the number of charged pions stays essentially constant. The rapidity density in Fig. 4.11 was calculated from the $p_\perp$ spectra (Fig. 4.46) by extrapolating exponential distributions in $m_\perp$ below the region of the spectrometer acceptance ($p_\perp < 300$ MeV/c); owing to the low- $p_\perp$ enhancement observed also at the AGS, the pion yield is therefore probably underestimated by as much as 20% (see subsection 4.2). The resulting K/ π ratios, integrated over $1.2 < y < 1.4$, are summarized in Table 4.5 [Abb90, Abb91].

The $p + \text{Be}$ data are comparable with pp results at corresponding energies [Abb90, Abb91] ($K^+/\pi^+ = 4\text{--}8\%$, $K^-/\pi^- = 2\text{--}5\%$), whereas the K^+/π^+ ratio is larger by more than a factor of 2 in central $\text{Si} + \text{Au}$. The increase in K^-/π^- is seemingly less, only 50%, but with a large statistical error. As can be seen from Fig. 4.47, these ratios are rapidity-dependent and range in $\text{Si} + \text{Au}$ 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 π 's probably reflect a different production mechanism: K^- are more centrally produced, in particular in $p\text{--}\text{Be}$ collisions, whereas the K^+ behave in a similar way to the protons and shift clearly backwards with increasing target mass. An enhancement of K^+ production (K^+ 'distillation') has been predicted to occur in very baryon-dense matter [Gre88a, Gre88b, Hei87] or in QGP formation [Raf82, Raf84], in which case the effect would indeed be most pronounced in the target fragmentation region, a region with presumably the highest baryon density. However, the gradual increase in K^+ production from pp to pA to AA , together with the change in slope of the transverse-momentum spectra (see subsection 4.2), 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 (for example, reactions such as $\Delta\pi \rightarrow YK$, $pN \rightarrow YK$, ...) can reproduce quantitatively the observed K/π ratios and the $p_\perp$ spectra [Mat89, Mat90, Sor91a]. 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 centrality [Eis90]. No dependence on impact parameter has been found, in contrast to the slight increase in K/π ratios seen by E802 [Cos91], and the inverse slopes of K_s^0 , Λ , and π are identical ($T_0 \approx 150$ MeV). The upper limit on $\bar{\Lambda}\Lambda < 0.07$ (95% CL) is still above the corresponding ratio measured in pp reactions ($\bar{\Lambda}\Lambda \approx 0.02\text{--}0.03$) [Whi74].

b) Results from the SPS

Charged kaons were measured in the external spectrometer of the NA34 experiment [VHe91] for low $p_\perp$ in the target fragmentation region ($0.8 < y < 1.3$). The K/π ratios plotted in Fig. 4.48 as a function of $p_\perp$ for $S + W$ and $p + W$ reactions, show the same trend as the one observed by E802 at the lower AGS energy: a gradual increase of up to a factor of 2 in the K^+/π^+ ratio when going from pp to $p + W$ and $S + W$, a K^-/π^- ratio which stays approximately constant, and a different $p_\perp$ slope for K^+ and K^- (see subsection 4.2). These similarities might be indicative of a common underlying mechanism (e.g. associated $\Lambda^0\text{--}K^+$ production) [Mat91], in particular as both experiments are measuring 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 $p_\perp$. This number, which is equivalent to a K^+/π^+ ratio of the order of 1, when plotted as a function of $m_\perp$ instead of $p_\perp$ [VHe91], happens to be close to the one predicted for chemical equilibrium.

Neutral strange particle production (K_s^0 , Λ , $\bar{\Lambda}$) has been measured by NA35 in $O + \text{Au}$ backward of mid-rapidity, $\langle y \rangle \approx 2$, 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. In $O + \text{Au}$, no change in the K_s^0 and $\bar{\Lambda}$ yields, normalized to negative particles, was seen compared to $p + \text{Au}$ or the FRITIOF Monte Carlo code, whereas Λ 's are again

produced about two times more frequently with the heavy target (both in $p + \text{Au}$ and $\text{O} + \text{Au}$) than predicted by FRITIOF [Bam89]. In the $\text{S} + \text{S}$ system, however, all neutral strange particles seem to be enhanced by about a factor of 2 in central collisions as compared to pp reactions [Bam90]. The corresponding ratios, extrapolated to full phase space ($1 < y < 5$, $p_{\perp} > 0$), are contained in Table 4.6¹³:

The rapidity distributions [Bam90] of K_s^0 and $\bar{\Lambda}$ are peaked at $y = 3$ (central production), whereas the $\bar{\Lambda}$'s are more spread out in y and probably trace, to some extent, the proton distribution [Str91], when proper care is taken of the effect of the limited $p_{\perp}$ acceptance. In Fig. 4.49, the multiplicity of neutral strange particles normalized to the total multiplicity $\langle h^- \rangle$ is shown as a function of $\langle h^- \rangle$ for peripheral, intermediate, and central collisions. In addition to the previously mentioned enhanced strangeness yield in central $\text{S} + \text{S}$, compared to pp (open circles) and, somewhat smaller, to $p + \text{S}$ (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 $\text{O} + \text{Au}$ and $\text{S} + \text{S}$, respectively, if not simply due to the small 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 $\text{O} + \text{Au}$ reaction, as compared to those in the lighter $\text{S} + \text{S}$ 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 strangeness density, whereas the non-equilibrium production in the hadron gas phase is expected to be suppressed owing to the large mass (Egg91, Raf91). The WA85 experiment, optimized to measure strange baryon decays in $2.3 < y < 3.0$ and $p_{\perp} > 1 \text{ GeV}/c$, has obtained the results shown in Table 4.7 in $\text{S}-\text{W}$ reactions at 200 GeV/A [Aba90, Aba91, Eva91, Nar91].

The Λ sample includes Λ 's from Σ^0 , whereas the contamination arising from cascade decays has been corrected for. Both Λ and $\bar{\Lambda}$ production increase by $\approx 70\%$ when going from $p + \text{W}$ to $\text{S} + \text{W}$, leaving the $\bar{\Lambda}/\Lambda$ ratio essentially constant (Fig. 4.50). Whereas the $\bar{\Xi}^-/\Lambda$ ratio is compatible with results from pp and e^+e^- reactions (see Refs. [Aba90, Aba91, Eva91, Nar91] and references therein), 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 [Ame91, Raf91]. However, in the high- $p_{\perp}$ region accessible to WA85, nuclear effects similar to the ones discussed in subsection 4.2 ('Cronin effect'), or different A -dependences for soft and hard processes, could alter particle ratios significantly with little influence on the integrated yields.

¹³ The published errors are a linear sum of statistical and extrapolation errors and were reduced in this table by $1/\sqrt{2}$ [Bro90a].

c) ϕ Enhancement

Shor [Sho85] first suggested that a strong enhancement of the ϕ/ω ratio over the one observed in pp collisions ($\approx 1/20$ [Blo75, Dri81]) could be a rather clean signature of QGP formation in heavy-ion collisions. The ϕ and the ω differ primarily in their quark composition: whilst the ϕ consists mainly of $\bar{s}s$, the ω consists of an isospin singlet combination of $\bar{u}u$ and $\bar{d}d$.

Recently, the NA38 Collaboration has studied the ϕ , ρ_0 , and ω production in p, O, and S + U reactions. The principal difficulty in the ϕ , ρ_0 and ω mass region ($0.6 < M_{\mu\mu} < 1.2 \text{ GeV}/c^2$) is the very high combinatorial background. However, by introducing a $p_\perp$ cut the $M_{\mu\mu}$ spectra exhibit a clear double-peak structure corresponding to the ϕ and $\rho_0 + \omega$ vector mesons [Bal90]. Plotted against $E_\perp A^{-2/3}$, i.e. something proportional to the Bjorken energy density [Bjo83], the ratio $\phi/\rho_0 + \omega$, normalized to the p + U value, shows a remarkable increase with $E_\perp$ (Fig. 4.51). A recent, improved estimate of the ϕ/ρ_0 ratio in a QGP by Koch, Heinze and Pisut [Koc90] yields a value of 0.38 at a plasma temperature of $T_c = 200 \text{ MeV}$. This would be an enhancement of a factor of ≈ 7 over the pp value.

However, as for the J/ψ suppression, non-plasma explanations are also possible. Koch et al. [Koc90] showed that a similar $\phi/\rho_0 + \omega$ enhancement, as a function of transverse energy, can be obtained via hadronic rescattering, represented by the solid curves in Fig. 4.51. Similarly to the hadronic absorption models accounting for J/ψ suppression, enormously high particle densities are required. In fact, the rescattering explanation of Koch et al. is strongly linked to the hadronic final-state absorption of the J/ψ and would, as the authors state, break down if it should turn out that hadronic absorption cannot explain J/ψ suppression.

4.5.3. Summary

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 recently. From the experimental point of view, a significant enhancement of strange-particle production has been observed in most channels, both at the AGS and at the SPS when comparing pp and AA reactions, with pA results in many cases being between them. The pattern is, however, far from being simple, depending on particle species, rapidity, $p_\perp$ 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 (in particular at low $p_\perp$), but experimental clarification of 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 (but not 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 been put forward so far for the observed increase of

antihyperons (Λ , Ξ^-). In any case, the rather large effects observed in AA collisions are a clear deviation from a simple superposition of independent nucleon–nucleon collisions. Their explanation requires, even in the most conservative models, a strong final-state rescattering and therefore an extended, interacting system, on its way to equilibrium.

4.6. Photon Production

The measurement of real or virtual photons (leptons pairs) is probably the only possibility of having direct access to the transient dense and high-temperature phase of a heavy-ion collision [Kaj81]. At present, the sensitivity of the experiments is limited by systematic errors mainly due to insufficient acceptance of the apparatus. An upper limit of 15% of the ratio $\gamma_{\text{thermal}}/\pi^0$ is determined by the measurements.

4.6.1. Thermal and hard photons

A source of abundant photon production in hadronic collisions is the electromagnetic decay of directly produced hadrons such as $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, $\Sigma^0 \rightarrow \Lambda^0\gamma$, etc. These sources of photons, although interesting in their own right, are the subject of this section only as background processes, which tend to obscure the signal of interest, namely the single, *thermal* photons. Usually, single photons are classified into a high- and a low- $p_\perp$ regime:

The high- $p_\perp$, *hard* regime is well understood on the basis of single-parton collision. In fact, the discovery of a significant prompt photon yield at large $p_\perp$, predicted by several authors [Hal78, Rüc78, Con79, Fer84], represented one of the successes of perturbative QCD. The leading-order ($\alpha\alpha_s$) processes responsible are the quark–antiquark annihilation and quark–gluon Compton scattering, the QCD diagrams of which are shown in Fig. 4.52. Owing to their direct relation to the quark and gluon contents of hadrons, hard direct photon measurement contributed to the clarification of the substructure of hadrons.

The low- $p_\perp$ or thermal regime is neither well understood theoretically nor experimentally established. Nevertheless, thermal γ 's are expected to be one of the major signatures of the quark–gluon plasma [Sh78, Kaj81, Hal82, McL85, Hwa85, Rah87]. The predicted ratio of direct photon to π^0 production from the plasma ranges from 5% [Neu89] to 40% [Hal82], mainly reflecting the systematic uncertainties of the theoretical estimates, in particular our ignorance about the initial temperature T_i . Photon–emission rates from the plasma are calculated in a similar way to the high- $p_\perp$ direct photon production. The major difference is that the structure functions which describe the momentum distribution of partons in nucleons have to be replaced by *thermal* distributions for fermions and bosons describing the partons of the plasma. The photons decouple directly after their production and do not, in contrast with strong interaction probes, suffer from reinteractions during the expansion and hadronization of the plasma. Thus, the photons emitted from the plasma should directly reflect the temperature of the deconfined phase (black-body radiation) [Kaj81].

A $p_\perp$ spectrum of single, thermal photons from a calculation by Neubert [Neu89] is shown in Fig. 4.53, together with other sources of photons, as discussed above. A window, where those photons produced thermally are detectable, if at all, is the $p_\perp$ region between 1 and

3 GeV/c, where the background from meson decay on the one hand and hard photons on the other, is at least comparable to thermal production of γ s. However, similar calculations at LHC energies have been carried out by Ruuskanen [Rus90]. In this energy range the ratio $\gamma_{\text{thermal}}/\pi^0$ becomes more favourable: at high-enough multiplicities, i.e. $dN^\pi/dy \approx 4000$, and a transverse momentum window of 2–3 GeV/c, the number of thermal photons even exceeds the photons from hadron decay.

4.6.2. Results

a) The NA34 external spectrometer

The technique chosen by the NA34 Collaboration to measure photons is via conversion into e^+e^- pairs. The small solid angle of the spectrometer does not allow π^0 and η reconstruction from the invariant mass of two photons. This is partly compensated via the measurement of charged pions in the same apparatus. For the $p_\perp$ spectrum of η , η' , and ω $m_\perp$ -scaling [Bou76] has to be employed. The restricted solid angle limits the statistics which can be accumulated during a run, but it is the systematic errors (9%) which put the most severe limits on the confidence level of the data. The major contribution to the error of γ_{observed} comes from the uncertainty (inefficiency) of the track finding. For the calculation of the hadronic background the main error is due to the lack of knowledge about η production. The contribution of the statistical error, for the $p_\perp$ -integrated $\gamma_{\text{observed}}/\pi^0$ is 4–11%.

Figures 4.54 a–c show the corrected inclusive $p_\perp$ spectra for photons observed in $p = W$, $^{16}\text{O} + W$, and $^{32}\text{S} + W(\text{Pt})$ at 200 GeV/A, respectively [Åke90a, Bar89]. The full line describes the spectra expected from hadronic sources π^0 , η , η' , and ω . The shape of the measured photon spectrum agrees well with the one expected from the hadronic background. In order to study the $E_\perp$ dependence (i.e. the centrality of the collision), the integrated ratios $\gamma_{\text{observed}}/\pi^0$ are shown in Fig. 4.55 as a function of the transverse energy. In order to study a possible change in $\gamma_{\text{observed}}/\pi^0$ as a function of the $p_\perp$ of the photon, the ratio is plotted both for an integration with $p_\perp > 0.1$ GeV/c and > 0.6 GeV/c. In both cases, and for all values of $E_\perp$, the values coincide within the error bars with those expected from hadronic sources within error bars.

b) The WA80 lead-glass spectrometer (SAPHIR)

The WA80 Collaboration has chosen finely granulated lead-glass calorimeters as a detector for photons. This technique is similar to most of the direct-photon experiments carried out at the ISR [Fer84].

The better acceptance, as compared to the slit spectrometer, allows the measurable $p_\perp$ range to be extended up to 2.5 GeV/c. However, the acceptance is not yet large enough to allow the measurement of η mesons over a sufficiently wide $p_\perp$ range. Thus, the systematic error of the estimated $\gamma_{\text{hadronic}}/\pi^0$ rate is also dominated by the lack of knowledge of η production [Alb91a, Dra89]. An advantage in measuring π^0 directly instead of charged pions is that some decay channels of hadrons (e.g. $\omega \rightarrow \pi^+\pi^-\pi^0$) are measured and do not have to be

included in the Monte Carlo calculations of the hadronic background. The systematic error amounts to 6–9%, depending on the particle density. The contribution of the statistical error is 6%. It should be noted, however, that these errors, different from Refs. [Åke90a, Bar89], are applied to individual $p_{\perp}$ bins and not to the integrated γ/π^0 ratio.

The other major source of systematic error is the uncertainty in the determination of the photon-detection efficiency, given by the probability of identifying a photon correctly as a neutral particle and the probability that no overlap with a nearby, unresolved shower has occurred. In the present experiment the efficiency drops from $\approx 90\%$ for peripheral (low multiplicity) to $\approx 30\%$ for central (high multiplicity) events.

Figure 4.56 a–d shows ratios $\gamma_{\text{observed}}/\pi^0$ for the reactions $p + C$, $p + Au$, $^{16}\text{O} + C$ and $^{16}\text{O} + Au$, as a function of $p_{\perp}$ for minimum-bias events [Alb91a]. The Monte Carlo estimate of the hadronic background $\gamma_{\text{hadronic}}/\pi^0$ is also shown as the hatched area. Both for the proton and the heavy-ion induced reaction no excess over the expected hadronic background is separable within the error. Figure 4.57 a and b shows the ratio for $^{16}\text{O} + Au$ for peripheral and central events, respectively. Again, the observed γ/π^0 agrees, within the error, with the hadronic background.

4.6.3. Summary

Table 4.8 summarizes the set-ups and results of the two experiments. Both experiments have consistently found, within their statistical and systematical errors ($\approx 15\%$), that there are no excess photons in the $p_{\perp}$ range investigated. Both experiments suffered from insufficient knowledge about the η meson production, and from the uncertainties involved in track finding (NA34) or shower identification (WA80). For the heavy-ion runs in 1990/91 the WA80 experiment has an improvement programme which aims at reducing the systematic error to a value $\leq 5\%$. This will be achieved by adding 2,500 more lead-glass modules, which will improve the acceptance for η mesons by a factor of 2 to 10, depending on the $p_{\perp}$ of the η s. In addition, intensive studies on the response of the lead-glass detector to hadron and lepton beams are being carried out, thus improving the shower recognition algorithms.

4.7. Dilepton Production

The theoretically predicted J/ψ suppression [Mat86] has been found experimentally and can be interpreted consistently as plasma signature [Sat90b]. However, competing non-plasma absorption and rescattering models describe the data equally well. Further systematic and high-statistic studies are required to differentiate between models.

4.7.1. J/ψ suppression

A J/ψ is formed in the hard scattering process by parton fusion $q\bar{q} \rightarrow c\bar{c}$, $gg \rightarrow c\bar{c}$ and by the decay (about 40% in pp collisions) of the χ_c . A theoretical prediction of J/ψ suppression by Matsui and Satz [Mat86], in the presence of a QGP, and its rapid experimental verification [Bus88b] via lepton-pair ($\mu^+\mu^-$) spectroscopy, promoted the spectroscopy of J/ψ 's to being one of the most promising tools to trace signals from the transient QGP state. Matsui and Satz

predicted that the J/ψ production should be suppressed in the presence of a QGP, the reason being a Debye screening of the $c\bar{c}$ binding potential by the freely-moving colour charges in the case of deconfinement. ϕ production has also been measured via the $\mu^+\mu^-$ decay channel. The ϕ , owing to its (hidden) strangeness content, has been predicted to be a possible QGP signature [Sho85]. Experimental results and theoretical interpretations are discussed in subsection 4.5.

The problem in showing an enhancement or a suppression of a signal is to find the corresponding non-enhanced or non-suppressed signals. The NA38 Collaboration has chosen to relate the J/ψ invariant mass peak to the underlying continuum:

$$S := \frac{J/\psi}{(\text{continuum})} \quad (4.35)$$

The underlying assumption, namely that the continuum is of the Drell–Yan type, and scales only with the number of hard collisions, i.e. with the number of projectile participants, is *a priori* not fully evident and has to be proven experimentally.

The calorimetric transverse energy, closely related to the energy density achieved in the reaction, is used as a scale for relating non-plasma (= peripheral) events to suspected plasma (= central) events. Figure 4.58 shows the invariant mass spectrum of dimuon pairs for two different selections of transverse energy for the reaction $^{32}\text{S} + \text{U}$ at 200 GeV/A [Son88, Bag89, Bag90, Var91]. A marked change of the J/ψ to continuum ratio is exhibited when comparing events with low transverse energy ($E_\perp < 51$ MeV) and high transverse energy ($E_\perp < 125$ MeV). The ratio S , according to Eq. (4.35) is shown in Fig. 4.59 for the reactions $\text{O} + \text{U}$, $\text{S} + \text{U}$, and $\text{O} + \text{Cu}$, at 200 GeV/A beam energy. For the heavier systems, S changes by a factor of 2 by going from low to high $E_\perp$. Assuming that the energy densities depend on $dE_\perp/d\eta$ via the hydrodynamic energy density relation of Bjorken [Bjo83], the ratio S scales with ϵ , consistent with the conjecture of J/ψ suppression for central, i.e. plasma, events. The figure also contains estimates for $p + \text{U}$ and pp reactions.

We now come back to the question whether a *continuum enhancement* could be responsible for the observed change in the ratio S . The most direct way to give evidence for a normally behaving, e.g. Drell–Yan continuum, would be to show that the production cross-section for continuum events scales with the number of projectile nucleons. This procedure, however, relies on the proper relative normalization of p-, O- and S-induced reactions. Indirect evidence for a 'normal' behaviour of the continuum is suggested by the Fig. 4.60 a and b [Bag90]. Both the $\langle p_\perp \rangle$ and $\langle p_\perp^2 \rangle$ distribution of the continuums are flat with increasing $E_\perp$, while they do not increase in the J/ψ region. The latter observation would indicate that the J/ψ is depleted predominantly in the low $p_\perp$.

In an intuitively evident picture, Blaizot and Ollitrault [Bla87], Karsch and Petronzina [Kar87, Kar88], and also Chu and Matsui [Chu88], have proposed the $p_\perp$ -dependence of the J/ψ yield or of the ratio S being a further signature of J/ψ suppression. The $c\bar{c}$ pair is created close together very early on in the collision in a hard scattering process, at a time $\tau \sim \hbar/2m_c \approx 0.07$ fm/c, where m_c is the charm-quark mass. In order to form a J/ψ the $c\bar{c}$ pair has to separate to the J/ψ binding radius $r_{J/\psi} \approx 0.45$ fm. In a frame where the longitudinal momentum is zero, the time to form the $c\bar{c}$ resonant state is Lorentz-dilated by a factor $[1+(p_\perp/M)^2]^{1/2}$. $c\bar{c}$ pairs of high $p_\perp$ are thus created outside of plasma region, and are not

therefore subjected to screening. In this picture the J/ψ suppression should be maximal at low $p_{\perp}$ and decrease for higher transverse momenta of the J/ψ .

A corresponding behaviour has been found in the data samples: Fig. 4.61 shows the ratio R defined as the J/ψ -to-continuum-ratio at the highest $E_{\perp}$ bin normalized to the same ratio at the lowest $E_{\perp}$ bin as a function of the $p_{\perp}$ of the J/ψ :

$$R := \frac{dN^{J/\psi}/dp_{\perp} \Big|^{E_{\perp};\text{high}}}{dN^{\text{cont}}/dp_{\perp} \Big|^{E_{\perp};\text{high}}} \Bigg/ \frac{dN^{J/\psi}/dp_{\perp} \Big|^{E_{\perp};\text{low}}}{dN^{\text{cont}}/dp_{\perp} \Big|^{E_{\perp};\text{low}}} \quad (4.36)$$

It can be seen that the ratio R increases for the reaction $^{16}\text{O} + \text{U}$ by more than a factor of 2 when comparing J/ψ production at low and high $p_{\perp}$, respectively. The increase for $^{32}\text{S} + \text{U}$ is of the order of 50%. The solid curves are calculations and will be discussed below.

a) Hadroproduction of the J/ψ in hA reactions

Before discussing model-dependent explanations of the experimental observations further, it is instructive to compare the heavy-ion induced reactions with those from hadron–nucleus reactions. Figure 4.62 shows the ratio of J/ψ production for heavy target to deuterium as obtained from 800 GeV proton induced reactions on a different nuclear target by the E772 Collaboration at Fermilab [Mos91]. As the mass of the target increases the ratio decreases by roughly 40%. The insert shows the dimuon mass spectrum. Figure 4.63 displays a compilation of NA3 and E537 data of the $p_{\perp}$ dependence of J/ψ production for different targets. It shows the ratio of $\sigma_{J/\psi}/\text{nucleon}$ of 126 GeV π^{-} on W and Be (150 GeV/c on Pt and H_2 for the NA3 experiment). Both sets of data consistently give an increasing ratio with increasing $p_{\perp}$ of the J/ψ . Both the A and the $p_{\perp}$ dependence of J/ψ hadroproduction is not completely understood [Kat88, Wag89]: it is discussed in terms of hadronic absorption of the J/ψ [And77, Sok86, Kna75, Got69], incident particle effects [Far75, Mic81, Krz79, Bod81, Chi87] or modification of the nucleon structure function in nuclei [Duk84]. For a more complete discussion of an explanatory scheme of the experimental phenomena see, for example, [Wag89, Bla89d].

The hadron–nucleus experimental results indicate that 'conventional', i.e. non-plasma explanations of the J/ψ suppression, cannot be excluded without further detailed investigations. However, a straightforward extrapolation of hadron–nucleus to nucleus–nucleus data is hampered by the comparably large experimental error bars and the inherent theoretical difficulties of such an extrapolation [Bla89d]. For instance, it is not completely evident how to obtain an $E_{\perp}$ dependence from such an extrapolation. We will, nevertheless, in the next section, sketch some of the models which attempt to explain the experimental phenomena on the basis of 'conventional physics', i.e. by extending the knowledge from hadron–nucleus collisions to nucleus–nucleus collisions.

b) Non-plasma models of J/ψ suppression

It is quite conceivable that at an early stage, when the $c\bar{c}$ pair is not yet a J/ψ , it might be destroyed by inelastic collisions with the surrounding matter. At later stages of the reaction the

J/ψ might encounter pions or hadronic resonances and undergo reactions like $\pi + J/\psi \rightarrow D\bar{D} + X$. Several authors [Fta88, Gav88, Vog88, Bla89a, Bla89b, Bla89c] have estimated the amount of J/ψ suppression due to these absorption mechanisms.

The absorption model estimates a survival probability $P = e^{-N}$, where N is the number of final-state collisions. N depends on the (not observable) absorption cross-section $\sigma_{hJ/\psi}$, the initial rapidity density of hadrons dN_h/dy , the expansion velocity of the hadron gas, and the time the $c\bar{c}$ needs to reach its binding radius. The latter condition implies that only collisions of the J/ψ after a formation time τ_ψ are considered, but not those of preformed $c\bar{c}$ clusters.

These models are capable of reproducing the $E_\perp$ dependence of the J/ψ suppression; they fail, however, to reproduce the dependence on $p_\perp$. The addition of initial-state interactions leads to a satisfactory description of the data. The NA10 Collaboration observed that the average $p_\perp^2$ of Drell–Yan muon pairs with mass $> 4 \text{ GeV}/c^2$ is increased when comparing heavy and light targets [Bre87]. Since the muons have no strong interaction, this has been associated with initial elastic scattering of the quark and antiquark in proportion to the path length they travel through the nucleus, before they annihilate in order to produce a $\mu^+\mu^-$ pair. For the case of J/ψ formation a similar initial gluon scattering before a $c\bar{c}$ pair is formed was expected. This was indeed found by the NA3 Collaboration [Bad83] studying the J/ψ production in $p + H$ and $p + Pt$ interactions at 150–280 GeV/c. In Fig. 4.61 the solid curves show the result of an absorption calculation including initial gluon scattering by Hüfner et al. [Hüf88], confronted with the NA38 data for $O + U$ and $S + U$ and 200 GeV/A. It can be seen that a satisfactory description is achieved under these assumptions.

A general criticism of all absorption models is that they have to assume a high initial hadron density in order to have sufficient absorption. The use of $N_0 \approx 4 \text{ hadrons}/\text{fm}^3$ (which has to be compared with $\approx 0.15 \text{ nucleons}/\text{fm}$ for normal nuclear matter) leads, to the conceptual difficulty of how a pion can remain a pion at such a high density.

4.7.2. Summary

The experimental data are in agreement with mutually exclusive models: QGP models on the one hand and absorption models, including initial state interactions, on the other. Both models require high energy densities ($\approx 2 \text{ GeV}/\text{fm}^3$): in the case of the plasma model, leading to an equilibrated system of freely-moving quarks and gluons; in the case of the absorption model, leading to an extremely dense hadron gas. The QGP leads to a (collective) Debye screening of the J/ψ binding potential; in the absorption models the J/ψ is destroyed by individual, incoherent collisions of the J/ψ with hadrons.

The present accuracy of both the data and the models does not allow further distinction between the models. On the experimental side, better statistics are necessary both for hadron–nucleus, as well as for nucleus–nucleus data. Nucleus–nucleus data at lower bombarding energies would be desirable because one would expect an 'onset' of J/ψ suppression at bombarding energies leading to energy densities which allow plasma formation; a persistence of J/ψ suppression at low bombarding energies would rule out plasma models.

5. Conclusions and Outlook

An impressive amount of data has been collected and analysed during 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 pp collision + geometry') to extremely optimistic ('clear signals of the QGP') views. By now, the field is becoming mature, the data are consolidating, and more balanced interpretations are emerging. No convincing evidence for the creation of a QGP at present energies and with the (light) heavy ions available to date, has been found. Nevertheless, a number of important milestones have been passed which established some necessary prerequisites vital for the study of dense and strongly-interacting matter by means of heavy ion collisions.

- *Energy density:* The study of global event features ($E_{\perp}$ and particle 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 been optimistically expected; indeed, the energy density in the present experiments might already be close or even above the threshold predicted for QGP formation. There is no 'nuclear transparency', and the (still scarce) data on baryon distributions even point towards a larger stopping (deceleration of nucleons in nuclear matter) than had been anticipated. The refined analyses of global-event characteristics, going beyond the important but trivial influence of nuclear geometry, is now leading towards a better understanding of the dynamics of the underlying nucleon–nucleon collisions.
- *Size and lifetime:* The transverse size of the reaction zone at freeze-out, as measured by pion interferometry, is increasing by almost a factor of 2 from the initial size at mid-rapidity; this is possible only in an expanding system with a 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 , could be marginal. On the experimental side, more and better interferometric data are needed to actually measure the lifetime of the rapidly expanding system, and on the theoretical side, the characteristic time scales ('relaxation times') of the different phases and processes have to be estimated.
- *Equilibrium:* The question of equilibrium and applicability of (QCD) thermodynamics remains somewhat ambiguous so far. The interpretation of transverse–momentum spectra, which ideally would measure the temperature of a system in thermal equilibrium, is aggravated by a number of complications: hard and semi-hard scattering (perturbative QCD), soft initial-state scattering of partons, (non-equilibrium) final-state rescattering of hadrons, resonance decays, phase-space effects, and, last but not least, lack of a thorough understanding of $p_{\perp}$ spectra already in pp reactions. Nevertheless, the significant nuclear effects which have been observed (e.g. the low- and high- $p_{\perp}$ enhancements), and in particular their systematic variations (rapidity, c.m. energy, target,

projectile, particle type) should provide sufficient constraints to unravel the various contributions and disclose the interesting collective parameters (temperature, pressure, flow, etc.). Likewise, the interpretation of particle ratios, which indicate the degree of chemical equilibrium attained in the collision, is hampered by the dynamical evolution from the (possible) QGP state through the phase transition and the unavoidable hadron gas phase. These transitions could, in general, dilute the strangeness content of the matter and readjust the particle ratios towards the respective equilibrium values at the various stages (which is indeed the very definition of a system evolving in equilibrium). A large increase in strange particle production (more than a factor of 2 compared to pp) is indeed seen in several channels (K, Δ , Ξ , ϕ , and antiparticles), but its importance in terms of chemical equilibrium and QGP is still being debated for the above-mentioned reasons. However, the sheer presence of significant differences in the inclusive spectra (both in $p_{\perp}$ distributions and particle ratios) between pp and nucleus–nucleus reactions excludes a trivial superposition scenario. It implies again at least the presence of dense and strongly interacting matter which, by means of rescattering between its constituents, must evolve towards equilibrium distributions. A final quantitative interpretation of the data, and in particular a search for surviving signals from the QGP, will depend to a large extent on a better understanding of the hadronization scenario and on the time scales and relaxation times available in the various phases.

- *Sensitive signals:* From the number of experimental observables which 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. Concerning photons, the experimental accuracy achieved at present ($\gamma/\pi^0 < 10\text{--}15\%$) is not expected to be sensitive to the thermal radiation of a QGP in the reactions studied so far. J/ψ suppression, on the other hand, has been observed with the characteristics predicted for a QGP. Debye screening in the plasma has, for some time, been the only explanation, which could, with reasonable assumptions, describe the particular $E_{\perp}$ - and $p_{\perp}$ -dependent suppression pattern. To date, taking into account new results for J/ψ and Drell–Yan production in pA reactions, it seems likely that a combination of initial-state parton scattering and final-state absorption in the dense reaction zone are sufficient to explain the nucleus–nucleus data. A full 'spectral analysis', comparing different charmonium and bottonium states in a number of projectile–target combinations, should eventually be able to distinguish between competing suppression mechanisms.

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, which 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 seem indeed an appropriate and promising tool to create and study 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. As was predicted by Van Hove in 1987 [VHo87], at the last Quark Matter Conference before experimental data were actually available, it does require a systematic and comprehensive search for deviations from theoretical expectations or from smooth extrapolations of existing pp and pA data. Only if several such anomalies are found in different observables, which 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. As summarized

above, a number of such 'anomalies' have indeed been observed, but conventional theoretical models have been improved from a (partially 'naïve') 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.

By now, the 'exploratory' phase in the still very young field of ultra-relativistic heavy-ion collisions can be considered essentially completed. Falling short of striking discoveries, it has nevertheless provided a 'principle proof of feasibility' and even substantiated the expectations that with the next generation of experimentation we should reach a new and uncharted territory. Based on our current understanding of the data, the upcoming experiments with really heavy ions at BNL in 1992 and at CERN in 1994 should lead to baryon 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 and independently help in driving the system further towards equilibrium, whether or not its internal degrees of freedom are of hadronic or partonic nature.

By the end of the century, a different regime of low-baryon-density matter will be accessible at the RHIC and LHC colliders. 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 $100,000 \text{ fm}^3$, and an initial energy density 50 to 100 times larger than that of normal nuclear matter. Even if for some reason no equilibrated QGP should be 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 ($\gg 10$ pions per cubic femtometer). 'New physics' of one kind or another seems therefore bound to appear somewhere along the road towards the quark gluon plasma.

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Table 3.1
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/A]	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)	$(10^9) \approx 10^{31}$	$(10^7) \approx 2 \times 10^{28}$	$(10^9) \approx 7 \times 10^{30}$	$(3 \times 10^8) \approx 4 \times 10^{29}$	$2 \times 10^{26} - 10^{27}$	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 large new	4-6 large	2-3 large	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 per burst (number in brackets), assuming a 10% interaction length target for A-A collisions and correcting for the duty cycle.

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

(5) Number of experiments at AGS/SPS shown separately for large, small and completed experiments.

Table 3.2

Coverage for global measurements by the NA34, NA35, WA80, E802, and E814 experiments

Expt.	Forward energy	Transverse energy	Charged particles
NA34	No	$-0.1 \leq \eta \leq 5.9$ (hadronic/e.m.)	$0.9 \leq \eta \leq 5.0$ (silicon pad detector)
NA35	$\vartheta \leq 0.3$ (calorimeter)	$2.2 \leq \eta \leq 3.8$ (hadronic/e.m.)	$0.5 \leq \eta$ (streamer chamber)
WA80	$\vartheta \leq 0.3^\circ$ (calorimeter)	$2.4 \leq \eta \leq 5.5$ (hadronic/e.m.)	$-1.7 \leq \eta \leq 4.4$ (streamer tube pad detector & plastic ball)
E802	$\vartheta \leq 0.4^\circ - 0.8^\circ$ (calorimeter)	$1.2 \leq \eta \leq 3.0$ (e.m.)	$-1.2 \leq \eta \leq 3.0$ (streamer tube pad detector)
E814	$\vartheta \leq 0.8^\circ$ (calorimeter/ spectrometer)	$-2.0 \leq \eta \leq -0.9$ $-0.5 \leq \eta \leq 0.8$ $1.3 \leq \eta \leq 4.0$	$1.3 \leq \eta \leq 4.0$ (silicon pad detector)

Table 3.3
Specific probes for heavy-ion reactions

Expt.	Detector	Acceptance	Signal
NA34	Slit spectrometer	$0.9 \leq \eta \leq 2.0$	$dN/dp_{\perp}$ (p, π, K, γ), thermal photons, strangeness (K/π)
	Dilepton spectrometer	$3.5 \leq \eta$ $p_{\mu}^{lab} > 5 \text{ GeV}/c$	$M_{\mu\mu} \leq 1 \text{ GeV}$
NA35	Streamer chamber	$0.5 \leq \eta \leq 4.5$	$dN/dp_{\perp}$ ($\pi^- K_S^0, \Lambda$) HBT($\pi^-\pi^-$), strangeness ($\Lambda/\bar{\Lambda}$)
WA80	Lead-glass spectrometer	$0.4 \leq p_{\perp} \leq 3 \text{ GeV}/c$ $1.5 \leq \eta \leq 2.1$ $\Delta\phi/\phi \approx 17\%$	$dN/dp_{\perp}$ (π^0, γ, η) thermal photons
	Plastic ball spectrometer	$0.2 \leq E_{kin} \leq 300 \text{ MeV}$ $-1.7 \leq \eta \leq 1.3$	$dN/dp_{\perp}$ (p, d, t, π^+) target fragmentation, HBT($\pi^+\pi^+$)
NA36	TPC	$y \geq 2.6$ (π) $y \geq 0.8$ (Ω)	$dN/dp_{\perp}$ ($K_S^0, \Lambda, \Xi^?, \Omega^?$) strangeness
NA38	Dilepton spectrometer	$2.8 \leq \eta \leq 4.0$	$M_{\mu\mu} \geq 0.5 \text{ GeV}$ J/Ψ -continuum ratio, $\phi/(\rho+\omega)$
WA85	Ω -magnet spectrometer	$p_{\perp} > 0.6 \text{ GeV}/c$ $2.2 \leq \eta \leq 3.2$	$dN/dp_{\perp}$ (K_S^0, Λ, Ξ) strangeness ($\Lambda/\bar{\Lambda}, \Xi/\bar{\Xi}$)
NA44 (1991)	focusing spectrometer	Small, ≤ 2 particles	$dN/dp_{\perp}$ (π, K, p) HBT ($\pi\pi, KK, pp$)
NA45 (1991)	Di-electron spectrometer	$1.9 < y < 2.8$ $M_{e^+e^-} \geq 100 \text{ MeV}/c^2$	$M_{e^+e^-}$ thermal dileptons
E802	Rotatable single-arm spectrometer	$25 \text{ msr}, 0.6 \leq \eta \leq 3.1$ $PID < 4.7 \text{ GeV}/c$	$dN/dp_{\perp}$ (π, K, p, d, t) strangeness (K/π), HBT ($\pi\pi$)
E810	TPC chambers	$2.0 \leq \eta \leq 6.0$	$dN/dp_{\perp}$ ($K_S^0, \Lambda, \Xi^?, \Omega^?$) strangeness
E814	Forward magnetic calorimetric spectrometer	$\eta > 5.0$	$dN/dp_{\perp}$ (p, n)

Table 4.1
Average transverse energies for 60 (a) and 200 (b) GeV/A bombarding energy
(The values are given in GeV).

a) For 60 GeV/A bombarding energy				
Target	η	Cu	Ag	Au
$\langle E_t \rangle$	$[-1.7, 0.6]$	3.1 ± 0.5	5.0 ± 0.7	7.8 ± 1.1
$\langle E_t^\pi \rangle$	$[-1.7, 0.6]$	2.3 ± 0.4	3.5 ± 0.5	5.0 ± 0.7
$\langle E_t^{\text{baryon}} \rangle$	$[-1.7, 0.6]$	0.8 ± 0.1	1.5 ± 0.2	2.8 ± 0.4

b) For 200 GeV/A bombarding energy				
Target	η	Cu	Ag	Au
$\langle E_t \rangle$	$[-1.7, 0.6]$	3.4 ± 0.5	5.3 ± 0.8	9.1 ± 1.4
$\langle E_t^\pi \rangle$	$[-1.7, 0.6]$	2.6 ± 0.4	3.8 ± 0.6	5.9 ± 0.9
$\langle E_t^{\text{baryon}} \rangle$	$[-1.7, 0.6]$	0.8 ± 0.1	1.5 ± 0.2	3.2 ± 0.5

Table 4.2
Pion source parameters extracted from a Gaussian fit for different rapidity intervals

	$R_\perp$ (fm)	R_L (fm)	λ
$1 < y < 4$	4.1 ± 0.4	$3.1 + 0.7$ $- 0.4$	$0.31 + 0.07$ $- 0.03$
$1 < y < 2$	4.3 ± 0.6	2.6 ± 0.6	$0.34 + 0.09$ $- 0.06$
$2 < y < 3$	8.1 ± 1.6	$5.6 + 1.2$ $- 0.8$	0.77 ± 0.19
$3 < y < 4.5$	$4.3 + 1.3$ $- 0.8$	5.8 ± 2.2	0.55 ± 0.20

Table 4.3
Pion source parameters extracted from a Gaussian fit for different targets and signs of the pion pairs

	$R_\perp$ (fm)	R_L (fm)	λ
Si+Au $\rightarrow 2\pi^-$ +X	4.3 ± 0.2	2.6 ± 0.3	0.86 ± 0.06
Si+Au $\rightarrow 2\pi^+$ +X	3.3 ± 0.4	3.4 ± 0.4	0.55 ± 0.07
Si+Al $\rightarrow 2\pi^-$ +X	3.5 ± 0.2	2.9 ± 0.3	0.95 ± 0.07
Si+Al $\rightarrow 2\pi^+$ +X	3.4 ± 0.4	3.2 ± 0.8	0.70 ± 0.14

Table 4.4

Pion source parameters extracted from a Gaussian fit for different rapidity intervals and targets and for a central trigger

	$-1 \leq y \leq 1$	
	R_{inv} (fm)	λ_{inv}
Au	2.38 ± 0.08	0.085 ± 0.007
Ag	3.45 ± 0.15	0.17 ± 0.04
Cu	3.33 ± 0.15	0.17 ± 0.04

Table 4.5

K/ π ratios from the E802 experiment [Abb90, Abb91] at the AGS

	p+Be	p+Au	Central Si+Au
K^+/π^+	$7.8 \pm 0.4\%$	$12.5 \pm 0.6\%$	$18.2 \pm 0.9\%$
K^-/π^-	$2.0 \pm 0.2\%$	$2.8 \pm 0.3\%$	$3.2 \pm 0.3\%$

Table 4.6

Neutral strange particles ratios from the NA35 experiment [Bam89, Bam90]

	h^-	Λ/h^-	$\bar{\Lambda}/h^-$	K_s^0/h^-
Central S+S / pp	36 ± 1.5	2.4 ± 0.2	3.2 ± 0.9	1.8 ± 0.4

Table 4.7

Strange baryon ratios from the WA85 experiment [Aba90, Eva91, Nar91, Aba91]

	$m_{\perp} > 1.72 \text{ GeV}$	$1 < p_{\perp} < 2 \text{ GeV}/c$
$\bar{\Lambda}/\Lambda$	0.13 ± 0.03	0.13 ± 0.03
Ξ^-/Ξ^-	0.39 ± 0.07	0.39 ± 0.07
Ξ^-/Λ	0.20 ± 0.04	0.11 ± 0.02
$\Xi^-/\bar{\Lambda}$	0.60 ± 0.20	0.33 ± 0.11

Table 4.8

Comparison of the NA34 (HELIOS) and the WA80 experiment
with respect to direct photon detection

	NA34	WA80
Detector	Converter + spectrometer	Lead glass
η range	$1.0 \leq \eta \leq 1.9$	$1.5 \leq \eta \leq 2.1$
ϕ coverage	0.75%–2.1%	17%
$p_{\perp}$ range	$0.1 \leq p_{\perp} \leq 1.5$	$0.4 \leq p_{\perp} \leq 2.5$
Reactions	p + W, ^{16}O + W, ^{32}S + W/Pt	p + C/Au, ^{16}O + C,Au
Energy	200 GeV/A	60, 200 GeV/A
γ/π^0 signal	Hadronic w/i error	Hadronic w/i error

Figure Captions

- Fig. 1.1 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 supernovae explosions, Big Bang evolution, and possibly in heavy-ion reactions at present and future accelerators.
- Fig. 2.1 The energy density ε and the pressure $3P$, normalized to the ideal Boltzmann gas limit, according to lattice QCD calculations (from (Got87a)).
- Fig. 2.2 Presence and absence of the finite-temperature QCD phase transition as a function of $m_{u,d}a$ and $m_{s,a}$. Mass values for which a transition is, and is not seen, on a $16^3 \times 4$ lattice are denoted respectively by solid circles and squares. The physical point, indicated roughly by the open circle, lies in the region of no transition (from [Bro90b]).
- Fig. 2.3 Schematic representation of a heavy-ion collision at impact parameter b , assuming 'clean cut' geometry.
- Fig. 2.4 A collision of two large nuclei $A + B$ in a space-time diagram. Here the two nuclei collide along the light-cone trajectories marked A and B. Particles are produced in the region of the forward light cone. The various stages of the expanding matter at various times are indicated in the figure.
- Fig. 2.5 'Longitudinal excitation' (a,b) requires all partons in a string to originate from one baryon, whereas 'colour exchange' (c,d) provides strings with partons from different baryons (from [Wer90]).
- Fig. 3.1 Total centre-of-mass energy of various heavy-ion reactions as a function of time (note the log-log scale on the ordinate!).
- Fig. 3.2 Experimental set-up of the NA34 Collaboration.
- Fig. 3.3 Experimental set-up of the NA35 Collaboration.
- Fig. 3.4 Experimental set-up of the NA36 Collaboration.
- Fig. 3.5 Experimental set-up of the NA38 Collaboration.
- Fig. 3.6 Experimental set-up of the WA80 Collaboration.
- Fig. 3.7 Experimental set-up of the WA85 Collaboration.
- Fig. 3.8 Experimental set-up of the E802 Collaboration.
- Fig. 3.9 Experimental set-up of the E810 Collaboration.
- Fig. 3.10 Experimental set-up of the E814 Collaboration.
- Fig. 4.1 Compilation of inelastic cross-sections in heavy-ion collisions from Ref. [And89]. The full line corresponds to a geometrical parametrization (see text).
- Fig. 4.2 Cross-section measurements $d\sigma/dE_{\perp}$ and $d\sigma/dN_{ch}$ for different reactions. Projectiles, targets, beam energy, and the acceptance in pseudorapidity η of the various experiments are indicated in the figures; the data are from a) E802 [Vid90], b) WA80 [Sor88, Alb87], and c) NA34 [Sch89b, Åke90b].
- Fig. 4.3 Fit to the $E_{\perp}$ cross-section from NA34 (O+W, 200 GeV/A, $E_{\perp}$ in $-0.1 < \eta < 2.9$) with a geometrical parametrization based on a convolution of independent nucleon-nucleon collisions [Åke88]. Within this model, the number NN of nucleon-nucleon collisions, of projectile participants N_p , and the impact parameter b corresponding to a given $E_{\perp}$, are extracted and shown as separate scales. The axis labelled σ indicates the fraction (in per cent) of the total

geometrical cross-section below a given $E_{\perp}$. The collision geometry corresponding to the 'neck' (1), 'plateau' (2), and 'central' (3) regions in the cross-section are schematically drawn below.

- Fig. 4.4 Correlation between the transverse energy $E_{\perp}$ in $2.4 < \eta < 5.5$, and the forward energy E_{ZDC} , measured in a zero-degree-calorimeter ($\eta > 6$) [Sor88, Alb87].
- Fig. 4.5 $E_{\perp}$ per charged particle in $2 < \eta < 4.2$ as a function of the energy in the forward direction divided by the beam energy. Peripheral collisions are at $E_{ZDC} \approx E(\text{beam})$, central collisions at $E_{ZDC} \approx 0$ [Lun88, Alb88b]. The shaded area indicates the trend observed by NA34 in $0.9 < \eta < 2.9$ [Sch88b, Åke90c] for collisions with increasing centrality.
- Fig. 4.6 Plot of $\log(N_{\text{target spectators}})$ against $\log(E_{\perp})$ for the $E_{\perp}$ carried by pions (open circles), and by baryons (filled circles). The lines are fits to the data and α represents the exponent of $E_{\perp} \propto N^{\alpha}$. The targets are Al, Ag, and W in (a), and Cl, Cu, and Au for (b).
- Fig. 4.7 Pseudorapidity distribution $dN_{\text{ch}}/d\eta$ in central O + emulsion interactions [Hol87]. The solid line corresponds to a calculation with the Monte Carlo code FRITIOF.
- Fig. 4.8 Negative particle rapidity distribution for O + Au interactions at 60 and 200 GeV/A. TET(130) and FET(56) refer to trigger requirements (essentially central collisions) [Str88].
- Fig. 4.9 Charged-particle pseudorapidity distribution $dN_{\text{ch}}/d\eta$ [Lun88, Alb88b]. The dashed line is a calculation with the Monte Carlo code FRITIOF; the full line corresponds to O + AgBr (emulsion) central collisions from Fig. 4.7. It is downscaled by 30% to the same height as the data of [Lun88, Alb88b]
- Fig. 4.10 Charged-particle pseudorapidity distribution $dN_{\text{ch}}/d\eta$ for three different windows in $E_{\perp}$ ($-0.1 < \eta < 2.9$) in O+nucleus reactions at 200 GeV/A [Sch88b, Åke90c]. The lines indicate predictions from the IRIS Monte Carlo.
- Fig. 4.11 Charged-particle pseudorapidity distribution in 14.6 GeV/A central Si-nucleus collisions. The full lines are the data for the Au target scaled by 47/79, 29/79, and 13/79, respectively. [Vid90].
- Fig. 4.12 Rapidity distribution of protons as obtained with the subtraction method discussed in the text. The black circles are data, the open circles are obtained from reflection symmetry at y_{cm} . The histograms are predictions from VENUS and the RQMD model, respectively ([Str89b, Sor91b, Wen90])
- Fig. 4.13 Yield of baryons as a function of the pseudorapidity η . The histogram represents the data, the circles and crosses show a calculation within Ranft's MCFM, assuming a formation zone parameter τ_0 of 5 and 10 fm/c, respectively (from [Alb90b]).
- Fig. 4.14 The angular distribution of grey prongs in ^{16}O + emulsion interactions. a) A comparison between the experimental results, using the FRITIOF and the Ranft model with $\tau_0 = 5$ fm/c at 200 GeV/A. b) A comparison between the experimental samples at 200, 60, and 14.5 GeV/A, and a result (solid line) from Otterlund et al. [Ott78]. c) a comparison between central and peripheral events. In this case the three energies, 200, 60, and 14.6 GeV/A are summed up to increase the statistics (from [Ada89]).
- Fig. 4.15 The target dependence of the charged-particle pseudorapidity distribution, parametrized as $dN_{\text{ch}}/d\eta \propto A^{\alpha}$, in different regions of η . The dependence is extracted from ^{16}O on Cu, Ag, and Au targets at 60 and 200 GeV/A [Lun88, Alb88b]. The A-dependence of $dE_{\perp}/d\eta$ reported by NA34 in $-0.1 < \eta < 2.9$ [Åke88], and NA35 in $2.2 < \eta < 4.0$ [Str88], show a similar pattern η . The shape of $dN_{\text{ch}}/d\eta$ is shown as a dashed line for orientation.
- Fig. 4.16 a) $\langle p_{\perp} \rangle$ for JACEE events; b) schematic plot $p_{\perp}$ -energy density from Salmeron.
- Fig. 4.17 Compilation of cross-sections as a function of transverse mass (from [Cra78]).

- Fig. 4.18 Different functions commonly used to fit $p_{\perp}$ distributions, all normalized with respect to each other at $p_{\perp} = 1$ GeV/c. The dashed line corresponds to a thermal distribution in a fixed (narrow) rapidity bin; it should be used to check the thermal nature of spectra because all other approximations deviate substantially at low $p_{\perp}$.
- Fig. 4.19 The momentum distribution of the pion and the nucleon coming from the decay $\Delta \rightarrow \pi + N$ when the Δ had a thermal (Boltzmann) distribution with a temperature of $T = 0.15$ GeV (from Ref. [Hag83]). Whereas the nucleon retains most of the original momentum the decay pion is very soft with an apparent temperature of $T \approx 0.09$ GeV.
- Fig. 4.20 Average transverse momentum as a function of rapidity for a) π^- in 16 GeV/c π^+p reactions [Bos73] and b) negative particles in pp reactions [Bre88] at $\sqrt{s} = 62$ GeV. At the lower energy $\langle p_{\perp} \rangle$ is nowhere independent of y , and also at the higher energy $\langle p_{\perp} \rangle$ starts to decrease from its maximum value at $y_{cm} = 0$, about 2 units away from the end of phase space.
- Fig. 4.21 Negative particle distribution from NA34 [Åke90a] for central collisions of p, O, S, (a, b, c) with a W target. Central reactions are selected by a cut on $E_{\perp} > 10, 60, \text{ and } 80$ GeV, respectively. For comparison, a parametrization of p + p data (see text) is shown as a full line.
- Fig. 4.22 Ratios of $p_{\perp}$ distributions from different reactions [Åke90a, Alb90a, Pei90a] (arbitrary relative normalizations). From top to bottom: proton–nucleus to proton–proton, nucleus–nucleus to proton–nucleus, nucleus–nucleus to nucleus–nucleus.
- Fig. 4.23 Ratios of $p_{\perp}$ distributions in A–A collisions to those in p + p [Åke90a, Str88, Str90b]. The S + S/p + p data from NA35 are connected by a dotted line for clarity. The rapidity dependence in O–W(Au), going from $\langle y \rangle = 2.5$ (NA35 full triangles) to $\langle y \rangle = 1.5$ (NA34 open circles), is much weaker at high than at low $p_{\perp}$.
- Fig. 4.24 Mass dependence of transverse-momentum distributions [Åke90a, Dre89] (see text). The full curve, which is the same in both plots, is a fit to the target dependence of the 'Cronin' exponent $\alpha(p_{\perp})$ of the p–A data [Cro75, Ant79, Klu77, Gar77, Cha79] in the upper part. The projectile dependence, extracted in the lower part from the ratios S + W/p + W and O + W/p + W, shows a similar functional form.
- Fig. 4.25 Average $p_{\perp}$ of negative particles as a function of $E_{\perp}$ in $-0.1 < \eta < 2.9$ from NA34 [Åke90a]. The mean value is determined from a fit to the data in $0.4 < p_{\perp} < 2.0$ GeV/c, assuming an exponential shape in the full range.
- Fig. 4.26 Average $p_{\perp}$ of photons calculated from the truncated distribution with $p_{\perp}(y) > 400$ MeV/c, as a function of entropy density from WA80. The entropy is estimated from the charged-particle multiplicity and the number of projectile participants A_{INC} as inferred from the energy flow in the forward direction (for more details, see refs. [Pur90, Alb88a]).
- Fig. 4.27 Ratio of $p_{\perp}$ spectra in S + W [Åke90a] in different regions of $E_{\perp}$. Central collisions ($180 < E_{\perp} < 240$ GeV) are used for reference and all spectra are normalized to unity.
- Fig. 4.28 Ratio of π^0 $p_{\perp}$ -distributions from central to peripheral collisions (both normalized to unity) in O + Au reactions ($y = 1.5\text{--}2.1$) from WA80 [Alb90a, Pei90a].
- Fig. 4.29 $p_{\perp}$ distribution of negative particles in O + Au reactions from NA35 [Str88, Str90b] at different rapidities. The spectra, approximately normalized to each other at $p_{\perp} > 0.4$ GeV/c, show a strong increase in the low- $p_{\perp}$ part with decreasing rapidity.
- Fig. 4.30 The data of Fig. 4.21 (h^- , $y = 1\text{--}1.9$ in S+W) as non-invariant cross-sections $dN/dp_{\perp}$ on a linear scale. The full line is a fit to the data with the sum of two exponentials $\exp^{-p_{\perp}/T}$. The soft component (dotted line) has an inverse slope $T \approx 0.05$ GeV and contributes almost 40%

to the experimentally-measured number of particles; the harder component (dashed line) has $T \approx 0.18$ GeV.

- Fig. 4.31 Ratio of transverse-momentum spectra of negative particles (from Ref. [Str88, Str90b]) from S + S over p + p (full circles). Also shown is the comparison of high to low multiplicity at 200 GeV (open circles), 'violent' to standard 'Double-Pomeron' events (open squares), $\sqrt{s} = 63$ to $\sqrt{s} = 31$ GeV p + p data (solid line), and high to low multiplicity (full squares) at $\sqrt{s} = 1.8$ TeV.
- Fig. 4.32 Inverse slope constants T_0 ; fitted with $\exp^{-p_{\perp}/T}$ to the transverse-mass spectra of various particles in p + Be, p + Au, and Si + Au reactions at 14.6 GeV/A. E802 data [Abb90, Mia91, Ste90, Cos91] are measured in $y = 0.9-1.7$ for $\bar{p}$, and in $y = 1.2-1.4$, otherwise E810 [Lov91, Eis91] in $y = 2.2-3$ (K^0) and $y = 1.2-3$ (Λ).
- Fig. 4.33 Transverse-mass distributions (note the unusual ordinate!) of negative particles (labelled π^-) K^0 , Λ and 'protons' (pos.-neg. charges) from NA35 [Har89, Ren89, Ody89, Pug89]. Reaction type and rapidity acceptances are given in the figure, and the full lines indicate an inverse slope of 200 MeV.
- Fig. 4.34 Transverse-mass distributions of identified particles in S+W ($y = 0.8-1.3$) from NA34 [VHe91].
- Fig. 4.35 Inverse slope constants T_0 fitted with $\exp^{-p_{\perp}/T}$ to the transverse-mass spectra of various particles in p+A and A+A reactions at 200 GeV/A. Data are from NA34 [VHe91], NA35 [Har89, Ren89, Ody89, Pug89, Der89, Bar90c], and WA85 [WA85LAM].
- Fig. 4.36 Global fit with a thermal model [Lee90] including radial collective flow to the data of NA35 [Har89, Ren89, Ody89, Pug89]. The various particle spectra are normalized to each other at $m_{\perp} = m$.
- Fig. 4.37 Experimental correlation function projected onto the $Q_{\perp}$ axis (for pairs with $Q_{\parallel} < 100$ MeV/c) for different rapidity intervals: a) $1 < y < 4$, b) $1 < y < 2$, and c) $2 < y < 3$. d) This represents FRITIOF calculations in the interval $2 < y < 3$. The projected Gaussian fit is shown (solid curve) for each case, and in a) the dashed curve shows the fit to the non-Gamov-corrected correlation function (from [Bam88]).
- Fig. 4.38 Experimental π^- correlation functions as a function of $q_{\perp}$ for the reactions $^{28}\text{Si} + \text{Al}$, Au at 14.6 GeV/A beam energy. The solid lines are Gaussian fits (from [Mor90]).
- Fig. 4.39 Systematic compilation of transverse source radii obtained at mid-rapidity in hadron-hadron and in relativistic nucleus-nucleus collisions. The data are plotted against charged-particle rapidity density at mid-rapidity. Hadron data are from the AFS, SMF, E802, and NA35 Collaborations (from [Sto90]). The solid and dashed curves are explained in the text.
- Fig. 4.40 Experimental π^+ correlation functions as a function of Q for central collisions measured in $-1 \leq y_{\text{lab}} \leq 1$. a) $^{16}\text{O} + \text{C}$, b) $^{16}\text{O} + \text{Cu}$, c) $^{16}\text{O} + \text{Ag}$, and d) $^{16}\text{O} + \text{Au}$ (from [Pei91]). The solid lines are Gaussian, the dashed lines are exponential fits. The dotted and dash dotted lines represent multi-parameter Ansätze for the correlation function.
- Fig. 4.41 Values of L_2 as a function of $\langle n \rangle$ [see Eq. (4.4.2)], and of L_3 as a function of $\langle n \rangle^3$, [see Eq. (4.30)]. Straight-line fits represent the result of a fit to the experimental data (from [Åke90b]).
- Fig. 4.42 The normalized variance Ω [see Eq. (4.31)] as a function of $\Delta\eta$ for central $^{16}\text{O} + \text{Au}$ interactions at 200 GeV/A for a) experimental data, and b) the FRITIOF sample. The histograms correspond to the calculations from Eq. (4.32), normalized at $\Delta\eta = 1.0$ (from [Alb89b]).

- Fig. 4.43 Scaled factorial moments for $^{32}\text{S} + \text{Au}$ interactions using the 'horizontal' (inclusive) analysis in the window $1.32 < \eta < 5.0$. The second, third, and fifth moments are shown, together with corresponding results from FRITIOF. The magnitudes from FRITIOF moments differ from those of the data owing to a slightly different multiplicity distribution within the pseudorapidity window $\Delta\eta$.
- Fig. 4.44 a) Comparison of the normalized slopes $\xi_i = 2\phi_i/i(i-1)$ as a function of the order of the moment obtained for 60 and 200 GeV/A bombarding energy by the EMU07 and EMU08 experiments. b) Normalized slopes for central 200 GeV/A $^{16}\text{O} + \text{Em}$ collisions from the EMU01, EMU08, and EMU-NA34 experiments. c) The same as (b) for $^{32}\text{S} + \text{Em}$.
- Fig. 4.45 Slopes of second order as a function of the average particle density for different systems and centrality cuts. The dash-dotted lines show fits for which ϕ_2 are proportional to $1/\langle\rho\rangle$ for the oxygen and silicon samples and for the sulfur samples. The dashed line is an extrapolation to the hadron-nucleus region (from [Ada90b]).
- Fig. 4.46 Invariant transverse kinetic energy distributions of identified particles in Si+Au reactions at 14.6 GeV/A. The dashed lines are fits with an exponential ($e^{-m_\perp/T_0}$) distribution with inverse slopes as indicated in the figure. The solid lines corresponds to a Boltzmann fit ($m_\perp e^{-m_\perp/T_0}$).
- Fig. 4.47 Rapidity distributions dn/dy for pion, kaons, and protons in p + Be, p + Au, and central Si + Au collisions at 14.6 GeV/A [Abb90, Abb91]. The Si+Au data are divided by 28 for comparison. The nucleon-nucleon (y_{NN}) and the participant (y_{part}) centre-of-mass rapidity are indicated by arrows.
- Fig. 4.48 K/π ratio for positive and negative particles as a function of $p_\perp$ for S + W (a), and p + W (b), reactions at 200 GeV/A [VHe91]. The error bars represent the statistical and the total (statistical + systematic) uncertainty. The dotted lines are K/π ratios as extrapolated from pp reactions to the relevant rapidity region, with a systematic error as indicated by the error bar on right.
- Fig. 4.49 Ratio of the mean multiplicities of Λ , K_S^0 , and $\bar{\Lambda}$ observed in the NA35 acceptance to the total negative particle multiplicity $\langle h^- \rangle$ as a function of the event multiplicity. Also shown are pp data (open circles), p + S minimum-bias (open squares), and the FRITIOF prediction (dashed line)
- Fig. 4.50 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 4.2 are drawn to guide the eye [Aba90, Eva91, Nar91, Aba91].
- Fig. 4.51 The $\phi/\rho_0 + \omega$ ratio from O and S + U reactions, normalized to the one measured in p + U collisions, as a function of the normalized transverse energy. The solid curves are calculations described in the text (from [Koc90]).
- Fig. 4.52 Feynman graphs representing direct photon production: a) quark-antiquark annihilation; b) quark-gluon-Compton scattering.
- Fig. 4.53 Transverse-momentum distributions of thermal photons in central $^{16}\text{O} + \text{W}$, and Pb + Pb at mid-rapidity. The hadronic backgrounds (dashed) and the yield of hard direct photons from primary parton collisions (dash-dotted) are also shown. A critical temperature $T_c = 200$ MeV is assumed (from [Neu89]).
- Fig. 4.54 Transverse-momentum distributions of photons for a) p+W at 200 GeV, $E_\perp < 200$ GeV in $-0.1 < \eta < 2.9$; b) $^{16}\text{O} + \text{W}$ at 200 GeV/A, $E_\perp > 60$ GeV in $-0.1 < \eta < 2.9$; c) $^{32}\text{S} + \text{W}$ at 200 GeV/A, $E_\perp > 80$ GeV in $-0.1 < \eta < 2.9$ (from [Åke90a])
- Fig. 4.55 Ratio of all photons relative to π^0 's measured over the integrated $p_\perp$ range > 100 MeV/c or 600 MeV/c as a function of $\langle E_\perp \rangle$ in $-0.1 < \eta < 2.9$. The full line represents the expected

ratio from hadronic decays only; the dotted line gives the uncertainty of this expectation (from [Åke90a]).

- Fig. 4.56 Ratio of the inclusive photon to the π^0 cross-section as a function of transverse momentum for 200 GeV p+C, 200 GeV p + Au, 200 AGeV ^{16}O + Au, and 60 GeV/A ^{16}O + Au events under minimum-bias trigger conditions. The squares indicate the data, and the shaded histograms are the Monte Carlo results representing hadronic decays (from [Alb91a]).
- Fig. 4.57 Ratio of inclusive photon to π^0 cross-section as a function of transverse momentum for central and peripheral 200 GeV/A ^{16}O + Au reactions. The squares indicate the data and the shaded histograms are the Monte Carlo results representing hadronic decays (from [Alb91a]).
- Fig. 4.58 Dimuon mass spectra observed in S+U collisions for low- and high- $E_\perp$. The solid lines represent fits to the data. The areas which were used to calculate the ratio S from Eq. (4.35) are shaded (from Son88).
- Fig. 4.59 J/Ψ to continuum ratio versus Bjorken's energy density ϵ (from [Son88]).
- Fig. 4.60 (a) $\langle p_\perp \rangle$, and (b) $\langle p_\perp^2 \rangle$ dependence of the J/Ψ , and the continuum as a function of the neutral transverse energy $E_\perp^0$ for O + U events at 200 GeV/A (from [Bag90]).
- Fig. 4.61 $p_\perp$ dependence of ratio R as defined in Eq. 4.7.2 for O+U (a) and S+U (b) reactions. The solid curves are calculations by Hüfner et al., described in the text (from [Abr89, Hüf88]).
- Fig. 4.62 The ratios of heavy nucleus to deuterium integrated yields for the J/Ψ and Ψ' resonances and the Drell-Yan continuum. The insert shows the raw (no acceptance correction) dimuon invariant mass spectrum (from [Mos91]).
- Fig. 4.63 Light to heavy target ratio $\sigma_{J/\Psi}/\text{nucleon}$ for π -induced reactions (from [Wag89]).

Fig. 1.1

Fig. 2.1

Fig. 2.2

Fig. 2.3

Fig. 2.4

Fig. 2.5

Fig. 3.1

Fig. 3.2

Fig. 3.3

BG	Beam Geometry Counters	IGD	Intermediate Gamma Detector
BT, BV	Si Beam Tag, Beam Veto	INC	Intermediate Neutral Calorimeter
Tg	Targets	FČ	Forward Čerenkov
U ₁ , U ₂ , U ₃ , W ₂	MWPC's	FGD	Forward Gamma Detector
D ₁ -D ₆	Drift Chambers	FNC	Forward Neutral Calorimeter
H ₁ , H ₂	Hodoscopes		
M ₁ , M ₂	Magnets

Fig. 3.4

Fig. 3.5

Fig. 3.6

Fig. 3.7

Fig. 3.8

Fig. 3.9

MPS E-810 Detectors
ZY

Fig. 3.10

Fig. 4.1

Fig. 4.2

Fig. 4.2

Fig. 4.3

200 A GeV $^{16}\text{O} + ^{197}\text{Au}$

Fig. 4.4

Fig. 4.5

Fig. 4.6

Fig. 4.7

Fig. 4.8

Fig. 4.9

Fig. 4.10

Fig. 4.11

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Fig. 4.37

Fig. 4.38

Fig. 4.39

O + C 200 A GeV

Fig. 4.40a

O + Cu 200 A GeV

Fig. 4.40b

O + Ag 200 A GeV

Fig. 4.40c

O + Au 200 A GeV

Fig. 4.40d

Fig. 4.41

Fig. 4.42

Fig. 4.43

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Fig. 4.61

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