

## Chapter 1

# Introduction

Relativistic heavy ion physics is a fascinating field. In a collision of two nuclei occurring at very high energy, whether in a fixed-target or in a collider mode, thousands of new particles are produced. Their identity and kinematical characteristics go beyond that what could be expected from a simple superposition of elementary nucleon-nucleon collisions, indicating the presence of some new phenomena.

Single events of high energy nuclear collisions were studied already in the 1950s in nuclear emulsions irradiated by cosmic rays in stratospheric balloon flights. It was found that the produced particles are strongly forward/backward collimated, with transverse momentum components limited to the values of the order of only a few hundred MeV/c. These early observations led to the notions of “multiple particle production”, and of “fireballs”, and stimulated new theoretical ideas. We shall limit ourselves to quote here just three papers of basic importance to this field.

Enrico Fermi [1] proposed a description of high energy hadronic (and nuclear) collisions in terms of the statistical thermal model, assuming a formation of a highly excited intermediate state, *a little fireball*, in which a thermal equilibration is reached, and the decay into final state particles follows the statistical rules.

Lev D. Landau [2] proposed a model in which the energy deposition in a small volume, of the size of the Lorentz-contracted nuclei, leads to the formation of a transient state which then undergoes a hydrodynamical expansion. While expanding, the system cools down until it reaches the freeze-out temperature  $T_f$ , being of the order of the pion mass, at which the formed hadrons become free particles.

Later, Rolf Hagedorn [3], while studying the mass spectrum of the then recently discovered numerous hadronic resonant states, made a conjecture

that a multi-hadron state should be described by thermodynamics with a limiting temperature. This temperature, now quoted as the *Hagedorn temperature*, turned out to be about 160 MeV, or again of the order of the pion mass.

Systematic experimental studies of collisions of relativistic nuclei in laboratory conditions began in the early 1970-ies, when at the Lawrence Laboratory in Berkeley, USA, and at the Joint Institute of Nuclear Research in Dubna, Russia, light nuclei were accelerated to energies of a few GeV per nucleon, using the old proton synchrotrons.

At the beginning, these experiments seemed not to promise anything exciting, but soon a hypothesis was formulated that at high temperatures and densities the hadronic matter should undergo a phase transition to a state of free quarks and gluons, called *the quark-gluon plasma* (QGP) [4–6]. In the following years the Quantum Chromodynamics (QCD) was developed as the theory of strong interactions, and calculations on the lattice (LQCD) led to more precise predictions. A phase diagram for the strongly interacting matter with the phase boundary between hadronic matter and quark-gluon plasma was drawn, and critical values of the temperature and density were determined to be  $T_c \cong (150\text{--}170)$  MeV, surprisingly close to the Hagedorn temperature, and  $\rho_c \cong (1\text{--}2)$  GeV/fm<sup>3</sup>, about ten times the matter density in nuclei. Conservative estimates show that such values could be reached in collisions of relativistic nuclei.

As quark-gluon plasma is believed to be the state of matter which existed for some microseconds after the Big Bang, collisions of relativistic heavy ions should recreate the conditions of the Early Universe. With this exciting hypothesis in mind, experiments with relativistic heavy ions became extremely interesting, and the program of accelerating heavy ions to much higher energies was launched at Brookhaven National Laboratory, USA, and at CERN, Geneva, Switzerland. At BNL ions were accelerated in the Alternating Gradient Synchrotron (AGS) to energies  $\sim 10$  GeV/nucleon, rather too low for the QGP search, but detectors and analysis methods suitable for studying multi-particle events were developed, and useful experience gained. At CERN ions were accelerated in the Super Proton Synchrotron (SPS) to energies ranging from 200 GeV/nucleon for light ions to 158 GeV/nucleon for those of lead. In the year 2000 the Relativistic Heavy Ion Collider RHIC was put into operation at BNL, increasing the effective collision energy (i.e. the energy in the centre-of-mass system) by another factor of ten.

Figure 1.1 shows a simplified picture of a central collision of two highly

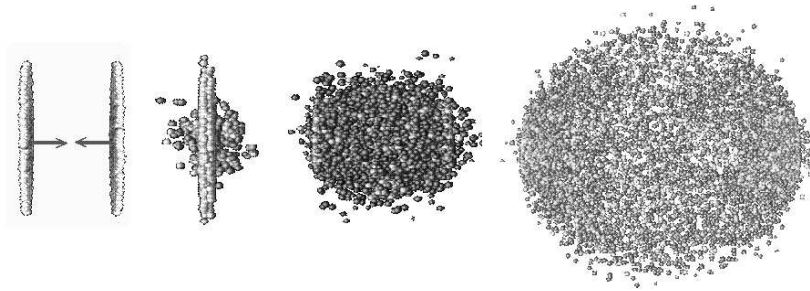


Fig. 1.1 Simplified picture of a central collision of two high energy nuclei in the centre-of-mass frame. Colliding nuclei appear as thin discs due to Lorentz contraction.

relativistic nuclei in the centre-of-mass reference frame. The colliding nuclei are Lorentz-contracted, and thus appear as thin discs. In the central region, where the energy density is the highest, a new state of matter — the quark-gluon plasma — is supposedly created. The plasma expands and cools down,<sup>a</sup> quarks combine into hadrons and their mutual interactions cease when the system reaches the *freeze-out temperature*. A multi-hadron final state is formed, and free hadrons move towards the detectors.

Figure 1.2 shows the space-time evolution of a collision process, plotted in the light-cone variables ( $z, t$ ). The two highly relativistic nuclei, identified in the Figure as “projectile” and “target”, move essentially along the light cone, until they collide in the centre of the diagram. Nuclear fragments emerge from the collision again along the (forward) light cone, while the matter between the fragmentation zones populates the central region. This hot and dense matter is believed to be in the state of QGP. Interactions within it bring the system into local statistical equilibrium, and its further evolution can be described by relativistic hydrodynamics.<sup>b</sup> The surfaces of constant proper time, delineating various stages of this evolution, are approximately hyperbolae in this representation, as shown in the figure. The hydrodynamic description of high energy nuclear collisions was developed in many subsequent papers [8–11], see also reviews [12, 13]. Dynamical particle producing reactions, described with dissipative and diffusion terms, have

<sup>a</sup>According to recent theoretical ideas, the system may pass through some intermediate states with different properties.

<sup>b</sup>The problem is that in order to reproduce correctly the experimental results, the hydrodynamic evolution should start at the time below 1 fm/c after the collision, what means a very short equilibration time [14, 15]. The hypothesis of an *instantaneous thermalization* was, however, discussed already more than 20 years ago — see *e.g.* Ref. [11].

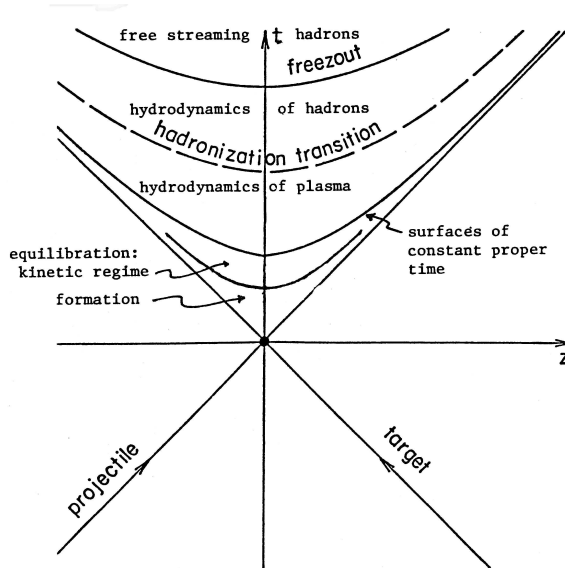


Fig. 1.2 Space-time evolution of a collision process of ultrarelativistic nuclei plotted in light-cone variables (from Ref. [7]).

been incorporated into relativistic hydrodynamics in Ref. [16], and the case of strangeness and/or heavy quarks has been discussed in Ref. [17].

Let us now try to estimate the energy density reached in relativistic heavy ion collisions. An estimate of the initial energy density is not straightforward: taking that of a Lorentz-contracted nuclei leads to unreasonably high values, and the so-called *Bjorken formula* is being used for this purpose. Bjorken [8] developed a rapidity-independent version of the Landau's hydrodynamical model in which the created transverse energy density,  $dE_T/dy$ , is related to the initial energy density,  $\epsilon$ , by the formula

$$\epsilon = \frac{1}{\tau_f S} \frac{dE_T}{dy} \cong \frac{3}{2} \frac{\langle m_T \rangle}{\tau_f S} \frac{dN_{\text{ch}}}{dy} \quad (1.1)$$

where  $\tau_f$  is the *formation time*, conventionally taken to be  $\tau_f = 1 \text{ fm}/c$ ,<sup>c</sup>  $S$  is the transverse overlap area of the colliding nuclei (for a central collision of two identical nuclei of radius  $R$  this is simply  $S = \pi R^2$ ),  $\langle m_T \rangle$  is the

<sup>c</sup>It should be pointed out that this choice of the formation time is arbitrary. Intuitively, the formation time should be at least as long as the "crossing time" of the colliding nuclei, what means  $\tau_f \geq 2R/\gamma$  where  $\gamma$  is the Lorentz factor of the colliding nuclei. For  $\tau_f = 1 \text{ fm}/c$  this condition becomes to be valid at SPS energies.

mean value of the transverse mass of secondary particles, and  $dN_{\text{ch}}/dy$  is the measured density of charged secondary particles per unit of rapidity. The approximate relation  $N \cong \frac{3}{2}N_{\text{ch}}$  is assumed. The values of the energy density obtained from this formula vary between the following limits

$$(2-3) \text{ GeV/fm}^3 \leq \epsilon \leq (5-6) \text{ GeV/fm}^3 ,$$

the lower values corresponding to energies reached in the CERN SPS, and the higher ones to those of RHIC. Let us note that already the lower values exceed the critical density for the phase transition obtained from LQCD. This, together with the temperature  $T \approx 140$  MeV obtained from the secondary particle spectra, and with the observation of some other phenomena predicted by theorists as signatures of the phase transition, led CERN to announce in February 2000 the discovery of the quark-gluon plasma.

Investigations of collisions of relativistic heavy ions have been further carried out at RHIC. Some new features have been observed, in particular a substantial collective flow was found in the emission pattern of secondary hadrons, what means that the created hot and dense system is rather a liquid than a gas. This “liquid” has a small viscosity, its properties are close to those of the “perfect” liquid. The *quark number scaling*, observed when comparing the flow of different particle species, points towards a partonic intermediate state, and can be considered as a strong evidence for the quark-gluon plasma.

The Large Hadron Collider (LHC) which should come into operation at CERN in the nearest time, will offer possibilities for investigations of collisions of heavy ions (Pb+Pb) at much higher energies. One can expect a substantial increase of the created energy densities, perhaps up to 10 GeV/fm<sup>3</sup>, or even higher, and a longer lifetime of the created system.

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