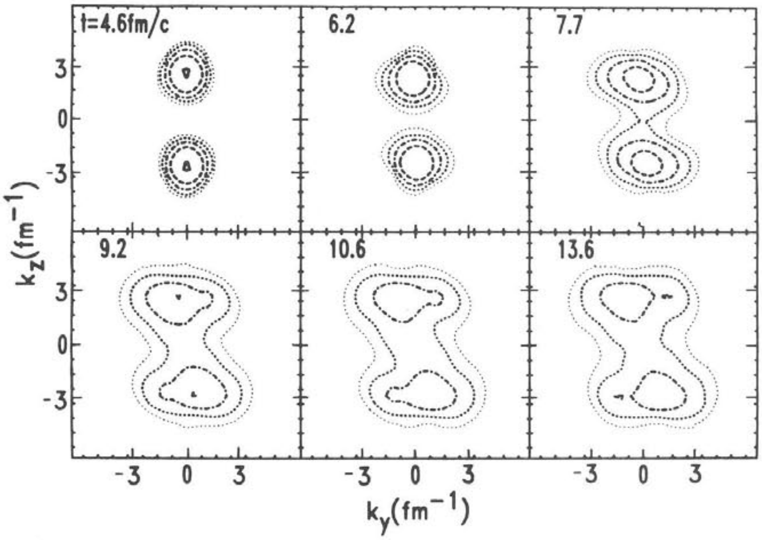

Fig. III.56. Momentum space density contours for the reaction ^{16}O (600 MeV/nucleon) + ^{16}O As obtained as a function of time from the solution of the time dependent Dirac equation (TDDE). The build-up of transverse momentum transfer is observed at $t > 7$ fm/c [Cus85].

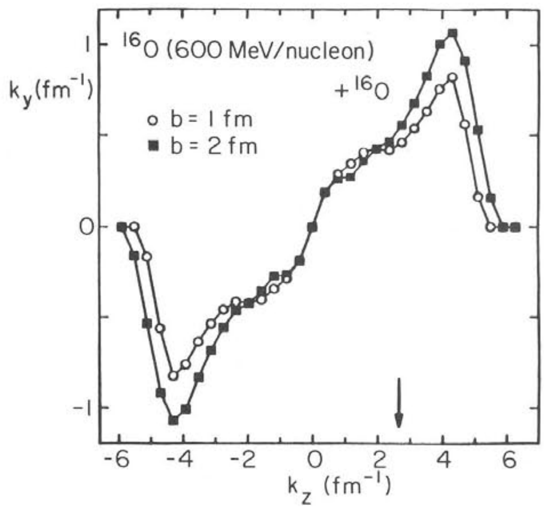

Fig. III.57. Projection of the in-plane transverse momentum per nucleon, k_y, versus the longitudinal momentum, k_z, as obtained from the TDDE approach [Cus85]. The results agree qualitatively with the data obtained by the GSI–LBL streamer chamber collaboration at higher energies and with more massive nuclei [Dan85].

IV. Creation of the quark-gluon plasma at ultra-relativistic energies – Space-time evolution of the high energy density region

The possibility of creating an entirely new form of matter, the deconfined quark-gluon plasma, in the laboratory has spurred a tremendous activity, both theoretical and experimental, in the high energy and nuclear community during the last few years [QM79, QM80, QM82, QM83, QM84, see also Cle85]. We have developed some of the statistical concepts frequently used in the theoretical description of this state in chapter I.

Here we will not consider the transition itself, but we will discuss the space-time evolution of the high energy density matter in ultra-relativistic heavy ion collisions, where the relativistic fluid description is used as a dynamical model. The foregoing chapters have presented evidence for hydrodynamical behavior at energies up to $E_{\rm Lab} = 4$ GeV/N. In the following we assume [Stö84] that hydrodynamics is also valid at higher energies, $E_{\rm Lab} > 4$ GeV/N. This extrapolation is questionable at very high energies, $E_{\rm Lab} > 100$ GeV/N, because of the longitudinal growth which may lead to the 'transparency' predicted by the inside out cascade [Nik81, Pok75, Gyu83]. The minimal requirements on beam energy and -mass are discussed in the following section.

Energy densities on the order of 1–2 GeV/fm^3 are predicted to be necessary for the deconfinement transition to occur. This number is derived from SU(N) Yang Mills theory (pure gluon matter) on the lattice [Eng82]. However, the idealized configuration of a zero net baryon number (zero chemical potential) plasma may be difficult to attain, even in the mid-rapidity region of collisions with $E_{\rm Lab} > 100$ GeV/N, since nuclei seem to be not as transparent as once thought [Bus83, Kaj83]. Thus it probably is necessary to study a baryon rich plasma. This may, in fact, prove very interesting, since it may be reachable at considerably lower energies [Stö84].

Whence the plasma is created, there is the additional problem of detecting it experimentally. Possible signatures of a quark-gluon plasma include enhanced production of lepton pairs [Dom81, Kaj81, Kaj82], influences on the photon spectrum [Kaj81, 82], and the relative abundance of strange particles [Raf82, Koc83, Elz84, Ka83, Bir82, Rat82]. Recently antinuclei have been proposed as a signature for the phase transition [Hei84, Mol84, Sub85]: The abundance of antiquarks in the quark-gluon plasma can favor the formation of antinuclei as compared to the – energetically less favorable – formation in the normal hadronic phase.

Let us first look at the simplified one dimensional hydrodynamical model with subsequent isentropic expansion. It can be used to study the maximum density and temperature obtained at a given energy [Stö80]. Results on the time evolution of the system are obtained using full 3-dimensional hydrodynamics.

Figure IV.1 shows the result of the simplified 1-D hydrodynamic calculations of the energy densities attainable in central collisions of heavy nuclei. Observe that the energy density obtained depends on the equation of state (EOS) used in the calculation. The different types of EOS used include a Hagedorn hadron gas with an exponentially increasing mass spectrum and a deconfined quark-gluon plasma. The different EOS lead to prediction of a regime of bombarding energies at which the 'critical' energy densities $e = 1$–2 GeV/fm^3, may be reached: $E^{\rm crit}_{\rm Lab} = 4$–$7$ GeV/N, values surprisingly modest compared to the values $E_{\rm Lab} > 100$ GeV/N generally believed to be necessary to form the baryon-free plasma. The one dimensional calculations give only the initial energy densities in the collisions. The system will subsequently expand as a result of the high pressure build-up. Hence the matter is accelerated, the density diminished and, because of energy conservation, the internal energy and temperature drop.

The dynamical path of a collision in the ρ–T plane, the phase diagram of hadronic matter, is depicted in fig. IV.2. The initial stage of high compression and excitation is followed by the isentropic expansion of the system. The matter cools only modestly during the dense stage where baryon densities exceed normal nuclear density. At densities below normal density, the system is cooled much more rapidly due to the formation of pions. Also shown in the figure are contours of constant energy densities of 1 and 1.5 GeV/fm^3 of the deconfined phase. Observe that according to this simplified calculation bombarding energies $E_{\rm Lab} > 2$–4 GeV/N should be sufficient for deconfinement to occur in stopping collisions. If deconfinement actually would occur at these rather modest energies, the energy gap

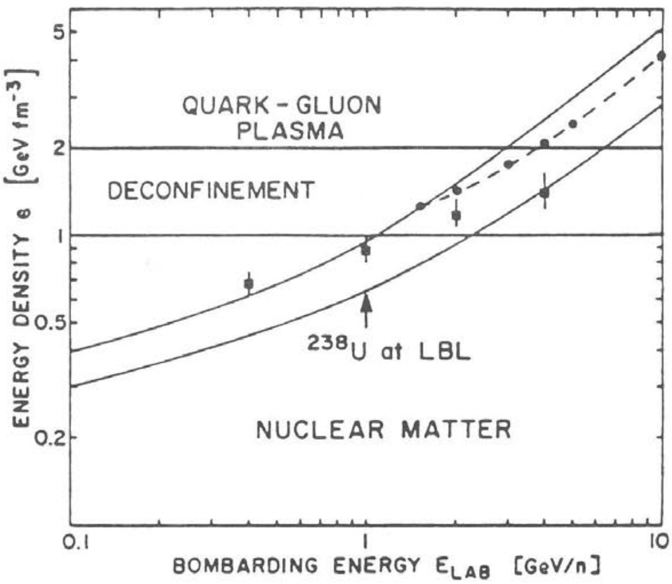

Fig. IV.1. The energy density obtained from the simplified 1-D hydrodynamic model is shown vs. the bombarding energy. Three different equations of state are used: Hagedorn gas, $K = 100$ MeV (upper curve), nucleon Fermi gas, $K = 300$ MeV (lower curve), and deconfined plasma of quarks and gluons (dash-dotted) [Stö84].

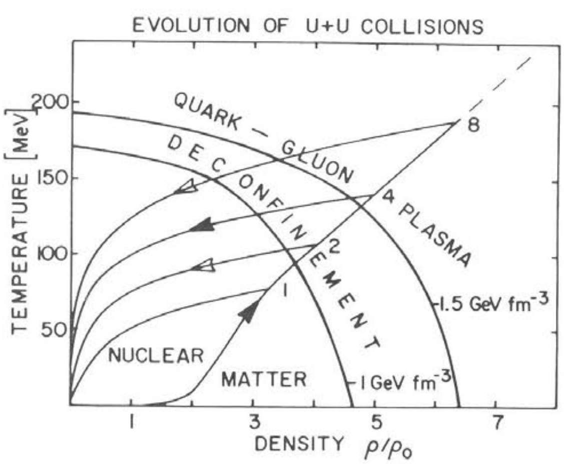

Fig. IV. 2. Dynamical path of nuclear collisions in the ρ–T diagram as obtained in the hydrodynamical model. Arrows indicate compression (towards right) and subsequent expansion (to left) at $E_{\rm Lab} = 1, 2, 4$ and 8 GeV/N for hadron matter. Critical energy density contours ($e = 1$ and 1.5 GeV fm^{-3}) of the plasma phase are also shown, indicating that the latent heat necessary for deconfinement may be achievable in the high baryon density region at laboratory bombarding energies in the 10 GeV/nucleon range [Stö84].

between confined and deconfined matter would result in temperatures and entropies substantially lower than those calculated under the assumption that confinement does not happen. The nuclear matter entropy exceeds 4 at $E_{\rm Lab} > 2$ GeV/N. The plasma entropy, on the other hand, is zero at the critical energy, $E_{\rm crit} = 2.2$ and 4.2 GeV/N for $\Lambda_{\rm VAC} = 190$ and 450 MeV/fm^3, respectively, necessary to overcome the energy gap between the hadron and the quark-gluon phase (see fig. IV.3). This mechanism of 'cold' plasma production has been emphasized before [Stö80c, Guy83, Bir83, Stö84].

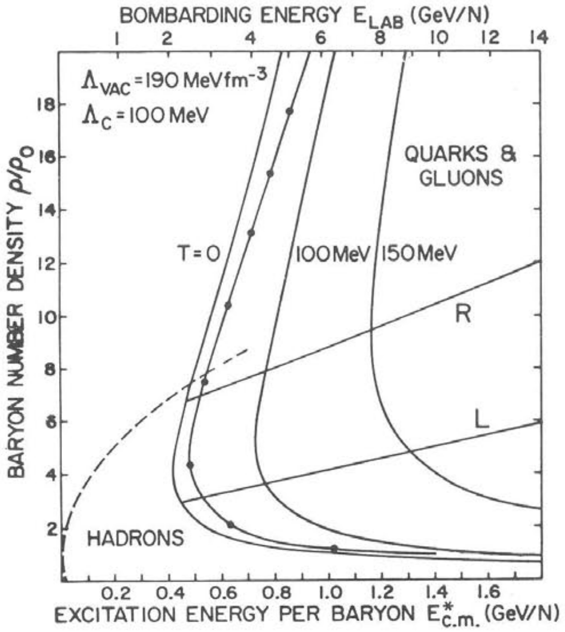

Fig. IV.3. The excitation energy per baryon needed to form the deconfined phase is plotted versus the baryon density ρ/ρ_0 for $\Lambda_{VAC} = 190$ MeV fm^{-3} and $\Lambda_{MOM} = 100$ MeV and $T = 0, 100, 150$ MeV. The dotted line gives the $O(\alpha^2 \ln \alpha)$ result for $T = 0$. The dashed line indicates normal nuclear matter. The lines labelled R and L represent the result of a combustion [Stö84] and fireball calculation of quark matter formation, respectively. The incident energy for these is given on the top of the figure [Stö84].

It should be noted that none of the discussed possible experimental signatures for the deconfinement transition (dilepton [Dom81], photon [Kaj81] and strangeness [Koc83] production) would necessarily make sense in this baryon rich region: These signatures rely on the very high temperatures predicted for the baryon free plasma, while the temperatures in the baryon rich plasma are much lower, even at the same energy density.

Let us now study the question of timescales and spatial size of the region of high energy density. Three dimensional relativistic hydrodynamical calculations have been done at high energies by Graebner et al. [Gra84]. The system Ne + Pb at energies of 5, 10 and 15 GeV/N is of particular interest as it will be studied in the near future (1986–87) at the upgraded alternating gradient synchroton (AGS) at BNL, Brookhaven and at the SPS at CERN.

Two equations of state have been considered in the fluid calculations, namely the linear and quadratic cases discussed in chapters I and III. The 'harder' quadratic EOS corresponds to the form deduced by Stock et al. [Sto82] from the excess pions produced in cascade calculations. In both cases the hadron gas thermal energy discussed in chapter I is used to describe the thermal behavior.

Figure IV.4 shows the number of nucleons contained in an energy density regime above a given threshold value, e_{crit}, as a function of the proper time in the rest system of the high energy density matter. The dependence of the bombarding energy ($E_{Lab} = 5$, 10, 15 GeV/N) and on the (linear and quadratic) EOS are shown. For example, there are >30 nucleons above the critical energy density $e_{crit} = 2$ GeV/fm^3 for a period of ca. 4 fm/c at 15 GeV with the linear EOS (fig. IV.4, right).

Figure IV.5 indicates the reduction of $A(e_{crit})$ with impact parameter for $e_{crit} = 2$ GeV/fm^3. The stiffer quadratic EOS shown on the left of fig. IV.4 results in a more rapid evolution: here a significant number of nucleons is in the $e > 2$ GeV/fm^3 region for only ca. 2 fm/c.

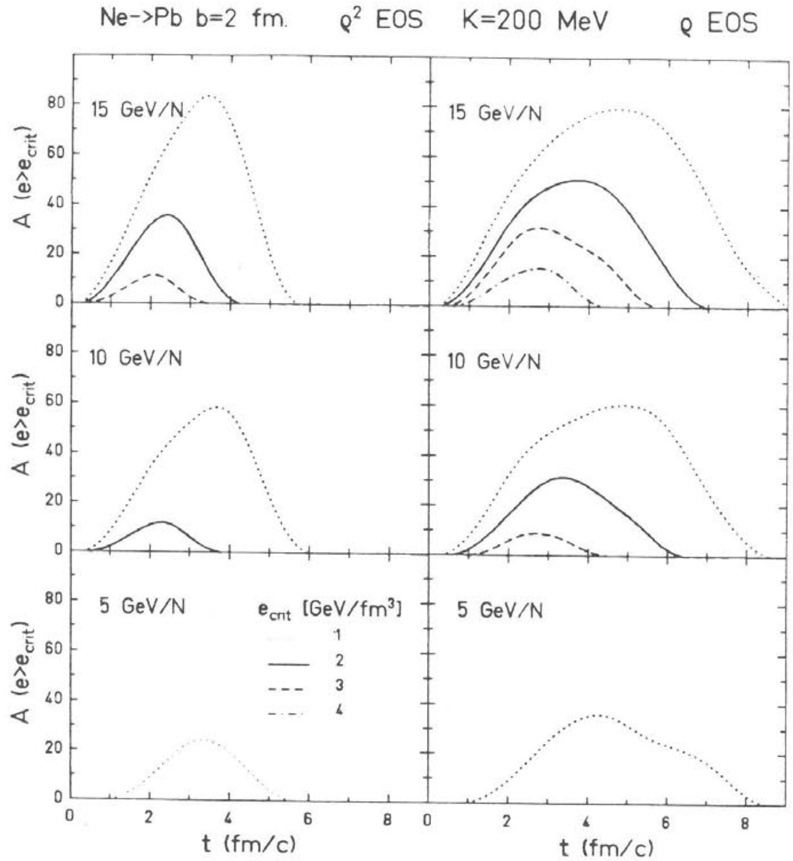

Fig. IV.4. The number of baryons in the region of high energy densities exceeding 1 (dotted line), 2 (solid line) and 3 GeV fm^{-3} (dashed line) as calculated for the system Ne + Pb with the relativistic fluid dynamical model is shown for various bombarding energies for a soft (right) and a stiff (left) nuclear equation of state [Gra84].

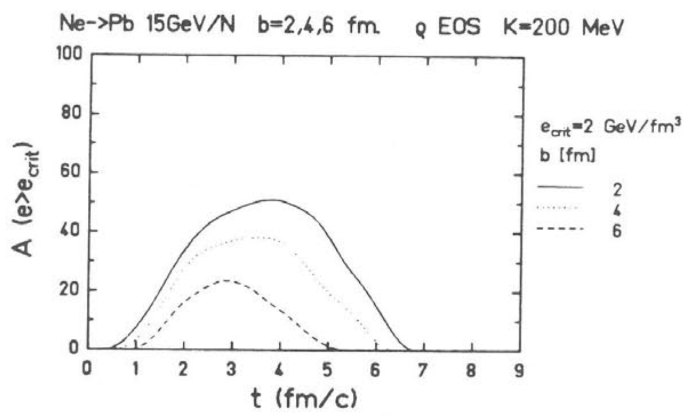

Fig. IV.5. The impact parameter dependence of the number of baryons in the high energy density region ($e > 2$ GeV fm^{-3}) for the reaction Ne (15 GeV/nucleon) + Pb as obtained in the relativistic one fluid model [Gra84] with the soft EOS.

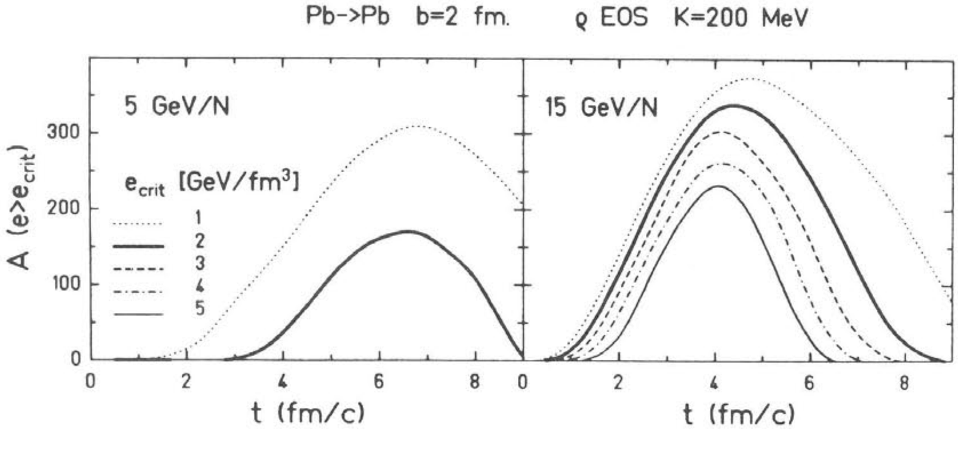

Fig. IV.6. Same as fig. IV.5, but for the system Pb + Pb. Observe the order of magnitude increase in $A(e > 2\ \mathrm{GeV\ fm}^{-3})$, even at $E_{\mathrm{Lab}} = 5$ GeV/nucleon. Also the duration of the stage of high energy density as well as the absolute magnitude of $e^{\max}$ are greatly enhanced whence the massive Pb projectile is used instead of the light Ne nucleus [Gra84].

Note that we have not examined the transition per se to the deconfined quark-gluon phase, but only the necessary condition for its occurrence: a large volume filled with high energy density matter. The timescale for establishing the deconfinement transition itself to occur must be obtained from other considerations and then compared with the time for which the high energy zone exists. Only then can one decide if the phase transition can actually take place. Should the phase transition develop rapidly enough, it may exert an influence on the dynamics of the collision itself. This remains to be investigated.

Very important information is the dependence of the energy density attainable on the mass of the projectile: fig. IV.6 shows the energy density attained in a collision of two very massive nuclei, Pb + Pb at 5 and 15 GeV/N. We want to highlight the following points:

(a) First, the maximum energy density achievable is doubled by going to the heavy system: Energy densities above $5\ \mathrm{GeV\ fm}^{-3}$ are attainable for a large number of nucleons ($A > 200!$) and a considerably prolonged time span, $\tau \approx 3\ \mathrm{fm}/c$.

(b) The total number of baryons in the high energy density regime increases dramatically: 200–300 baryons rather than 30–50 are at $e > e_{\mathrm{crit}}$.

(c) Energy densities $E > 2\ \mathrm{GeV\ fm}^{-3}$ can be obtained for a large number of baryons and for a rather long period, $\tau \approx 5\ \mathrm{fm}/c$ at much lower bombarding energies, $E_{\mathrm{Lab}} < 5$ GeV/N, with the lead projectile, while there are no baryons in the high energy density regime, if the light neon projectile is used.

Therefore, it seems to be extremely promising to study collisions of massive nuclei at comparatively moderate bombarding energies (e.g. Pb + Pb at $E_{\mathrm{Lab}} \approx 5$ GeV/N) rather than reactions at higher energies, but with light projectiles (e.g. Ne + Pb at 15 GeV/N). This should be considered for the plans of future experimental facilities: It is easier to compress a fluid with a piston than with a pin.

Conclusions

We have reviewed the exciting recent progress made in the understanding of the fundamental physics of relativistic heavy ion collisions. A wealth of new phenomena related to the bulk properties of nuclei and nuclear matter is being investigated. Heating of nuclear matter and shock compression, the key mechanisms for investigations of bulk properties of nuclear matter, have been observed, as predicted in 1974 [Sch74]. In particular one seems to have extracted first information on the equation of state of hot dense hadronic matter from recent data.

We presented the statistical concepts employed in the study of the properties of infinite hadronic systems at high density and finite temperatures, the equation of state and the conjectured phase transitions. The formalisms appropriate to describe the dynamical evolution of the highly excited strongly interacting system – nuclear fluid dynamics, the intra-nuclear cascade model, classical equation of motion simulations and the Vlasov–Uehling–Uhlenbeck theory – have been derived.

Recent 4π experiments on fragment formation, pion production and collective flow have been presented. Evidence for the same surprisingly stiff nuclear compression energy has been obtained independently from the distinct data sets by comparison to both macroscopic and microscopic theories.

We also discussed the possible creation of a deconfined quark-gluon plasma at future ultra-relativistic heavy ion facilities. Relativistic fluid dynamical calculations have been presented, which indicate that energy densities as high as several GeV/fm^3 may be attainable for considerable time spans in the bombarding energy range $E_{\mathrm{Lab}} = 5$–15 GeV/N. Thus it may indeed be possible to produce quark-gluon matter in the future BNL and CERN experiments. Uncertainties remain, however, in the transition mechanism and the possible detection of the quark-gluon plasma. The calculations suggest that massive projectiles can be used to explore the behavior of matter under extreme temperatures and densities that prevailed in the big bang, in neutron stars and in supernova explosions.

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