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Nuclear Matter from Nuclear Collisions

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The properties of nuclear matter at $T \leq 100$ MeV are discussed in the light of recent experimental data on nuclear collisions from a few tens AMeV up to a few AGeV incident energy.

1. INTRODUCTION

The understanding of the properties of nuclear matter over a wide range of temperature and density remains one of the most important challenges for nuclear physics. It is also one of the most difficult. Theoretically, the N-body quantum problem must be treated with a complex interaction: the strong interaction. Experimentally, the only way to produce hot and dense matter in the laboratory is by means of high energy nuclear collisions. The difficulty is then to extract the relevant observables from complex transient processes.

Ground state properties of nuclear matter are known for a rather long time: the equilibrium density ($\rho_0 = .17 \text{ fm}^{-3}$) and the binding energy per nucleon ($E_{bind} = -16 \text{ MeV/u}$) have been obtained from the ground state properties of atomic nuclei while the compression modulus (K) has been extracted from the study of the Giant Monopole Resonance (GMR) and is close to 220 MeV. However, the properties of the equation of state (EoS) over a broad range of temperatures (T) and densities (ρ) are far from being elucidated.

On the one hand, the nucleon-nucleon force exhibits a short range repulsive part and a long range attractive part and thus the behaviour of nuclear matter should present some analogies with a Van der Waals macroscopic fluid. Consequently, a liquid-gas transition is expected at a critical density around $\rho_0/3$ and $T \simeq 10 - 20 \text{ MeV}$. On the other hand, hadrons are made up of quarks and gluons. A transition from hadronic matter to a quark-gluon plasma is thus predicted by QCD at T_c around 150-160 MeV and/or $\rho_c \leq 5-10 \rho_0$ [1]. There is also a strong interest in the study of medium effects related to chiral symmetry restoration at high matter density. This would result in changes in the masses of hadrons as well as their decay and scattering properties [2].

The properties of nuclear matter are not only important for the understanding of the subatomic world but have also strong implications on the fate of astrophysical objects in the universe. The EoS is, for example, an essential ingredient in the description of the contraction of massive stars leading to supernovae explosion and neutron star formation [3].

Experimentally, the exploration of the EoS is made possible by producing hot and

compressed nuclear matter in violent nuclear collisions. Therefore, data of very good quality is a prerequisite to characterize quantitatively the system in terms of physical variables and reaction mechanisms. Considerable progress has been achieved in the recent years with the advent of a second generation of high quality multidetectors and with new developments in analysis techniques [4].

2. NUCLEAR COLLISIONS AND NUCLEAR TRANSPORT MODELS

2.1. Nuclear collisions from 20 MeV/u to a few GeV/u

At low incident energies (say less than 20 MeV/u) [5], the reaction mechanisms are essentially governed by the long range part of the nuclear force and hence by the mean field. The basic processes are fusion for the most central collisions and binary dissipative reactions for peripheral ones. As the incident energy increases, complete fusion cross sections slowly decrease as a consequence of the increasing inefficiency of the mean field to damp the relative motion of the two reaction partners. Thus, the dominant mechanism becomes binary dissipative processes.

However, recent studies have revealed the presence of emission of matter at mid-rapidity (i.e. at a velocity between that of the projectile-like and target-like fragments) [6]. Such processes have been attributed to either a strong deformation of the two partners in the exit channel or to the formation of neck-like structures indicating the onset of participant-spectator-like processes such as is observed at relativistic energies (see below). They are accompanied by the emission of fast pre-equilibrium nucleons and composite particles and also by the production (although with small cross sections) of mesons and hard photons [7]. In such reactions, fast thinning and stretching of the matter could induce sheet instabilities [8]. There is also some theoretical evidence for the production of neutron-rich matter [9] at mid-rapidity as confirmed by recent experimental results [10,11].

However, for the most central collisions corresponding to cross sections of a few tens of millibarns [12,13], matter is almost completely stopped leading to strong dissipation and thus to excitation energies close to or even larger than the total binding energy of the system [14]. These are collisions where a moderate compression/expansion phase is possible and where bulk instabilities can take place on time scales compatible with thermalization [15].

In the relativistic energy range [16,17], the dynamics are dominated by hadronic cascades with a strong stopping power of the matter due to the opening of the phase space and consequently the shortening of the mean free path. The reaction mechanism is then governed by geometrical concepts leading to the so-called participant-spectator picture, whereby nucleons which do not belong to the overlapping zone of the two nuclei do not suffer hard collisions and constitute the spectators while the others are the participants. In the participant zone, at such energies, a copious production of particles and resonances occurs and allows for the study of in-medium properties of hadrons. In addition, high compression may be achieved allowing for large excursions in the $T - \rho$ plane.

The physics of the spectators has been extensively studied over the last few years by the EOS and ALADIN collaborations. It was often assumed in the past that the spectators were released in relatively "cold" states after separation from the participant zone. This assertion is in fact not true and it turns out that sizeable excitation energies

can be reached, thus opening up the possibility of studying the fate of hot (and moderately compressed) nuclear species in peripheral and semi-peripheral relativistic collisions. Very large values exceeding the binding energy per nucleon can be reached for source sizes from 50 up to 150 mass units. These conditions are comparable with those obtained in dissipative collisions in the Fermi energy range making the two approaches complementary.

Lastly, a number of experiments have been performed using light projectiles, such as protons, anti-protons or ^3He in the GeV region, and charged particle multidetectors [18] and/or neutron multiplicity meter [19]. Such collisions allow 'dynamical' effects such as compression and also angular momentum transferred to the target to be minimized. Significant excitation energy depositions (up to the total binding energy of the target) have been measured.

The theoretical description of high energy nuclear collisions must consider processes from the very beginning of the reaction up to the last evaporation steps. Up to now, the most achieved theoretical tools to handle this programme are the microscopic nuclear transport models.

2.2. Nuclear transport models

At low bombarding energies, the relaxation time for intrinsic degrees of freedom is much smaller than the typical time scale for collective motion and therefore the reaction can be safely described by using a few collective degrees of freedom coupled to a heat bath. This leads to a description based on Fokker-Planck equations [20]. The situation is different at higher energies mainly because the time scales become comparable. Thus, the reduced description quoted above is no longer valid and a full dynamical description based on the nuclear Boltzmann equation is needed. Consequently, microscopic models taking into account both the nucleonic and hadronic degrees of freedom must be used to describe nuclear collisions at energies above 20 MeV/u. Over the last decade a number of significant improvements have been achieved in such models:

- Introduction of covariance and inelastic channels in nucleon-nucleon collisions for the application of the theory at relativistic energies - Relativistic Quantum Molecular Dynamics (RQMD) [21] and Relativistic Boltzmann Uehling Ulenbeck (RBUU) [22].
- Implementation of momentum dependent interactions (MDI's) and sophisticated Skyrme forces [23–25].
- Stochastic extensions to take into account fluctuations beyond the 'one-body' description [20,26].
- Introduction of medium effects for mass, scattering and decay of hadrons [2].
- Inclusion of genuine quantum effects by proper antisymmetrization and diffusion of the wave packet - Fermionic Molecular Dynamics (FMD) [27] and Antisymmetrized Molecular Dynamics (AMD/AMD-V) [28].

In the following, the various probes of nuclear matter in nuclear collisions are discussed by following schematically the time development of the reaction according to the predictions of a semi-classical transport model displayed in Fig.1.

Figure 1. *Time evolution of the central reduced density (top) and transverse energy per nucleon (bottom) as predicted by a microscopic transport model (BUU) for central Au+Au collisions at 400 MeV/u. From [29].*

3. PROBING NUCLEAR MATTER IN NUCLEAR COLLISIONS

The very early instants of the collision are associated with a compression phase (up to $2-3 \rho_0$ at relativistic energies). At such densities, medium effects can be investigated by studying the behaviour of particles such as kaons (see below).

After about 10 fm/c (a few 10^{-23} s), the expansion phase begins with the establishment of a collective motion whose magnitude can represent a sizeable fraction of the total available energy. This motion reaches its asymptotic value around 30-40 fm/c at which time matter is nearly back to its normal density. The study of this phase can shed light on the transport properties of hot matter, in particular the nuclear viscosity. The final step of the reaction is associated with an excursion to low densities. Then, there is a time at which the chemical as well as the thermal distributions of the matter are fixed - the so-called freeze-out stage. A detailed study of the various species produced at this time can provide signatures for thermodynamical equilibrium and the occurrence of a phase transition.

3.1. The first instants: properties of hot and dense matter

In the first instants of the reaction, hard nucleon-nucleon collisions provide an efficient means to relax the internal degrees of freedom and lead the system to thermalization on a short time scale. On the way to thermalization, particles (in particular mesons) are produced [16]. The systematics of meson production is displayed in Fig.2. The production

Figure 2. Meson production probability per participant nucleon as a function of $E - V_c$ (the incident energy minus the Coulomb barrier) normalized to the meson production threshold E_{thr}^{NN} in elementary free nucleon-nucleon interactions. From [16].

probabilities for pions and η 's fall close to a single curve over 11 orders of magnitude. Systematic deviations from this behaviour are observed for kaons which may be down by as much as a factor 5. At low bombarding energies, very high energy-cost or sub-threshold particles can be produced. Close to the absolute threshold, pion production has been extensively studied for a long time [30]. More recently, subthreshold kaon production has been observed in the $^{36}\text{Ar} + ^{48}\text{Ti}$ system at 92 MeV/A beam energy leading to a cross section at the picobarn level [31].

Such particles are probes of the tails of the nucleon momentum distribution and their production rates are very sensitive to the features of in-medium nucleon-nucleon inelastic channels and also to fluctuations in the nuclear medium [23,33]. In the case of kaon production, no incoherent production mechanism is able to account for the measured yield demanding a description in terms of "cooperative" few-body processes [32].

At low bombarding energies, the study of hard photons ($E_\gamma \geq 30 \text{ MeV}$) is of particular interest because of their weak interaction with the surrounding medium. Hard photons are produced in nucleon-nucleon collisions by the Bremsstrahlung process. Fig. 3 shows the systematics of hard photon production in the Fermi energy range [34]. The huge difference between the probability for the elementary process in the vacuum and the in-medium probability emphasizes the role of collectivity in producing energetic particles. Microscopic transport models (BUU in this case) are in reasonable agreement with the data over the whole energy range. A detailed analysis of $\gamma\gamma$ correlations can provide

Figure 3. *Systematics of hard photon production: the ordinate is the probability per individual nucleon-nucleon collision in the medium while the abscissa is the incident energy corrected for the Coulomb barrier. The upper solid line is the prediction of BUU while the other is the probability to produce a hard photon in an elementary free nucleon-nucleon interaction. From [34].*

access to the space time characteristics of the reaction by the technique of the intensity interferometry as shown, for example, in [35].

At high energy, near threshold, the study of kaon production has proven to be very instructive from two different perspectives:

- Kaon production is a severe test of transport theories in particular through the influence of medium effects on the propagation. Fig. 4 shows experimental results obtained at SIS with the FRS [36] and Kaos [37] set-ups for the production of K^- in the GeV/u range. Data have been compared with RBUU calculations [38]

whereby the lowering of the effective mass in the medium improves significantly the agreement of the calculations with the data.

- Kaon production exhibits a sensitivity to the stiffness of the EoS - data are better reproduced with a soft EoS as shown in Fig. 5.

Figure 4. *Invariant cross-section for the production of K^- detected at 44 degrees with Kaos and at 0 degrees with the FRS in Ni+Ni collisions at 1.5 GeV/u. Lines are the results of a transport model for two different prescriptions of the in-medium K^- mass. Data from [36](FRS) and [37](Kaos). Calculations from [38]. Figure taken from [39].*

These results are very promising but their interpretation is still a matter of debate. More data and new theoretical developments in the study of particle production are needed (see 4.1).

3.2. The expansion phase: matter flows

After the compression stage, matter starts to flow under the influence of the pressure gradient. In mid-central collisions, the flow is anisotropic and has been studied both in (sideways flow) and out (squeeze-out) of the reaction plane.

3.2.1. Sideways flow and squeeze-Out

A quantitative estimate of the sideways flow is based on the study of the transverse momentum per nucleon p_x/A in the reaction plane. The flow parameter (obtained as the slope of $\langle p_x/A \rangle$ around mid-rapidity) has been extracted for a variety of reactions

Figure 5. *Double differential cross-section for the production of K^+ at 54 degrees in Au+Au collisions at 1 GeV/u. Data from Kaos are compared with the prediction of RBUU [40] for two different EoS by varying the incompressibility modulus K .*

at many incident energies, E_{inc} . F can be evaluated at each impact parameter and reaches a maximum, F_{max} , in mid-central collisions. One manner to gather the data for different projectile-target combinations (A_1 - A_2) is to plot the reduced flow parameter: $F_{max}^{red} = F_{max}/(A_1^{-1/3} + A_2^{-1/3})$.

In Fig. 6, the behaviour of F_{max}^{red} as a function of E_{inc} is displayed. The evolution from negative values to positive values is associated with a transition from energies where the nuclear force is attractive to a region where it becomes repulsive. This region is especially sensitive to the in-medium corrections of the elastic nucleon-nucleon cross section [24] with a value close to the free one giving the best agreement with the data. After a large increase in F_{max}^{red} , the decrease observed above 400-500 MeV/u is interpreted as a softening of the EoS and could be a first hint of a transition from hadronic matter to a quark-gluon plasma. From a general point of view, the trends of the data are better reproduced by semi-classical transport models using momentum dependent interactions (MDI's) and a soft EoS.

Below 100 MeV/u, the flow parameter remains close to zero. In order to be able to make quantitative comparisons with the predictions of the transport models, the balance energy E_{bal} is defined as E_{inc} for which F becomes null - E_{bal} is therefore associated with the change of sign of F . Fig. 7 shows a compilation of the balance energy as a function

Figure 6. *Compilation of F_{max}^{red} in nuclear collisions from 20 MeV/u up to a few GeV/u.*

of the mass of the system [41]. The data show a mass dependence of $A^{-1/3}$ which may be roughly understood in the following manner. The mean field part of the interaction is mostly attractive and corresponds to a $A^{2/3}$ dependence while the repulsive nucleon-nucleon scattering scales as A . Here again, the trends of the data are better reproduced with a soft EoS and momentum dependence is found to be a crucial ingredient to correctly describe the transport properties.

We now consider the out-of-plane emission often referred to as 'squeeze-out'. This process is associated with the ejection of particles out of the reaction plane and is presumably related to the stiffness of the EoS - the larger the effect, the harder the EoS. Squeeze-out is studied with the help of azimuthal distributions.

In the Fermi energy range, it turns out that the squeeze-out is very small and the emission is preferentially in the reaction plane. This is in contrast with the results obtained at relativistic energies (see Fig. 8) [42]. The transition from a preferentially in-plane to out-of-plane emission is observed for Au+Au collisions around 100 MeV/u.

One should note the very similar trends observed in the evolution of both the sideways flow and squeeze-out: both increase up to 400 MeV/u and then decreases in similar fashions. These two observables thus constitute complementary probes of the EoS.

Figure 7. Mass dependence of the balance energy. The solid line corresponds to a $A^{-1/3}$ mass dependence as predicted by geometrical arguments. The two points without error bars are the predictions of a microscopic transport model with a soft EoS. From [41].

3.2.2. Radial flow in central collisions

In central collisions, there are expectations that the observed anisotropic flow in mid-central collisions evolves towards an isotropic radial expansion of the whole system including the massive fragments. The measurement of the energy stored in the collective motion is obtained by a comparison of the data with simple phenomenological prescriptions [44] based essentially on the assumption of a collective self-similar motion or by means of the 'blast' model [42] in which the light particle kinetic energy distributions are fitted assuming a superposition of a disordered thermal motion and an ordered expansion term.

A compilation of the collective velocity measured over a large range of incident energies is shown in Fig. 9. The threshold is located around 30-40 MeV/u and is followed by a rapid rise. A comparison with model calculations (BUU and QMD) is also displayed in the same figure. The models perform satisfactorily, although it turns out that BUU predicts an anisotropic flow (more flow in the transverse direction than in the longitudinal one) while the data are compatible with an isotropic expansion. One should note that other transport model calculations predict isotropic flow in the Fermi energy range [43].

Another point of interest is the apparent weak dependence upon the stiffness of the

Figure 8. *Compilation of the experimental results for squeeze-out. From [42].*

EoS as shown by the results of QMD simulations. One way to understand this feature is that a soft EoS leads to high densities and a low pressure gradient, while a hard EoS gives rise to the contrary but both lead to the same value of the flow.

3.3. The freeze-out stage: physics of expanded systems

3.3.1. Slow expansion and low temperatures: the search for the liquid-gas transition

The collective radial flow discussed in the previous section drives the system to low density and can therefore induce instabilities in the system and a transition from a liquid phase at normal density towards a gas phase at low density. In the following, experimental signatures for a liquid-gas transition are discussed from three different points of view.

'Topological' signatures: the decay modes of hot nuclei

The various decay modes of hot nuclei have been investigated as a function of the excitation energy ϵ^* [4]. At moderate ϵ^* , the dominant decay modes are evaporation leading to residues or fission accompanied by pre- and post-light particle emission [45].

When ϵ^* is raised to around 3 MeV/u, Intermediate Mass Fragment (IMF's) emission takes place indicating the onset of nuclear fragmentation. Fragmentation is then the dominant process (although evaporation and fission are still present) until ϵ^* becomes close to the binding energy where a fall in IMF production is observed as shown in Fig.

Figure 9. *Systematics of the collective energy as a function of the beam energy for medium and heavy mass systems. Data are compared with the predictions of BUU and QMD.*

10. The maximum in IMF production is around 9 MeV/u and then decreases progressively as it is replaced by vaporization (i.e. the decay by emission of particles with $Z=1$ and 2 only). Such a process has been observed in Ar+Ni collisions [46] and constitutes the ultimate decay mode of hot nuclei.

Fragmentation is therefore the transition regime from a liquid-like state to a gas-like state of matter. There remains, however, a question regarding the very nature of nuclear fragmentation: is it a natural continuation from fission or the signature of new physics? [8,51].

Dynamical signatures: the spinodal decomposition

A first indication of the answer to this question is provided by fragmentation time scales (see for instance Fig.9 in [6]). Fragment emission times are estimated by analysing space-time correlations between fragments taking advantage of the 'proximity' effects induced by the Coulomb interaction. A fast decrease of the emission time is found from values close to a thousand fm/c, at around $\epsilon^*=3$ MeV/u, to values close to 100 fm/c ϵ^* around 5 MeV/u. For such short time scales, fragments are emitted almost 'simultaneously' (often referred to as 'multifragmentation') so that fragment emission cannot be treated independently. One should note that sequential statistical models fail to reproduce the

Figure 10. *Evolution of the reduced IMF multiplicity as a function of ϵ^* . From [6] and references therein.*

observed fragmentation characteristics in this energy range [52].

Such results suggest a transition from surface and Coulomb instabilities (as in fission) to bulk instabilities in the decay of hot nuclei. Assuming such a dilute phase and short emission time scales, multifragmentation statistical models [47,48] have met much success. It should, however, be noted that input parameters must be provided in these models.

Moreover, such models do not address by nature the key question of the formation of the fragments. This subject is still a matter of debate. Recently, it has been possible to make a comparison of the data with a dynamical model taking into account all stages of the reaction up to fragment production [50]. Reasonable agreement has been achieved, thus suggesting a process driven by a mechanical instability - the so-called spinodal decomposition commonly observed in macroscopic systems such as binary alloys. This process is associated with the system entering a regime in a region where density fluctuations are no longer damped but exponentially amplified leading to its fragmentation. Molecular dynamics approaches, however, advocate a faster non-equilibrated process triggered earlier in the reaction [49]

Thermodynamical signatures: caloric curves, reducibility and critical behaviour

One of the possible thermodynamical signatures for a first order phase transition is a discontinuity in the heat capacity. Nuclear thermodynamics is based on nuclear calorimetry (measurement of the excitation energy, ϵ^*) and nuclear thermometry (measurement

of nuclear temperature, T) [4]. Nuclear temperatures are measured by determining the

Figure 11. *Systematics of measured nuclear temperatures with the three methods described in the text as a function of ϵ^* . From [6] and references therein.*

slopes of the kinetic energy distributions of evaporated light particles ('kinetic' temperatures), the ratio of the populations of discrete states for selected clusters ('excited state' temperature) [53] or by the double-ratios of isotopic yields ('double-ratio' temperatures) [54].

These three methods have been used for a variety of systems in different collision regimes. Some recent results are compiled in Fig. 11. For a given method, data from different collaborations agree while the three methods do not give the same values. Consequently, it may be considered that only apparent temperatures are measured. The 'kinetic' temperatures follow approximatively a Fermi gas law while the 'excited state' temperatures seem to saturate (see also [55]) and the 'double ratio's to slowly increase with ϵ^* . This apparent contradiction can be resolved within the framework of the Quantum Statistical Model [56] by including excluded volume effects [57], although it should be noted that other explanations are possible. In particular, cooling [58,59] may be an important effect whereby nuclear species would be produced at different steps of the disassembly process. Light particles would then be emitted first (even before equilibrium is achieved), while fragments would be emitted later at lower temperatures, thus implying a hierarchy in the different temperatures as observed experimentally.

By assuming the 'double ratio' temperature to be the correct one, it has been claimed that the ϵ^*-T correlation (the so-called 'caloric curve') was the signal for a first order liquid-gas transition [60]. This statement is very controversial and has triggered a great deal of theoretical work. Up to now, no clear consensus has been reached within the community concerning the meaning of such curves and this subject constitutes a truly open question for future studies.

Phase coexistence is another key signal of a phase transition. The Berkeley group [61] has analysed fragment multiplicity distributions. They conclude that these are reducible in terms of elementary process thus suggesting a strong phase space dominance. Moreover, a detailed study of charge distributions indicates a phase coexistence (see Fig. 30 and 31 of [61]) showing the transition from univariance to bivariate.

Lastly, the search for critical behaviour has been pursued by the EoS collaboration [62] in a study of the atomic number distributions in terms of critical exponents. After reduction of the distributions by means of techniques applied to critical phenomena, the data fall onto a universal curve - the so-called nuclear scaling function. The critical exponents obtained are very close to those expected for a liquid-gas transition and show departures with respect to the predictions of percolation (see table 1). These results are promising and clearly call for future analyses.

	τ	β	γ	$1 + \frac{\beta}{\gamma}$
<i>Percolation</i>	2.20	.45	1.76	1.25
<i>Lattice - Gas</i>	2.21	.33	1.24	1.27
<i>Au + emul.</i>	$2.27 \pm .1$	—	—	$1.2 \pm .1$
<i>Au + C</i>	$2.14 \pm .06$	$.29 \pm .2$	$1.4 \pm .1$	$1.21 \pm .1$

Table 1

Critical exponents obtained for various systems. Theory: Percolation [63], Lattice-Gas [64], Data: Au+emulsion at 1 GeV/u [65], Au+C at 1 GeV/u [62]. From [66].

Theoretically, the study of phase transitions (thermal or non-thermal) in finite nuclear systems has received much attention in recent years. Most of the new developments are based on Ising-like lattice gas models [67] pioneered by the application of percolation theory to nuclear data a few years ago [66,68]. Because of the universality of second order phase transitions, the general features of the observables and in particular the value of the critical exponents (see table 1) do not depend on the details of the interaction but only on general properties such as the dimensionality of the space and the order parameter. It is for this reason that generic information on the transition can be obtained from such schematic models.

We are, however, still far from a quantum description of clusterization and fragmentation processes in nuclear reactions which would be needed to describe within a single approach the whole range of excitation energies range which may be reached in nuclear reactions.

Figure 12. *Systematics of nuclear temperatures in central collisions as a function of the incident energy per nucleon for two symmetrical systems. The solid line is the prediction of a transport model [29].*

3.3.2. Fast expansion and high temperatures: hadro-chemistry

The estimate of temperatures at high energy are based on fits of the kinetic energy distributions. A compilation of nuclear temperatures obtained both 'kinematically' (by means of kinetic energy distributions) or 'chemically' (by means of particle yields) is shown in Fig. 12. Transport model calculations compare rather well with the measured temperatures. The slight differences between the theory, the 'kinematical' temperatures and the 'chemical' ones could be due to cooling effects.

'Chemical' temperatures are obtained as well as the baryon chemical potential through the analysis of the various yields of particles using thermal models. Such models turn out to be 'universal' since they have been applied successfully over a wide range of temperatures and densities (from $T=5-20$ MeV [56,57] to 50-100 MeV [69] and above 100 MeV [70,71]). In Fig. 13, the thermodynamical path from stable cold nuclei up to very high temperatures close to the expected limits of the transition from hadronic matter to the quark-gluon plasma is shown.

Figure 13. *Freeze-out conditions in the Temperature-Chemical potential plane. Points: AGS [70], SPS [71], SIS [69], GANIL [46].*

4. PERSPECTIVES AND SUMMARY

4.1. Perspectives

The future of the field is ensured both by the development of new facilities and/or new detectors and new ideas. A summary of future prospects may be found in [72]. Here we discuss two promising avenues:

- **HADES and dileptons:** In the relativistic regime, the link between the hadronic and the quark-gluon worlds is provided by the study of the in-medium properties of hadrons over a broad range of densities and temperatures. The development of pion beams at SIS opens up the possibility to study chiral symmetry at density close to the normal nuclear density. The study of vector mesons represents a challenge for the future as it requires a detailed study of dilepton production. Such a programme is the main objective of the HADES project which should be operating in 1999 at SIS [16].
- **The advent of new radioactive beam facilities** (see [73,74]) should trigger new experimental developments and new physics programmes. Recent calculations have shown the richness of nuclear thermodynamics when the N/Z degree of freedom is explicitly taken into account. Indeed, new 'chemical' instabilities are pre-

dicted in such systems [75]. From a dynamical point of view, the study of nuclear reactions with neutron-rich or proton-rich nuclei can provide new information on the isospin dependence of the in medium nucleon-nucleon scattering cross-section by studying the sideways flow [41]. The question of equilibration can also be addressed by studying the 'isospin mixing' of the system as a function of the centrality of the collision [76].

However, this requires the upgrading of the present multidetectors to measure simultaneously the atomic number and the mass number across a wide range of values. Clearly, this will require a strong experimental effort and thus represents a true challenge for the experimentalists.

4.2. Summary

Over the last ten years, a very broad ranging experimental effort in the study of nuclear matter from nuclear collisions has been pursued using a new generation of 4π detectors. From a theoretical point of view, the improvements of the models based on microscopic transport theories have made possible quantitative comparisons with a wide variety of experimental observables.

The study of reaction mechanisms in the Fermi energy range has revealed new characteristics. In mid-central collisions, the occurrence of space-time configurations corresponding to neck-like structures have been observed. The study of the decay of such structures has opened up the possibility of investigating neutron-rich matter at low density. In the relativistic energy range, peripheral and semi-peripheral collisions have proven to be efficient in producing hot and moderately compressed matter, while central collisions remain the best means for the study of highly compressed matter.

From the probing of nuclear matter at various instants of the reaction, the following results have been obtained.

- Particle production (pions and kaons) in the deep sub-threshold region put strong constraints on dynamical models requiring a treatment of higher order fluctuations that go far beyond the one-body description of nuclear transport. Close to threshold, strangeness production demonstrates the role of medium effects and opens up the possibility to study the restoration of chiral symmetry. It also supports a soft EoS.
- Nuclear collective motion has been investigated in both peripheral and central collisions. The evolution of sideways flow and squeeze-out show very similar trends. Generally, data are better reproduced by transport models using a soft EoS and momentum dependent interactions. At very high energy, a softening of the EoS is observed that could indicate the occurrence of new degrees of freedom. In central collisions, radial flow is now established across the whole incident energy range explored and is found to depend weakly on the stiffness of the EoS. There is also a clear indication that the system is driven to expansion at low density thus providing for the study of nuclear disassembly and clusterization.
- At low energy, all possible decay modes of excited matter from evaporation to vaporization have now been observed. Fragmentation data shows reducibility and thermal scaling suggesting phase space dominance. While such findings are reproduced by

statistical multifragmentation models, they still represent a matter of debate and the situation remains rather unclear. Recent microscopic transport calculations claim that a spinodal decomposition of the matter occurs while others suggest a much faster non-equilibrated process.

- Within nuclear thermodynamics, there remain questions about the interpretation of the caloric curves in terms of a first order liquid-gas transition. Clearly, ambiguities in nuclear thermometry must be resolved. However, an indicator for phase coexistence has been proposed and critical exponents have been obtained. Both aspects require further data and new analyses.
- At much higher energies, a study of hadron production by means of thermal models suggests a surprisingly high degree of equilibration. For such systems, freeze-out conditions in terms of temperature and density have been determined up to the expected limit at which the quark-gluon plasma regime begins.

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