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**NUCLEUS - NUCLEUS COLLISIONS IN THE SIS ENERGY
REGIME**

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(Invited talk given at Nucleus- Nucleus 1997, Gatinburg,USA, 2. - 6. June 1997)

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Nucleus-Nucleus Collisions in the SIS Energy Regime ¹

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1. INTRODUCTION

Nucleus-nucleus collisions at relativistic energies, i.e. at bombarding energies per nucleon comparable to the nucleon rest mass ($\approx 1 \text{ GeV}/c^2$), have been studied during the last approximately 25 years, starting with the pioneering experiments at the BEVALAC in the 1970's. These reaction studies were initially aimed at the determination of the equation of state of nuclear matter, and have provided a wealth of information which is still not described in all facets by theoretical models. The unique feature of heavy-ion collisions in this energy regime is that compressed nuclear matter can be produced and studied at moderate temperatures ($T \approx 70\text{-}100 \text{ MeV}$) over appreciable time scales ($\tau \approx 10\text{-}15 \text{ fm}/c$) [1,2]. The space-time evolution of such a collision is illustrated in Fig. 1 which shows the result of a transport model calculation with the IQMD code [3]: two nuclei collide with a relative velocity of 90 % light velocity. Since the projectile nucleons

Figure 1. The space-time evolution (in time steps of $\approx 10 \text{ fm}/c = 3 \cdot 10^{-23} \text{ s}$) of a central nucleus-nucleus collision (Au + Au at 2 AGeV) simulated within the IQMD-model [3].

move much faster than the sound velocity in nuclei a pile up of nucleons occurs in the collision zone leading to baryon densities of 2 - 3 times normal nuclear matter density. This high density matter in the center of the collision zone is in the focus of our investigation. Due to the repulsive interaction among nucleons at small distances the system subsequently expands in a violent explosion.

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In astrophysics similar phenomena are observed in supernovae explosions, although on quite different space-time scales. At the end of the lifetime of a star an iron core is formed as the result of a series of fusion processes. Since iron is the most strongly bound nucleus no more energy can be released in further fusion reactions. As a consequence, the electron pressure can no longer withstand the gravitational attraction among the nucleons, resulting in a gravitational collapse. In the interior of the star densities of a few times normal nuclear matter density are reached, i.e. comparable to those generated in heavy-ion collisions. Apart from the difference in temperature it is the same physics which subsequently drives the system apart. A shock wave propagates through the star and ejects the mantle, and in the high neutron flux of this explosion elements heavier than Fe are synthesized in neutron capture reactions [4]. This is an illustrative example for the close link between astrophysics and the physics of heavy-ion reactions.

Returning to the question of nucleus-nucleus reaction dynamics, one is interested to know where the initial kinetic energy in the entrance channel goes. Part of the energy is converted into chaotic or thermal motion of nucleons and nuclear fragments, another part goes into compression, followed by the collective expansion of the system. In addition, some of the initial kinetic energy of the two colliding nuclei in the entrance channel is also stored in the internal degrees of freedom of the nucleons. Being composite systems of quarks and gluons, the nucleons can be excited to short-lived resonance states which decay by meson emission. Meson production studies thus allow to deduce the fraction of nucleons excited during the high density phase of the nuclear collision.

Consequently, to study all facets of such collisions one has to pursue two experimental approaches: the investigation of nucleon and fragment emission patterns and the measurement of meson production. These two directions have been the guideline for a rich and rewarding research program pursued at several accelerators worldwide. The most recent developments in this field are reviewed in this article, however, due to space limitations only a very subjective selection can be presented.

2. COLLECTIVE PHENOMENA IN NUCLEUS - NUCLEUS COLLISIONS

2.1. Collective radial flow

A crucial aspect in the study of heavy-ion reactions has been the quest for collective phenomena: is a nucleus-nucleus collision just an ensemble of more or less independent nucleon-nucleon collisions going on in parallel or are there qualitatively new features of collective character? A major break through in this discussion has been the recent observation of radial flow in central nucleus-nucleus collisions [5]. If the expansion of the collision zone is a collective motion, all particles - irrespective of their mass - will move with the same local *flow* velocity, i.e. the total kinetic energy is proportional to the particle mass: $E_{kin} = A \frac{m_0 v^2}{2}$ or $\epsilon_{coll} = \frac{E_{kin}}{A} = \text{const.}$ In case of thermal motion the kinetic energy is proportional to the temperature T , i.e. $\frac{E}{A} \sim \frac{T}{A}$. A superposition of both types of motion will give rise to a mass dependence $\frac{E}{A} \sim \frac{T}{A} + \epsilon_{coll}$. This has been observed experimentally for selected central events by the FOPI collaboration as shown in Fig. 2. During the expansion fragments are formed in a clusterisation process similar to the formation of galaxies in the expanding universe. Although predicted long ago, the explosion of the collision zone, the so-called nuclear blast, could only be experimentally established after

Figure 2. (a) left: average fragment velocity as a function of fragment charge for Au-Au collisions at 150 A MeV [5]. The velocity saturates at large $Z \sim A$ indicative of collective motion. The thermal contribution is indicated by the dotted curve. The inset shows the characteristic azimuthally symmetric event topology of a central collision. (b) right: systematics of transverse flow velocities for different collision systems and bombarding energies.

methods of selecting central collisions had been refined by, e.g. requiring a high degree of azimuthal symmetry of the event topology (see Fig. 2a).

Subsequent studies by the FOPI [8] and EOS [9] collaborations for a large number of collision systems and bombarding energies (see Fig. 2b) have revealed a systematic increase of the transverse expansion velocity β_t reaching $\approx 35\%$ of the velocity of light at 2 A GeV. This implies that - depending on the incident energy - 20-50 % of the initially available kinetic energy is converted into this collective expansion in the SIS energy regime. For higher energies, AGS and SPS experiments [10–13] indicate a saturation around $\beta_t \approx 0.4c$.

2.2. Collective sideward flow

Historically, the first collective effect established in heavy-ion reactions was the directed sideward flow observed by the plastic ball group [14]. In contrast to the azimuthally symmetric radial flow in central collisions, the sideward flow is observed in non-central collisions. Here, the presence of spectator matter defines a reaction plane and introduces

an in-plane/out-of-plane asymmetry. The spectators which do not experience first chance collisions because of lack of geometrical overlap are deflected sideways by the exploding collision zone and by repulsive field gradients at the border between participant and spectator matter [7]. A quantitative measure for the collective sideward flow is the slope at midrapidity of the $\langle p_x/A \rangle$ versus rapidity curve: $F_y = d \langle p_x/A \rangle / dy$. Here, $\langle p_x/A \rangle$ is the average transverse momentum per nucleon projected onto the reaction plane. As shown in Fig. 3 and discussed by W. Reisdorf [7] in a contribution to this

Figure 3. sideward flow defined as $F_y = d \langle p_x/A \rangle / dy$ plotted as a function of bombarding energy. The plastic ball [18] and EOS [19] data are for p,d,t, and He, the AGS data for p [10]. The FOPI data refer to intermediate mass fragments (extrapolated to infinite mass [6]) and are downscaled by a factor 1.4 for a better comparison [7].

conference the sideward flow goes through a maximum at a few hundred A MeV incident energy. The steep rise near 100 A MeV may be associated with the transition of attractive to repulsive mean fields in nucleus-nucleus reaction dynamics [15]. The fall at higher projectile energies may be primarily attributed to the shortening of the interaction time between spectators and participants. The decrease of sideward flow should, however, be carefully studied since a disappearance of sideward flow at higher energies may be indicative of the softest point of nuclear matter and a possible phase transition, e.g. to the quark-gluon-plasma [16]. (In the mixed phase at a phase transition no pressure is exerted from the collision zone onto the spectator matter). Ongoing experiments with the EOS detector [17] at the AGS will soon provide new data in the energy range from 2 - 8 A GeV and supplement the result previously reported for 10 A GeV [10] (see Fig. 3). This information is essential as it will show how important it is to extend these flow studies to higher than AGS energies at possible future accelerator facilities.

3. PARTICLE PRODUCTION IN NUCLEUS - NUCLEUS COLLISIONS

3.1. Properties of dense and hot hadronic matter

In the course of a heavy-ion reaction many nucleon-nucleon collisions occur which are energetic enough to excite the intrinsic degrees of freedom of a nucleon. As any composite system, the nucleon exhibits a rich excitation energy spectrum with broad ($\Gamma \approx 100$ MeV) resonance states which decay by meson ($\pi, \eta, K, \omega \dots$) emission to the nucleon ground state. The study of meson production is thus the appropriate approach to learn more about the conversion of the initial kinetic energy of the two colliding nuclei into internal excitations. π -emission from the lowest excited state of the nucleon, the $\Delta(1232)$ resonance, is the predominant source of pions in heavy-ion reactions at SIS energies. Higher lying, mostly overlapping resonances also emit pions but are less frequently populated. The η -meson plays a special role as it is a selective probe for the excitation of the $S_{11}(1535)$ resonance which is the only known baryon resonance with a sizable ($\approx 50\%$) η -branching ratio.

Meson production in heavy-ion collisions has been studied for over 20 years. The results are summarized in Fig. 4 where the production probability per participant nucleon is plotted as a function of the bombarding energy. To allow for a comparison of different particle species the bombarding energy per nucleon is divided by the threshold for producing the respective particle in free nucleon-nucleon collisions. The production probabilities for pions fall close to one curve over 11 orders of magnitude. Also η -mesons follow this trend as shown more clearly in Fig. 4b. K^+ - and K^- - production probabilities are down

Figure 4. (a) left: meson production probability per participant nucleon as a function of the bombarding energy normalized to the meson production threshold in free nucleon-nucleon collisions; (b) expanded version of left hand panel showing the production probabilities for mesons with strange quarks; updated figures adapted from [20,21].

by a up to a factor 5 and the Φ - yield is even smaller compared to π, η -production. This indicates that the strangeness degree of freedom is not equilibrated at SIS energies while this may hold for π - and η -emission.

An equilibrated system emitting pions and η -mesons can be analyzed within a thermal model at chemical freeze out. This point is reached in the expansion of the collision zone when the baryon density has dropped so far that inelastic collisions among hadrons, i.e. particle species changing reactions, die out and the hadrochemical composition of the system is no longer changed. Following the work of Braun-Munzinger et al. [11], the system at chemical freeze out is regarded as a hadron gas consisting of $\pi, \eta, N, \Delta(1232), N^*(1440)$, and higher lying baryon resonances in chemical and thermal equilibrium; the density of each constituent is given by two parameters, the temperature T and the baryochemical potential μ_B :

$$\rho(\mu_B, T) = \frac{g}{(2\pi\hbar)^3} \int 4\pi p^2 f(pR) dp \int \frac{A(m) dm}{\exp[(E - \mu_B B)/T] \pm 1} \quad (1)$$

where g is the spin-isospin degeneracy, $A(m)$ the resonance mass distribution and $f(pR)$ a finite volume correction. The $\pm$ sign refers to the different statistics for bosons or fermions, respectively.

From the particle production ratios $\pi^0 / \langle A_{part} \rangle$ and η / π^0 [23] and the production rates of π, Δ, p, d [24] the parameters μ_B and T have been determined for different collision systems and bombarding energies using (1). The results are included in Fig. 5a which shows the phase diagram of hadronic matter. The figure also contains (T, μ_B) -

Figure 5. (a) left: phase diagram of hadronic matter; the temperature T is plotted versus the baryochemical potential μ_B derived from particle production ratios in nucleus-nucleus reactions at different bombarding energies [11,13,24,23]. (b) right: the shaded areas represent baryon resonance populations at freeze out derived from the T, μ_B parameters of ref [23]; the data points correspond to the measured meson yields.

determinations from particle production experiments at AGS and SPS energies [11,13]. The phase diagram illustrates that at freeze out the collision system is near the phase transition to the quark-gluon-plasma for AGS and SPS energies while in the SIS energy regime only moderate temperatures are reached and freeze out occurs at baryon densities of $\rho_B \approx 0.2-0.4 \rho_0$.

Having determined the (T, μ_B) -values the population of all baryon resonances can be calculated within the thermal model using eq.(1), thereby providing information on the hadrochemical composition of the collision system at chemical freeze out. As an example, the population of the $\Delta(1232)$ and $S_{11}(1535)$ resonance are plotted in Fig. 5b as a function of the available energy, together with the meson production probabilities which served as input parameters. At 2 AGeV about 15% of the nucleons are found to be excited to resonance states at freeze out.

Although knowledge about the collision system at freeze out, i.e. in the end phase of the heavy-ion reaction, is very valuable it is of even greater importance to learn more about the high-density phase of the reaction. This information is difficult to get via strongly interacting probes as they decouple from the system only when the baryon density has already dropped. Leptons, to be discussed in section 3.2.2, provide a direct view of the hot and dense medium. Some information from hadronic probes can nevertheless be obtained by comparison to model calculations [22] such as in Fig. 6 which describes the time evolution of a central Au-Au collision at 1.5 AGeV. The figure illustrates that the

Figure 6. Time dependence of the baryon density (dotted), the number of Δ -resonances (solid), higher baryon resonances (dashed), pions (dotted), as well as the sum of all baryon resonances and pions (dot-dashed) for a Au-Au collision at 1.5 AGeV. The curves are the result of a BUU calculation [22].

total number of intrinsic excitations represented by the sum of pions, Δ 's, and higher resonances (dot-dashed curve) is determined at the end of the high density phase and changes only little ($\leq 20\%$) thereafter through absorption processes (mostly $\Delta N \rightarrow NN$). Furthermore, Fig.6 shows that the maximum number of nucleons in excited states during

the high density phase amounts to about 80% of the asymptotically observed number of pions. With a pion production probability per participant nucleon of $\approx 35\%$ measured at 2 AGeV we deduce - bearing the uncertainties of transport model calculations in mind - a resonance population of $\approx 30\%$ at high density compared to $\approx 15\%$ at freeze out (see above). Combining the informations on the baryon density and the resonance population probabilities one derives a baryonic resonance density of $\rho_{res} \approx 0.3\rho_b \approx 0.3 \cdot 2.5\rho_0 \approx 0.8\rho_0$. This implies an average spacing among baryon resonances of about 2 fm which is within the range of the strong interaction. Consequently, the density of resonances is so high that they start interacting among each other which has consequences for the production of heavy mesons and which suggests to characterize the system as *resonance matter* [25].

3.2. Chiral symmetry breaking and restoration

3.2.1. Pseudoscalar mesons

The previous sections have shown that we have already learned a lot about the properties of compressed hadronic matter produced in relativistic nucleus-nucleus collisions: we know about the collective behaviour, the excitation of intrinsic degrees of freedom and the achievable baryon densities and temperatures. We will now address the question whether in this kind of hadronic medium the properties of hadrons may change. This question is related to the breaking and partial restoration of chiral symmetry which has recently attracted much attention, both theoretically and experimentally.

Starting from effective chiral perturbation theory, an in-medium dispersion relation for

Figure 7. Effective masses of K^+ and K^- mesons in symmetric nuclear matter as a function of the baryon density ρ in units of the normal nuclear matter density ρ_0 . The figure is taken from ref. [28]. The solid curves include Pauli blocking, binding and Fermi motion while the dashed curves show the additional effects of nucleon-nucleon correlations [29].

kaons can be derived ([26–29] and references therein). The total energy is not only given by the K-mass and momentum as for free kaons but there are additional terms due to the

Figure 8. Cross sections for K^+ - and K^- - production in Ni-Ni and p-p reactions. The incident energies for the nucleus-nucleus reactions correspond to the same energy below the nucleon-nucleon production threshold. The figure is taken from [30].

interaction of kaons with the medium:

$$\omega_{K^\pm}(p, \rho_b) = \sqrt{m_K^2 + p^2 - \frac{\Sigma_{KN}}{f_K^2} \rho_s + \left(\frac{3\rho_B}{8f_K^2}\right)^2} \pm \frac{\rho_B}{f_K^2} = \sqrt{m_k^{*\pm 2} + p^2} \quad (2)$$

The so-called $\text{KN}\Sigma$ -term reflects the explicit chiral symmetry breaking due to the non-zero strange quark mass. The additional terms can be rewritten as a scalar and vector potential or they can be further absorbed into effective kaon masses which - due to different signs in the additional terms - behave differently for K^+ and K^- as a function of baryon density (Fig. 7). While the effective K^+ mass increases slightly, a dramatic decrease in the K^- -mass is predicted, reaching 50 - 60 % of the free K^- -mass at $2.5 \rho_0$. An experimentally observable consequence would be an enhanced K^- -yield as it would be energetically much easier to produce K^- -mesons in dense hadronic matter (when leaving the collision zone K^- -mesons acquire their free mass from the total energy in the system).

Recent experiments with the KaoS spectrometer at GSI have provided tentative evidence for this scenario [30]. Fig. 8a shows a comparison of K^+ and K^- spectra taken at 1.0 and 1.8 AGeV, respectively. The incident energies have been chosen such that the available energy below the free nucleon-nucleon production threshold is identical, taking the associated production mechanism into account. At these equivalent energies the production cross sections for K^+ and K^- mesons are roughly the same. This is in line with the systematics of Fig.4b, but surprising in so far as for the same available energy in free proton-proton collisions (see Fig. 8b) the K^- -production cross sections is lower by about an order of magnitude compared to K^+ -production over a wide energy range. In

the heavy-ion reaction one would expect an even smaller K^- -yield because of strong K^- -absorption in nuclear matter, while the mean free path for K^+ mesons is comparable to the dimensions of a nucleus. Consequently, the observation of equal cross sections for K^+ and K^- -mesons at equivalent energies rather implies a strong K^- -enhancement in nucleus-nucleus reactions, which may be first evidence for a possible lowering of the K^- -mass in the medium. Indeed, transport model calculations [27,31] find better agreement with the nucleus-nucleus data if a dropping mass scenario according to Fig. 7 is implemented.

In this comparison of kaon spectra at equivalent energies one has, however, to keep in mind that the K^- -spectrum was taken at a higher absolute bombarding energy which implies somewhat higher temperatures and densities. Furthermore, secondary pion induced reactions play an important role in kaon production which diminishes the role of production thresholds in nucleon-nucleon collisions.

Another experimental test for the predicted in-medium behaviour of kaons, in particular the interplay of scalar and vector potentials, is the measurement of kaon flow [32] which is discussed in greater detail by W. Reisdorf [7] in his contribution to this conference.

3.2.2. Vector mesons

Vector meson (ρ, ω, Φ) masses in the medium may be affected by a possible restoration of chiral symmetry at high densities and temperatures. In the chiral limit, all quark masses would be zero and - being massless - quarks would maintain their helicity in all interactions with gluons. The order parameter for the transition from the real world, where the chiral symmetry is broken, to a chirally symmetric scenario is the so-called

Figure 9. The chiral condensate calculated within the Nambu Jona-Lasinio model as a function of temperature and baryon density [33].

chiral condensate $\langle q\bar{q} \rangle$. This quantity has been calculated within the Nambu Jona-Lasinio model and is shown in Fig. 9 as a function of temperature and baryon density [33]. It is still a matter of debate whether the predicted and undisputed decrease of the

Figure 10. e^+e^- invariant mass spectra measured in central S-Au and Pb-Au reactions at 160 AGeV [35,36]. The solid curve represents the sum of e^+e^- pairs from hadronic decays.

Figure 11. e^+e^- invariant mass spectra measured in inclusive Ca-Ca and C-C reactions at 1 AGeV [38]. For comparison the π^0 - and η - Dalitz decay contributions, derived from TAPS data [43–45], are shown.

chiral condensate implies a corresponding drop in vector meson masses. This scenario [34] can, however, be tested experimentally as temperatures and baryon densities can be achieved in heavy-ion reactions at SIS and SPS energies for which a dramatic decrease in $\langle q\bar{q} \rangle$ would be expected (see Fig. 9). The best way to measure the in-medium mass of a vector meson is to detect its e^+e^- or $\mu^+\mu^-$ decay since dileptons can leave the compressed interaction zone undisturbed. The mass of the vector meson can thus be reconstructed from the 4-momentum vectors of the two leptons. The vector meson produced in the nucleus-nucleus collision has, however, to be sufficiently short-lived to decay within the high density phase ($\Delta t \leq 10 \text{ fm}/c$) of the reaction before the collision zone expands. From this point of view the ρ -meson ($\tau = 1.3 \text{ fm}/c$) is ideally suited while the corresponding measurement for ω ($\tau = 23 \text{ fm}/c$) and Φ ($\tau = 44 \text{ fm}/c$) mesons depends on additional in-medium broadening effects which reduce the decay time.

Corresponding experiments have already been performed at the CERN-SPS [35,37] and the BEVALAC [38]. Figs. 10, 11 show the dilepton invariant mass spectra for central S-Au and Pb-Au collisions at 160 AGeV [35] and for inclusive Ca+Ca and C+C collisions at 1 AGeV [38]. In both cases, an enhancement of the dilepton yield compared to e^+e^- and $e^+e^-\gamma$ Dalitz decay contributions from known hadronic sources is observed. The CERES-data have been explained in a number of theoretical papers, e.g. [39,40] incorporating secondary collisions (e.g. $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$) and a dropping mass scenario, i.e. the dilepton excess in the mass range from 200-600 MeV is attributed to e^+e^- -decays of ρ -mesons which are shifted down in mass. It should be noted, however, that other interpretations based on in-medium many-body effects have also been suggested [41,42]. Despite several attempts no theoretical interpretation of the DLS-data has been found so far.

This line of research will be taken up at GSI with HADES (High Acceptance Di-

Figure 12. left: kinematics for almost recoilless production of ω mesons in the reaction $\pi^- p \rightarrow n \omega$ on a bound proton [48]; right: expected e^+e^- invariant mass distribution for π^- -induced ω -production on ^{208}Pb (solid histogram) and ^{12}C (dashed histogram) according to ref. [49]. A cut on the ω -momenta $p_{||}, p_{\perp} \leq 250 \text{ MeV}/c$ has been applied to enhance the contribution of ω -mesons decaying within the nucleus.

Electron Spectrometer) [46], which features a lepton-pair acceptance of 20-40%, a mass resolution of 1% and a high count rate capability (10^6 interactions/s). The detector system is presently being installed by a European collaboration, and first commissioning experiments are planned for 1998/99. These results as well as those from upcoming SPS experiments are eagerly awaited as they will show how important it will be to push the baryon densities to the extreme and to explore the currently inaccessible domain of highest baryon densities, which requires incident heavy-ion energies between 10 to 40 AGeV.

In conjunction with the π -beam at GSI [47], which will become available in 1998, HADES will also allow the measurement of the ω -mass at normal nuclear matter density [48] where - according to Fig. 9 - a shift in mass by 10-20% might be expected. The kinematics of the $\pi^-p \rightarrow n\omega$ reaction on a bound proton (see Fig.12a) allows for almost recoilless ω -production in nuclei. By requiring ω -momenta less than the Fermi-momentum ($p_\omega < p_F$) the fraction of ω -mesons decaying within the nucleus is enhanced. Fig. 12b shows the expected dilepton signal from the decay of an ω -meson with reduced mass in Pb [49]. For a small nucleus like C this effect should be suppressed. The peak at the free ω -mass in Fig. 12b arises from ω -mesons produced in the nuclear surface which decay outside of the nucleus. The advantage of the ω -mass measurement at normal nuclear matter density is that the interpretation can be based on much more solid theoretical ground.

4. CONCLUSIONS

25 years of intensive studies have revealed many of the properties of compressed hadronic matter. Systematics for collective motion (radial as well as sideward flow) are emerging as a result of careful investigations of system size-, centrality- and bombarding energy-dependencies. Possible in-medium effects have opened up new perspectives for particle production studies. Despite all the progress that has been made, the determination of the equation of state of nuclear matter remains an unfinished task, calling for still more accurate and systematic data as well as for a unified theoretical description of the various phenomena observed in nucleus-nucleus collisions at SIS- and higher energies.

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