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Hadrons and Nuclei far Away from Equilibrium

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Abstract

In this introductory keynote talk I discuss some of the new, most stimulating developments in heavy-ion physics since the last Nucleus-Nucleus Conference. After a short summary of our understanding of particle production I put particular emphasis on the formation of resonance matter in relativistic heavy-ion collisions and on possible experimental signatures of in-medium properties of hadrons and their interactions. I also discuss the newly discovered 'radial flow' and the approach to the gas-liquid phase transition point through fragmentation reactions.

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In this introductory keynote talk I discuss some of the new, most stimulating developments in heavy-ion physics since the last Nucleus-Nucleus Conference. After a short summary of our understanding of particle production I put particular emphasis on the formation of resonance matter in relativistic heavy-ion collisions and on possible experimental signatures of in-medium properties of hadrons and their interactions. I also discuss the newly discovered ‘radial flow’ and the approach to the gas-liquid phase transition point through fragmentation reactions.

1. INTRODUCTION

One of the exciting developments of heavy-ion physics of the last few years is that we have finally learned how to exploit the two additional degrees of freedom that are accessible through the study of heavy-ion collisions, namely those of density and temperature. The exploitation of these degrees of freedom runs like a red line through all of my talk. I will discuss the various features and phenomena connected with hadrons and nuclei far away from equilibrium and essentially follow the time-development of a heavy-ion collision from the initial state to the final fragmentation stage.

I will, therefore, first discuss what we have learned about particle production. Then I will talk about some recent very exciting new developments in the study of nuclear flow. I will then discuss the discovery of resonance matter and its consequences; this topic is obviously linked to a study of in-medium properties of hadrons. In this context I will cover topics where heavy-ion physics meets more fundamental physics, namely QCD and hadron physics. And then, finally, I will describe how in the late stages of the collision the dilute nuclear system formed at high energies fragments. A summary concludes this talk.

2. PHENOMENA IN HEAVY-ION COLLISIONS

2.1. Collision History

A pictorial representation of a time history of heavy-ion collisions both at high and low energies is shown in Figures 1 and 2. Fig. 1 shows a central collision of Ca + Ca at 500 MeV/u, Fig. 2 that at 40 MeV/u. What is shown in both cases is in the upper row the spatial development and in the lower row the development in momentum space. What

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Figure 1. Time development of a $^{40}\text{Ca} + ^{40}\text{Ca}$ reaction at 500 MeV/u. The upper sequence gives the density-evolution, the lower one that of the momentum-space configuration. The time-step between frames is 10 fm/c.

we can see is that at both energies the nuclear system runs through a highly compressed stage and then later on expands. In momentum space the development is much more violent in the high energy case; initially the two-momentum spheres are well separated, but upon contact nucleon-nucleon collisions set in and drive the system towards equilibrium. At the end, the momentum space configuration is very much like that for an equilibrium configuration. In the low energy collision, of course, the change in the momentum representation is not quite as drastic. The two momentum spheres overlap already in the initial stage of the collision, but the momentum distribution is again thermalized, although the equilibration does obviously not take such a long time as in the former case.

The standard theoretical framework to describe such collisions is nowadays that of semiclassical transport theories (BUU, LV, QMD and the such) [1–5]. The whole field of heavy-ion physics has really made dramatic progress in the course of the development of such transport theories which allow one to follow the time-development of a nuclear collision all the way from the initial state to the final break-up stage. As will also become apparent during this conference the analysis and understanding of hardly any heavy-ion experiment is possible nowadays without looking at transport-theoretical simulations. One has to realize the major step that was made here by looking at the situation about

Figure 2. Same as Fig. 1 for an energy of 40 MeV/u. The time-step between frames is now 20 fm/c.

20 years ago, when reaction phenomena were often arbitrarily and in an ad-hoc way put into two categories, the pre-equilibrium and the thermal one, with ad-hoc assumptions about the nature of the processes involved. This is no longer necessary here, because the transport equations describe the transition from a highly non-equilibrium configuration into a thermal one, if the latter actually occurs. In that sense intermediate and relativistic heavy-ion physics is still much ahead of the situation in ultra-relativistic physics where such theoretical methods are still lacking and where most theoretical analyses either treat the extreme pre-equilibrium situation alone, or start out with the discussion of the thermalized system and ad-hoc assumptions about its expansion and hadronization.

In order to get a feeling for the processes that happen during the course of such a collision we will now follow the time-development of such a reaction. As an example I show in Figure 3 a central $Au + Au$ collision at 600 MeV/u. The results shown there were obtained with a relativistic BUU method [6,7], but they would be very similar in QMD and LV calculations. In the upper part of the Figure the development of temperature as a function of time is plotted; the two lines there show two parameters that reflect the corresponding momentum distributions, the transverse and longitudinal “temperatures”. These two so-called “temperatures” do not agree at all during most of the collision; what we find, and what we know nowadays, is that only the transverse “temperature” is a real temperature in the true sense of the world already quite early in the collision. The longitudinal momentum distribution, on the other hand, equilibrizes only very late. The

Figure 3. Time-development of temperature and pressure in a noncentral $Au + Au$ collision at 600 MeV/u. The uppermost frame shows the nuclear density, the middle frame contains the longitudinal and the transverse temperatures T_l and T_t , respectively, and the density. The lowest frame contains the longitudinal and the transverse pressures, p_l and p_t , respectively, and the energy-density ϵ . For a definition of these quantities see [6,7].

transverse temperature reaches values of about 40 to 50 MeV at the bombarding energy considered here (600 MeV/u), stays there for some while and then slowly falls down. Only in the very late stages of the collision, where the density is already below ρ_0 , and where the temperatures have cooled down to values of the order of 10-20 MeV, they tend to coincide although some non-isotropy in the momentum-distributions always remains [6,7]; only then can we talk about equilibration. In the lower part of the Figure the same behavior is shown for the pressure development. The densities reached in this collision are of the order of $2.5 \rho_0$ and the energy densities go up to about 350 MeV/fm^3 , to be compared with the energy density of nuclear matter in equilibrium, 150 MeV/fm^3 , and with the energy density at the transition point to a quark-gluon plasma of about 2 GeV/fm^3 .

2.2. Particle Production

One of the first processes to happen during a heavy-ion collision is that of particle production. The major step forward that has been made over the last few years is that we have understood particle production in such collisions as an incoherent superposition of individual nucleon-nucleon collisions [8–10]. Once two heavy-ions collide they act like two interacting bags of nucleons and the nucleons then scatter individually (for reviews see [3–5,11]). The cross-section is thus in general given by an impact parameter integration over the sum of all elementary nucleon-nucleon production amplitudes, and by typical in-medium corrections, that take into account that the final states of the participating nucleons may be Pauli-blocked.

The old question if there is also a coherent radiation must be answered by “in principle yes”, but in practice it will be very hard to observe. All indications that we have and very simple estimates in terms of reaction times, reaction rates, interaction distances, etc. point to the fact that the collective coherent radiation spectrum is much softer than that of the incoherent radiation[8,3,12]; only in heavy very heavy systems the coherent source may dominate the spectrum at small energies. This component has so far not been seen.

That this picture of particle production via incoherent nucleon-nucleon collisions works quite well can be illustrated with the very nice recent experiment on photon production at the bombarding energy of 44 MeV/u shown in Figure 4; the data were taken by the MEDEA detector, built and developed by the Catania group [13]. The slope parameter of the photon spectrum falls off as a function of impact parameter. This reflects the local momentum distribution inside the individual nuclei: the nucleons in the center of the nucleus have the highest momenta whereas they move much more slowly if they are at the surface. Thus, in a central collision the two volume components overlap and nucleons with high Fermi momenta collide to produce a rather hard spectrum, whereas in a non-central collision only the slower nucleons in the tails interact and lead to a much steeper fall-off in the photon spectra. This behavior illustrated here for photons holds in general for all particles.

It is also valid both in the Fermi-energy and in the relativistic regime; at energies above about 1 GeV/u, however, new degrees of freedom open up. There not only nucleons, but also nucleon resonances are involved, and particles like pions are so copiously produced that they contribute significantly to the cooling of the reaction volume. In such a situation perturbative descriptions of particle production are no longer adequate and all the various nucleon-resonance-meson channels have to be treated on an equal footing.

2.3. Coupled Channel BUU Method

We [14,15] and other groups [16,17] have therefore developed a method, that I call Coupled-Channel-BUU (*CCBUU*), in which not only nucleons but also all the relevant nucleon resonances and the relevant mesons are coupled together and are propagated under the influence of each other and under the influence of a mean-field. Such a method describes the evolution of the system from entrance via the pre-equilibrium stage to thermalization and takes into account the cooling, for example, of a high energy collision through the emission of pions.

Figure 4. Slope parameter of the photon spectrum measured with the MEDEA detector for $Ar + V$ collisions at 44 MeV/u (from [13]).

2.4. Resonance Properties and Meson Production

The high production rate of resonances and the development of the CCBUU method leads to the question if we can actually use heavy-ion physics to learn something about nucleon resonances in dense nuclear matter? Simple answers are provided by a quick look at the N^* strength distributions for the elementary electromagnetic and pionic strengths [18]. These strengths are quite clearly peaked in the Δ -region; at higher energies there are only comparably small, rather broad oscillations and a continuum of strength. Very recent data on photoabsorption on nuclei also point out that the Δ retains its identity up to densities of ρ_0 , whereas the higher-lying resonances are considerably broadened [19]. This indicates that in nuclei the higher lying nucleon resonances overlap to a large extent and hardly stick out of the continuum. In heavy-ion collisions the smearing of the resonances through Fermi-motion is even larger than in photonuclear experiments because of the *two* momentum spheres involved. This implies that we will not learn much about higher lying resonances by the study of photon or pion channels except about the Δ , which determines the low-energy pion spectra.

There is, however, one other resonance that is quite unique; this is the S_{11} (1535)

resonance that decays with 35 % into an η meson and with about 50% into a pion. The η -meson, a pseudoscalar meson, decays into two photons and can thus be detected by photon spectrometers like TAPS. η spectroscopy can thus yield unique information on the η properties in dense matter and on properties of the $N(1535)$ resonance in such an environment.

Building on the older experiments performed at the BEVALAC in the 80's measurements of pion spectra have recently been taken up again at SIS by the FOPI, KAOS and TAPS collaborations. The latter has also performed measurements of η production at 1 and 1.5 GeV/u.

The typical sort of agreement one can get in the theoretical understanding is shown in Figures 5 and 6. The calculations are completely parameterfree and indicate quite clearly that the overall features of the spectra are quite well understood. A closer look at the pion spectra, however, shows, that there are some deficiencies, particularly at low p_T ; these deficiencies may contain information on the behavior of pions and Δ 's in dense matter [21,22].

That something happens with the Δ 's is illustrated in Figure 7 where the calculated lifetime distribution of Δ -resonances in such a collision is plotted. We see clearly two components in the spectrum, one corresponding to a width of 120 MeV – the free value – and another one with a width of 75 MeV, i. e. nearly 1/2 of the free value. This lowering has a dynamical origin that is a typical in-medium effect that could not be observed in free hadronic processes. During the collision first high mass Δ 's are populated. By subsequent pion emission and pion reabsorption the Δ mass drops by about 50-60 MeV until at freeze-out the Δ 's do not have a mass of 1232 MeV anymore, but instead of only about 1170 to 1180 MeV. This explains naturally an observation in the BEVALAC experiments that a thermal-model analysis of the observed pion spectra required a Δ mass that was lowered by about 50 MeV [23].

2.5. Resonance Matter

The other fascinating discovery that we have made in these calculations is that the number of Δ 's produced in the central reaction volume is actually very large [24]; this result has recently been verified by the authors of [25]. In Figure 8 I show the baryonic composition of the central $\approx 32 \text{ fm}^3$ in the reaction volume. Even in the SIS energy regime the Δ -density amounts to 20-30 %. This agrees with experimental results obtained at SIS, which show that the production probability for a pion pro participating nucleon is of the order of 30 % [26].

A simple calculation shows that since the nucleon density is of the order of 3 times ρ_0 , the Δ -density is of the order of the nucleon density at the nuclear equilibrium point. The Δ 's in the central reaction volume are as close together and are as strongly interacting with each other as are the nucleons in the groundstate. That the system actually lives for for a significant amount of time is shown in the lower part of the Figure which gives the Δ -distribution as a function of time. The average lifetime is $\approx 10 \text{ fm}/c$; this corresponds to ≈ 6 times the free lifetime of a Δ .

The most striking consequence of such a formation of resonance matter is seen in the production of far-subthreshold particles. In all of the calculations one observes that the farther the particles are below their threshold, the more they are produced through

Figure 5. π^0 spectra for the collisions indicated. Data are obtained by the TAPS collaboration. The dashed curves give results of a BUU calculation ([14]), the solid lines those of a QMD calculation ([20]).

Figure 6. η spectra for the reactions indicated in the figure. Data are from the TAPS collaboration; the solid line gives results of a BUU calculation [14].

Figure 7. Δ -lifetime distribution in a 1 GeV/u collision of $^{40}\text{Ca} + ^{40}\text{Ca}$. Also shown by the dot-dashed curve is the lifetime-distribution of the $N(1535)$ resonance.

collisions in which one or two of the participants are Δ 's. This is illustrated, for example, in Figure 9 for the extreme case of antiproton-production that was studied recently by the FSR group at SIS. Shown there is the relative weight of the various reaction channels involved in the production of antiprotons. Up to a bombarding energy of about 2 GeV the $\Delta\Delta$ -channel wins by far, then the $N + \Delta$ -channel takes over, while at all energies the nucleon-nucleon channel contributes only at the 10 % level. This result implies the dominance of either four-nucleon or three-nucleon-processes in $\bar{p}$ production. For example, two nucleons first collide with each other and produce one Δ ; then two Δ 's collide again and produce a proton-antiproton pair. It is obvious that these processes are proportional to high powers of the density and that they are thus also a direct signal for high density formation [27].

There is another exciting fact connected with the antiproton production experiments.

Figure 8. Baryonic composition in the central reaction volume for a $Au + Au$ collision (upper part). The lower part shows the number of baryons in the various resonance channels together with the density and the number of pions as a function of time.

All the theoretical analyses now agree that the description of the data, and in particular of the excitation function, requires an attractive potential for these antiprotons of at least 100 MeV at ρ_0 [27,28]. This is the first compelling evidence for a genuine in-medium effect on particle production.

2.6. Dilepton Production

Another quite interesting consequence of the formation of resonance matter in these collisions is the observed high pion multiplicity. The pion production probability per nucleon-nucleon collision is nearly of the order of 1. This offers a unique possibility, which is nowhere else available in hadron physics, namely, to study the pion-pion interaction in the dense medium formed during a heavy-ion collision. The channel to study here is the production of dileptons through the reaction $\pi^+\pi^- \rightarrow e^+e^-$. Data on dilepton production that were taken by the DLS collaboration during the last years of the BEVALAC

Figure 9. Relative weight of the baryon-baryon channels contributing to antiproton production as a function of bombarding energy (from [27]).

operation, are summarized in Figure 10 together with results of our calculations [14,15]. All the spectra for heavy-ion collisions can at first sight be described by two dominant components only; one reaching up to about 500 MeV of invariant mass – the Dalitz decay of the η -meson –, and a second, higher energy one which comes from $\pi^+\pi^-$ annihilation. This component shows a shoulder-like a structure with a peak in its upper part. This peak is due to the resonance-like structure of the pionic formfactor which is well known to be dominated by the ρ -meson.

Why is this appearance of a ρ signal in heavy-ion induced dilepton spectra interesting? The interest stems from the fact that there are predictions, based on QCD sum rules, of a strong decrease [29–31] of the vector meson mass in dense matter; this is a precursor phenomenon to chiral symmetry restoration [32]. In detail, however, these theories do not agree with each other. Also, there are predictions based on “classical”, well-tested hadronic theories that do not give a lowering of the mass, but instead a significant broad-

Figure 10. Dilepton invariant mass spectra for the systems indicated. The lines show the contributions of the various elementary processes, the data are from the DLS group (from [14,15]).

ening of the resonance with increasing density [33]. It is thus important to look for observable consequences of such a behaviour. We have, therefore, performed calculations based on two particular predictions [14]. The change in the spectrum is shown in Figure 11 for a $Au + Au$ collision, where one sees that indeed the “humplike” structure in the dilepton spectrum disappears if the calculated density-dependence is correct. The calcu-

Figure 11. Observable effect of the density dependence of the ρ meson properties in dense matter. The thick solid line gives the results of a calculation using the free pion formfactor, whereas the thin solid line contains the in-medium changes (from [15]).

lation correctly takes into account that the density changes during the collision; because we know at each point in time and space where the annihilation takes place, we can pick out the corresponding formfactor. If measured, and if experimentally verified, this would be the first experimental verification that hadronic properties change in dense matter. A new international collaboration HADES has been formed to look for such effects in experiments at SIS [34].

2.7. Radial Flow

I would now like to come to a topic which has caught the attention of many of us already about 10 years ago, namely that of nuclear flow. There is a quite exciting new development in this field. While it was well-known that nuclear matter is pressed to the side during the collision, building up the sideways flow [35], it was realized only recently, that superimposed on this flow, that takes place in the reaction plane, there is also a much more azimuthally symmetric flow. This so-called radial collective flow [36] is much stronger than the sideways flow and had escaped experimental detection. In Figure 12 I show the spectra for various particles from protons to Beryllium obtained by the FOPI group at GSI for a $Au + Au$ collision at 150 MeV/u with a very central trigger². A thermal fit using the same temperature for all particles is shown in comparison with the measured spectra. It is obvious that the heavier the particle, the less thermal the spectra are. On the other hand, these spectra can be quite naturally described by a thermal distribution superimposed on an overall expansion. By adjusting such a model to the data one can then determine the flow velocity. By performing in addition a statistical analysis of the fragment mass distributions the FOPI group has also determined the temperature and density at the break-up point [37].

What is so remarkable and exciting is that the energy connected with this new type of flow is about one order of magnitude larger than that in the sideways flow. The temperatures and break-up densities extracted from the fragment distributions are of the order of about 10 MeV and $1/3 \rho_0$, respectively. It would clearly be most interesting if future experiments could tackle such questions as if the flow is really radially symmetric or more cylindrical and if light and heavy particles are emitted at different time-scales. Furthermore, the search for the quite pronounced flow pattern in asymmetric heavy-ion collisions (see Figure 13) should now be taken up.

2.8. Gas-Liquid Phase Transition

Flow happens already in a rather late stage of the collision when expansion takes over. How does the expansion actual proceed? The system cools down and the temperature changes quite drastically as a function of time until finally, close to break-up, thermal equilibrium is nearly established. This suggests the use of thermodynamical concepts for the description of the near-to-final stages of a heavy-ion collision.

Without knowing that we did already in 1976 calculations of van der Waals isotherms for the equation of state of nuclear matter [39], the original result is shown in Figure 14. What one sees is that nuclear matter clearly exhibits a critical point with a temperature of about 18 MeV and a break-up density of about $0.3 \rho_0$; many later calculations have yielded values very close to these. Of course, the latter values have been determined for infinite, uncharged nuclear matter, but we expect that smeared-out remnants of this critical point will survive also in a finite-size system with the long-range Coulomb force, although probably at a lower temperature. Remember that the FOPI flow data indicate a break-up density of just that value and a temperature range of values of about 10-14 MeV.

The actual expansion follows to a remarkably large extent lines of constant entropy, so-

²The phenomenon has recently been verified also by the EOS group at LBL and by an MINIBALL-ALADIN collaboration at the GSI.

Figure 12. Spectra (thin lines) of the particles indicated in the figure for a $Au+Au$ collision at 150 MeV/u. The dots in each figure represent a thermal fit with the temperature of 54 MeV (from [37]).

Figure 13. Flow pattern of the asymmetric heavy-ion collision $Ne + Au$ at 1 GeV/u . The calculation was performed with the code of [6,38].

Figure 14. Isotherms of nuclear matter calculated with a Skyrme force (from [39]).

called isentropes [40,7]. The entropy first rises steeply, then reaches a plateau when the density is at its maximum and from then on increases only slightly during the expansion phase. Expanding along an isentrope the nuclear system may reach an unstable region in the van der Waals plot and then fragment and break apart.

The isentropes at 150 MeV/u and at 800 MeV/u, for example, bracket the critical point, they are quite close to it, and they both run into the instability region. This means that we are finally close to the discovery of the gas-liquid phase transition in nuclei.

A suggestive experimental indication is contained in the results of the MINIBALL-ALADIN MSU-GSI collaboration shown in Figure 15 [41]. There the number of in-

Figure 15. Number of intermediate mass fragments as a function of a reduced impact parameter for a $\text{Au} + \text{Au}$ collision at 3 bombarding energies (from [41]).

intermediate mass fragments is shown as a function of impact parameter for three different bombarding energies, 100, 250, 400 MeV. The number of intermediate mass fragments formed at zero impact parameter, i. e. in very central collisions, decreases rapidly when the bombarding energy increases. This phenomenon has been called the “onset of vaporization” by these groups.

2.9. Summary

Since I have now reached the final step of the heavy-ion collision, this brings me to the summary of my talk. I first wanted to stress that transport theories combine pre-equilibrium and thermal models without having to make ad-hoc assumptions about the degree of equilibration reached. This is a major step forward that has helped our understanding of high-energy heavy-ion collisions tremendously.

One of the facts that we have learned from such calculations and sophisticated new experiments is that particle production in heavy-ion collisions can be understood in terms of incoherent superpositions of nucleon-nucleon collisions.

One of the most stimulating results is surely the finding in transporttheoretical calculations that resonance matter is formed already at SIS energies. Since already there around 20-30 % of all the baryons in the central reaction cell exist in the form of nucleon resonances, it is interesting to ask what will happen at higher bombarding energies. A calculation by Hofmann et al. [42] has shown that at 10.7 GeV, a typical AGS energy, we already have an inversion of the population where there are more resonances than nucleons in the reaction system. The cross-over point is somewhere close to 5 GeV/u. I am convinced that this is the optimal energy for dedicated studies of resonance matter, because there, on one hand, sizeable compressions are already reached and, on the other hand, theoretical descriptions may still use hadronic degrees of freedom. They may still describe the reaction in terms of nucleons, baryons, mesons, and their resonances, i. e. on a basis which has been well tested for a multitude of other phenomena in hadron physics. Promising first experimental results on flow and related phenomena at AGS energies have recently been obtained [43,44]. It would clearly be of great interest if an upgrade of the SIS accelerator with its sophisticated experimental equipment into the energy regime around 5 GeV/u could be obtained.

Observables connected with the formation of resonance matter are particles produced at far-subthreshold energies as I have demonstrated for the extreme case of antiproton production. On the other hand, the high pion multiplicities connected with the formation of resonance matter allow the study of vector mesons in-medium and thus may offer access to the fundamental question of chiral symmetry restoration. All of this illustrates that some of the most exciting developments of hadron physics nowadays take place in heavy-ion physics!

At the end, I find it very exciting that the long-predicted compression driven flow may finally have been discovered. Furthermore, we may now be closer than ever before to an observation of the gas-liquid phase transition, a transition that has escaped us for so long. We have learned more and more to determine densities and temperatures from quite different experiments; they all point to a temperature regime of around 10 MeV at freeze-out and break-up densities of about $1/3 \rho_0$. With an eye on the search for the quark-gluon phase transition I find it essential that we learn to identify a phase transition

in a nuclear system that exists without any doubt in nuclear matter and that is within reach of experiments at various laboratories.

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