

PROPERTIES OF DENSE BARYONIC MATTER AT 2 A GeV*

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Phase space distributions and integrated yields of baryons from central collisions at 1.9 A GeV are discussed in context of thermalization problem. Elongations of rapidity distributions of protons, deuterons, and inclusive baryon samples are shown for energies of 0.04–1.9 A GeV and wide range of system sizes. Inverse slopes from a Boltzmann fit to transverse mass distributions are systematized as a function of particle's mass. Experimental ratios of integrated yields are compared to the Statistical Model and UrQMD. Kinematic temperature parameter characterizing Ni+Ni collisions at 1.93 A GeV is found to be higher than the one obtained within the Statistical Model.

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1. Introduction

During heavy-ion collisions at beam energies around 2 A GeV a hot and dense zone is created, where the baryonic matter is compressed up to 2–3 times above the normal nuclear density. Colliding nucleons are abundantly excited to their resonant states like $\Delta(1232)$ [1]. While baryons [2] and pions [3] constitute the bulk of colliding matter, production of hadrons containing strange quarks has been widely observed by the KAOS [4–8] and FOPI [9–11] collaborations. At beam energies around 2 A GeV the latter particles are created either below or near thresholds of free nucleon–nucleon (NN) channels (*e.g.* 1.6 GeV for $N + N \rightarrow N + K^+ + \Lambda$ and 2.5 GeV for $N + N \rightarrow K^+ K^- NN$). Modifications of their self-energy in dense hadronic

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medium [12] affect the respective production cross-sections and dynamical evolution [5, 8, 10, 13]. The collision is estimated to last about 20–30 fm/ c , both by the theoretical calculations [1] and the interferometry measurements [14]. Such a short timescale and complex collision mechanism raise the question whether the thermal equilibrium can be reached at freeze-out.

An indication for an insufficient time for reaching a chemical equilibration comes from the BUU transport model containing resonances and string degrees-of-freedom [15]. In this calculation, nuclear matter has been contained in a cubic box with periodic boundary condition, and initial values of baryonic-, strangeness- and energy densities have been set. Fig. 4 of the above mentioned paper demonstrates, that for the maximum SIS energy density $\varepsilon_E = 0.65$ GeV/fm³, the pion yield saturates exponentially with the decay constant τ below 10 fm/ c . In contrast, the abundance of kaons needs $\tau \sim 60$ fm/ c to reach the same fraction of its value at freeze-out. As the duration of a heavy-ion collision at *ca.* 1–2 A GeV beam energy is 20–30 fm/ c , the time is insufficient for kaons to saturate their yield.

In the last decade, results of the Statistical Model (SM) fits to the freeze-out yield ratios of collision products at SIS beam energies [16, 17] were often plotted on the T – μ_B (temperature–baryochemical potential) phase diagram together with the fit results from AGS, SPS and RHIC beam energy regimes [16, 18, 19]. Such an approach implies that the colliding matter has reached the chemical equilibrium at freeze-out. Attempts were made to apply the same formalism also to the SIS energies [16, 17, 20]. Below it will be argued that while the SM fit may relatively successfully parametrize the yield ratios at freeze-out, the underlying equilibrium assumption might not be upheld.

This paper is organized as follows. In Section 2, the FOPI experimental setup is briefly described. The emission patterns of different baryonic species are discussed in Section 3. An analysis of particle yields (integrated over the phase space) is presented in Section 4, and the conclusions are enclosed in Section 5.

2. FOPI experimental setup

FOPI is a large acceptance detector system designed to measure charged particles emitted from heavy-ion collisions. It is installed at the beam line of the SIS-18 accelerator at GSI-Darmstadt. Its modular structure allows to cover nearly the full solid angle in the laboratory frame. The innermost parts of FOPI are two tracking chambers: CDC (covering a wide range of polar angles $33^\circ < \theta < 145^\circ$ ¹) and Helitron ($7^\circ < \theta < 30^\circ$). After the recent upgrade, the CDC is surrounded by two Time-of-Flight detectors: the

¹ The dimensions in this section are given in the laboratory angle with respect to the nominal position of a target.

Multi-strip Multi-gap Resistive Plate Chamber (MMRPC) [21] (with excellent timing capabilities of $\sigma_{\text{MMRPC}} \approx 65 \text{ ps}$) and the Plastic scintillation Barrel, both positioned inside the magnet solenoid. The setup is covered at front by two scintillation detector systems: Plastic Wall ($7^\circ < \theta < 30^\circ$) and the innermost Zero Degree ($1.2^\circ < \theta < 7^\circ$). The Start detector is mounted at the beam line, 200 cm upstream from the target. The identification of particle mass in the tracking chambers is based on a correlation between specific energy loss and a curvature of tracks in the magnetic field. Time-of-Flight information combined with the particle momentum inferred from the CDC allows for more precise identification of a mass. Measurement of an energy loss and Time-of-Flight by the forward detectors delivers the identification of the particle charge. Thanks to the large acceptance coverage of FOPI apparatus the collision centrality and reaction plane can be determined from the multiplicity and momenta of the reaction products. FOPI is also capable of reconstructing neutral particles decaying into charged products (*e.g.* $K_S^0 \rightarrow \pi^+ + \pi^-$, $\Lambda \rightarrow p + \pi^-$), whose tracks can be detected by the CDC. More details on the FOPI performances and measurement principles can be found in references [22].

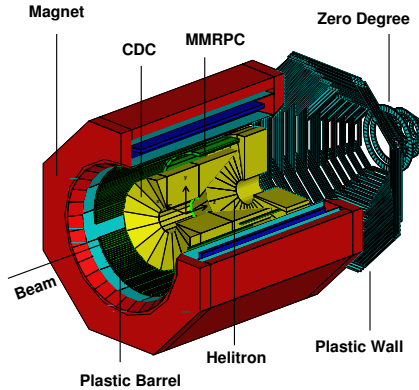


Fig. 1. Configuration of the FOPI apparatus. The 3 arrows marking the coordinate system are of length corresponding to 50 cm, and are placed at the nominal position of a target.

3. Emission patterns of baryonic matter

Different experimental observations suggest non-equilibration of baryons. A purely thermal scenario described by the Boltzmann distribution, or a “thermal plus blast-wave” approach expressed by the so-called Siemens–Rasmussen formula [23] predict a nearly-Gaussian profile of rapidity dis-

tribution, with a dispersion obeying

$$\sigma = \sqrt{\frac{T}{m}}, \quad (1)$$

where T is the temperature of a source, and m is the mass of emitted particle. For central collisions of Ni+Ni at a beam energy of 1.93 A GeV it has been shown, that the transverse mass distributions of protons and deuterons obey the Boltzmann recipe, with the inverse slopes of about 125 and 140 MeV respectively (*cf.* Fig. 5 and Table II in Ref. [24]). However, their rapidity distributions are far elongated with respect to the prediction of Eq. (1) (*cf.* Fig. 6 *ibid.*), and particularly the rapidity profile of deuterons deviates from the Gaussian shape. In other words, the protons and deuterons “prefer” the directions correlated with the initial state of collision: their “memory” was not “reset”.

An elongation of rapidity distribution has been observed for inclusive samples of all emitted charged baryons throughout beam energies of 0.04–1.9 A GeV. A relevant observable was constructed by comparing transverse and longitudinal rapidity distributions. The ratio of their variances, dubbed *var_{tl}*, should be equal to unity for an isotropic emission, and smaller (larger) than unity, if the emission pattern is prolate (oblate). The values of *var_{tl}* obtained for Au+Au and Ca+Ca systems throughout the beam energies in question are shown in the left panel of Fig. 2, after Refs. [2, 25]. They clearly demonstrate, that the emission pattern of charged baryons is prolate, in other words the stopping of the charged baryonic matter is incomplete. For the large Au+Au system, in the beam energy range 300–700 A MeV

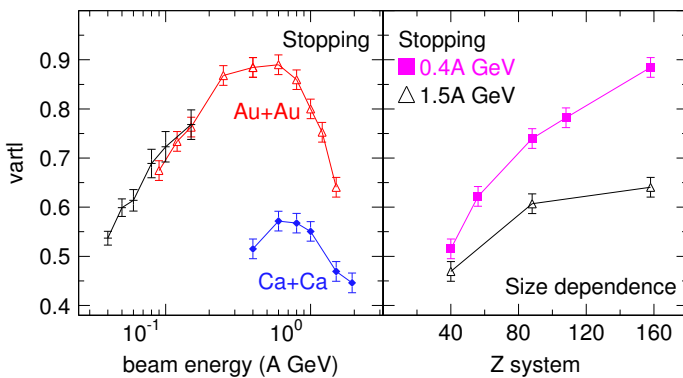


Fig. 2. Stopping of charged baryons expressed as ratio of dispersions of transverse to longitudinal rapidity distributions as a function of a beam energy for small and large colliding system (left panel) and of a system size for two different beam energies (right panel). Figure after Refs. [2, 25].

the v_{rtl} comes nearby unity, however it drops considerably at higher energies. For the smaller Ca+Ca system, the elongation in the beam direction is pronounced for all investigated beam energies. A clear monotonous rise of stopping with the system size is observed at energies both 400 A and 1500 A MeV (see the right panel of the figure above). One could naively explain the observed elongation by a pressure gradient directed along the beam axis. However, in such a scenario, an elongation caused by a pressure gradient should rather not decrease with system size, which is a correlation observed experimentally. Therefore an alternative scenario is put forward, where the interpenetrating matter of colliding ions to some degree does not interact (in other words, is partly transparent), which results in the preference of emission angles along the beam axis. This might explain the system size dependence, as the more of nuclear matter the traversing nucleon finds on its path, the stronger should be the effects of the nuclear interaction. In addition, partial transparency would imply that the colliding matter is not equilibrated.

The FOPI Collaboration investigated strangeness production for Al+Al (small size) and Ni+Ni (medium size) systems at a beam energy of 1.93 A MeV. Two neutral strange particles, K^0 and Λ were reconstructed for about 20% most central collisions of the total geometrical cross-section, in their respective main decay channels: $K^0 \rightarrow \pi^+ + \pi^-$ (BR = 69%) and $\Lambda \rightarrow \pi^- + p$ (BR = 64%) [26]. Between 3 and 10×10^4 particles were found in the investigated channels on the signal to background (S/B) level of 0.8–2. A wide acceptance of the FOPI setup allowed to inspect the phase space of particles in question nearly in full. More details on the experiment, *e.g.* the reconstruction strategy, can be found in Ref. [11]. The analysis of phase spaces of K^0 s and Λ s revealed that the thermal Boltzmann and Siemens–Rasmussen models are capable of describing both the profiles of transverse mass distributions in subsequent rapidity bins, and the rapidity distributions. In Fig. 7 of the above mentioned paper, the rapidity profile of K^0 was compared to that of K^+ , obtained by FOPI and KAOS collaborations [6, 9], and both distributions were found to be in agreement. However, a comparison of rapidity profiles of Λ s and protons, having similar masses, exhibits clear differences demonstrating the extent of elongation of proton distribution discussed in the above paragraphs. In other words, while Λ , K^0 and K^+ particles at their freeze-out times have the memory of the initial channel reset (at least to the level observable here), protons still keep a trace of the state at the beginning of the collision. Therefore, globally no mutual equilibrium has been reached among those particles.

Measured inverse slopes characterizing freeze-out distributions of different particles emitted from Al+Al and Ni+Ni at 1.93 *A* GeV can be plotted as a function of their masses, *cf.* Fig. 3. In a simple non-relativistic approximation, the kinetic energy (E_{kin}) of particles can be expressed by two terms describing the chaotic thermal motion (parametrized by a temperature T) and the collective radial flow (expressed in terms of its velocity $\beta_{\text{rad}}c$) as follows:

$$E_{\text{kin}} = \frac{3}{2} kT + \frac{m\langle\beta_{\text{rad}}c\rangle^2}{2}, \quad (2)$$

where m is a mass of a particle. As the measured transverse mass distributions reflect the total motion of a particle, the extracted inverse slopes T_{eff} should be interpreted rather as effectively summing up both above mentioned contributions, thus yielding $E_{\text{kin}} = 3/2 kT_{\text{eff}}$. Within this simple approximation, the kinematic properties of different particles at freeze-out should be characterized by common values of temperature and velocity of radial flow. As the second term is proportional to the mass, a distinction between two types of motion should be found by fitting the formula 2 to Fig. 3. The fit results deliver the temperatures of respectively about 88 (105) MeV and the velocities of radial flow of 0.17*c* (0.25*c*). A less pronounced flow of the Al+Al system can be linked to the smaller size with respect to Ni+Ni. In the following section these temperatures, dubbed “kinematic” ones, will be compared to the “chemical” temperatures obtained by the SM fit to the ratios of particle yields.

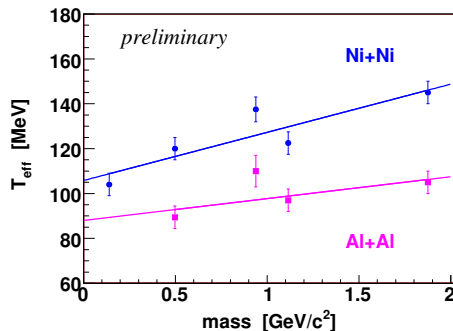


Fig. 3. Effective inverse slopes as a function of mass of particle for Al+Al and Ni+Ni collisions at 1.93 *A* GeV and the best linear fits (see text).

4. Analysis of integrated particle yields

FOPI has also investigated the production of strange resonances: $\Sigma^{*\pm}(1385)$ and $K^{*0}(892)$ (called below Σ^* and K^* , respectively) at the central collisions of Al+Al at 1.93 *A* GeV, in the dominant decay channels

of those particles: ($\Sigma^* \rightarrow \Lambda + \pi^\pm$, $\Lambda \rightarrow p + \pi^-$ and $K^* \rightarrow K^+ + \pi^-$). The short lifetimes of those resonances ($\tau_{\Sigma^*} = 5 \text{ fm}/c$, $\tau_{K^*} = 4 \text{ fm}/c$) make their decay products experimentally indistinguishable from particles building up their phase space backgrounds. Despite the large abundance in those backgrounds, about 3100 ± 500 and 6100 ± 850 resonances were found on the significance level of 9 and 10 [28], at the invariant masses in agreement with values reported by the Particle Data Group [26]. In order to minimize systematic errors stemming from the strategy of particle reconstruction, the yields of investigated resonances have been related to the abundances of particles having at least one common decay product. The following ratios of particle yields were found:

$$\frac{P(\Sigma^{*+} + \Sigma^{*-})}{P(\Lambda + \Sigma^0)} = 0.125 \pm 0.042 \quad \text{and} \quad \frac{P(K^*)}{P(K^0)} = 0.032 \pm 0.012. \quad (3)$$

One should point out, however, that the yields of reconstructed resonances have a different nature than those of particles characterized by the lifetime considerably longer than the duration of a heavy-ion collision. For the latter group, the yield observed experimentally can be identified as the abundance at freeze-out, as the decay products are mainly not affected by rescattering effects, thus an original particle can be localized on the invariant mass distribution of its decay products. Resonances, decaying mainly during the collision, are different in this context, as their products are typically considerably affected by the rescattering effects. As a result, the number of experimentally reconstructed resonances is the sum of those existing within some time duration, convoluted with the probability of their decay products to survive the collision unaffected, rather than an abundance attributed to a moment of a last interaction. While dynamical models make predictions on the time evolution of a resonance's yield [1], the experimental state-of-art does not permit to extract the time information from the reconstructed resonances.

Production of ϕ mesons in central collisions of both Al+Al and Ni+Ni at 1.93 A GeV has been investigated in the dominant decay channel $\phi \rightarrow K^+ + K^-$ (BR = 49.1%). Preliminary analyses allowed to reconstruct, respectively, 195 and 100 ϕ mesons [29, 30] at the S/B level of 1.1 and 1.3. Following preliminary yields were obtained: $2.2 \pm 0.2 \times 10^{-4}$ for Al+Al and $6 \pm 2 \times 10^{-4}$ for Ni+Ni. The obtained yields were compared to the production rates of respectively K^* and K^+ , cf. Fig. 4.

In total, 6 (8) independent ratios of particle yields were constructed for central collisions of Al+Al (Ni+Ni) systems at a beam energy of 1.93 A GeV. These ratios were compared to the Statistical Model predictions performed by the THERMUS code [31], as shown in Fig. 4. The calculations were done in frame of a strangeness-canonical ensemble, where strangeness is

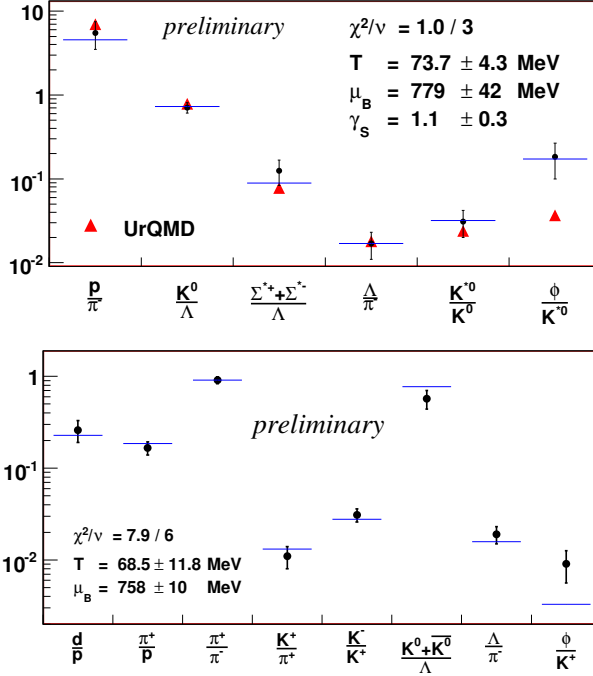


Fig. 4. Yield ratios for central collisions of Al+Al (top) and Ni+Ni (bottom) at 1.93 A GeV obtained experimentally (dots), and compared to the predictions of Statistical Model (lines) and UrQMD (triangles).

exactly conserved, while baryon number and charge are conserved on average (see [31] for details on the method). Due to a necessity to constrain the strangeness number S at low abundance of produced strange quarks at 1.9 A GeV, a canonical ensemble was used for particles characterized by $S \neq 0$ [19]. In general, a good quality of fitting was obtained, expressed by $\chi^2/\nu = 0.3$ (1.3) for Al+Al and Ni+Ni, respectively. The best fits were found for the Statistical Model parameters of temperature of about 74 (68) MeV and baryo-chemical potential of about 780 (760) MeV respectively, well in line with an observed trend on the phase diagram (*cf.* Fig. 11 in [33]). In the case of Al+Al it was possible to fit in addition the strangeness undersaturation factor γ_S , being non-equal to unity in the case of non-equilibration of the yield of particles containing strange quarks [16]. However, it was found to be consistent with unity within experimental errors. These results demonstrate that the SM with two (three) free fit parameters of T , μ_B (and γ_S) is capable of reproducing the experimental yield ratios at 1.9 A GeV, despite its underlying assumption of a complete equilibrium being at odds with the experimental rapidity profiles observed in the reaction.

The fitted SM parameters of “chemical” temperature (T_{chem}) can be compared to the “kinematic” temperatures (T_{kin}) extracted within the approach of Eq. (2). While for the Al+Al system, both model temperatures appear to be in agreement within 1.5 standard deviation, in the case of Ni+Ni the T_{kin} is considerably larger. For higher beam energies of AGS and SPS regime the trend is found to be reversed [34]. It has been long perceived as intuitive, as the chemical equilibrium (stabilization of produced yields) is expected to be established at earlier stages of the collision than the kinematic equilibrium (freezing and chaotization of momentum directions due to rescattering). However, at SIS beam energies the collision process may not result in a thermalization. Also the modelling of the collision dynamics by the Eq. (2) may be an oversimplification. More investigation is needed to reach an understanding of the above mentioned observation.

The obtained yield ratios for the Al+Al system were also compared to the predictions of transport UrQMD model (showed as triangles in the top panel of Fig. 4), where no equilibrium condition is assumed. Results were found to be in agreement not only with experimental data, but also with the predictions of the SM. One exception is the ϕ/K^* yield ratio, however the UrQMD code is known to underestimate the ϕ meson yield [32]. An observation that predictions of both theoretical models having entirely different assumptions agree within errors with the experimental data suggests, that the yield ratios may not be a sensitive observable in search of thermalization scenarios during the collision in the investigated region of beam energies, at least at the state-of-art level of available data.

5. Conclusions

Kinematic distributions of a broad sample of particles emitted from central heavy-ion collisions at the SIS beam energy region were measured by the FOPI Collaboration. Rapidity distributions of protons, deuterons and a sample of charged baryons exhibit an elongation, with respect to both the predictions of thermal models, and distributions of that variable for strange particles like $K^{0,+}$ and Λ . This elongation has been interpreted in terms of nuclear transparency and shows the lack of equilibrium among particles at freeze-out. Other particles containing strange quarks: $\Sigma^{*\pm}(1385)$, $K^{*0}(892)$ and ϕ were reconstructed, and their total yields obtained. A comparison of ratios of particle abundances to the predictions of both Statistical Model and UrQMD shows, that two theoretical models assuming different understanding of a heavy-ion collision deliver predictions in agreement with the experimental data. In the case of Ni+Ni collisions, the temperature parameters obtained with the analysis of kinematic spectra are found to be higher than the ones delivered by the statistical model fit to the yield ratios, an order opposite than at the AGS and SPS energies.

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