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Strangeness from SPS to FAIR

Searching for the onset of deconfinement

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Abstract. Since the early days of heavy-ion physics, strangeness has been considered a sensitive probe of the state of matter created in nuclear collisions. This assessment still holds today, where we are witnessing renewed interest in collisions at moderate energies, manifested in the running or projected experimental programmes at RHIC, SPS, FAIR, and NICA. In this article, we will review the current understanding of strangeness production at lower energies and discuss how far future measurement of strange particles can contribute to understanding the properties of dense QCD matter and to the search for the onset of deconfinement.

1 Introduction

Nuclear matter, when sufficiently heated or compressed, is expected to undergo a transition to a deconfined state, where the degrees-of-freedom are not hadronic, but partonic. In this "Quark-Gluon Plasm", the quarks as basic constituents of matter are not bound into hadrons, but can move quasi-free over a volume much larger than the typical hadron size. Numerical simulations of Quantum-Chromodynamics on a discrete space-time lattice predict the deconfinement transition to take place at a critical temperature of about 160 MeV at vanishing net-baryon density.

In the terrestrial laboratory, heated or compressed QCD matter can be produced by the collision of heavy nuclei, although only for small time intervals and volumes. In the course of such collisions, a hot and dense zone is formed in the overlap area of the two colliding nuclei ("fireball"), which, depending on the collision energy, may be in the deconfined phase. After expansion and cooling, the system decomposes into a multitude of hadrons. It is the task of heavy-ion physics to connect the measured properties of this hadronic final state with the state of the system in the early stage of the collision.

Experimentally, heavy-ion physics has a history of several decades by now, from first experiments in the early 1970's at the Bevalac to the currently ongoing nuclear collision programme at the LHC. Progress was achieved by the availability of new accelerator facilities, giving access to higher beam energies and, consequently, larger energy densities in the reaction zone. The experimental results strongly suggest that in heavy-ion reactions at RHIC energies ($\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$), and probably already at top SPS energy ($\sqrt{s_{\mathrm{NN}}} = 17.3\,\mathrm{GeV}$), a deconfined state of matter is indeed created. The properties of this state are currently being investigated in detail at the highest available collisions energies at the LHC.

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In parallel to these investigations of QCD matter at highest energies, a number of experimental programmes at lower, moderate collisions energies are proposed or already under way: the beam energy scan programme at RHIC, the NA61 experiment at the CERN-SPS, the CBM experiment at GSI-FAIR, and the MPD at JINR-NICA (the latter being facilities under construction). Because of the nature of baryon stopping, collisions at lower energies produce a medium with moderate temperature but high net-baryon density. Varying the beam energy thus allows to a certain extent to study strongly interacting matter at different conditions. This is illustrated in Fig. 1, showing a speculative phase diagram of QCD matter. This diagram may contain a rich structure in particular at high net-baryon densities: a first-order chiral transition, possible distinguished from the deconfinement transition by a third, "quarkyonic" phase, and a critical point separating the region of first-order chiral transition from the crossover at low density. Only a small part of the phase diagram is theoretically accessible from first-principle calculations (lattice QCD). For the larger rest, effective models are employed to study the properties of QCD matter. The experimental confirmation of the conjectured properties and structures would provide a breakthrough in the understanding of QCD.

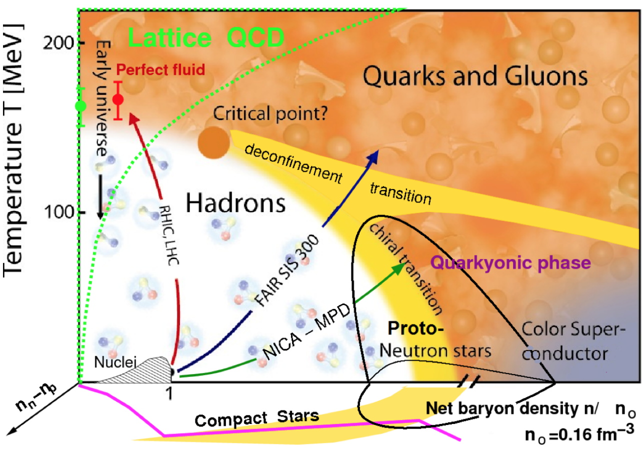

Figure 1. Conjectured phase diagram of strongly interacting matter in terms of net-baryon density and temperature. (Courtesy A. Sorin)

In the following, we discuss the role of the measurement of strange particles in the experimental study of the phase diagram, in particular in the study of the transition from confined to deconfined matter. We begin with a brief review of the current understanding of strangeness production at moderate energies, outline the open questions, and finally propose some observables which are most promising to address the issue of deconfinement.

2 The interest in strangeness

Since the beginning of the search for the Quark-Gluon Plasma (QGP), particles containing strange quarks were considered a key probe. A straightforward and qualitative reason for this is of course that there is no strangeness in the entrance channel of the nucleus-nucleus collision; all strange quarks seen in the final state hadrons are thus produced in the reaction and are not remnants of the incoming nucleons.

Quantitatively, it was shown that the different production mechanisms of strangeness in a partonic scenario, compared to "conventional" hadronic processes, lead to quite different expectations for the amount of strangeness produced in the collision. The reason for this can be traced to the mass of the lightest strangeness carrier, which is the Kaon ($m \sim 500$ MeV) in the hadronic case, and the s quark ($m \sim 100$ MeV) on the partonic side. Producing strange hadrons in hadronic processes like, e.g., $\mathrm{p + p \rightarrow pK^+\Lambda}$, is thus energetically much more expensive than the partonic production of $\mathrm{s\bar{s}}$ pairs, e.g., $\mathrm{qq \rightarrow s\bar{s}}$. In fact, partonic processes were shown to saturate the amount of strange quarks in a (sufficiently hot) QGP on a time scale of a few fm, well within the lifetime of the fireball [1, 2]. The most effective process was found to be the gluon fusion ($\mathrm{g + g \rightarrow s\bar{s}}$). Hadronisation is expected to preserve the amount of strange quarks, which show up in strange hadrons in the final state. The prediction thus was that there is more strangeness production in nucleus-nucleus reactions relative to p+p collisions if a deconfined phase is formed. This so-called "strangeness enhancement" was the earliest predicted signature for the Quark-Gluon Plasma.

An enhanced production of strange hadrons in central Pb+Pb reactions relative to p+p collisions was in fact observed by experiments at the CERN-SPS in the late 1990s at a bombarding energy of 158 GeV ($\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV) [3, 4]. The enhancement observed a strict hierarchy determined by the number of strange valence quarks: while Kaons and Λ with one strange valence quark are found to be enhanced by a factor of about two, an enhancement factor of 15 was observed for Ω (sss) (see Fig. 2).

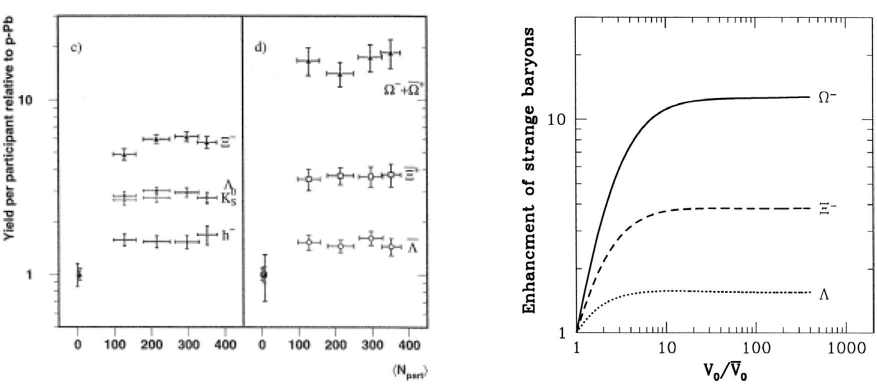

Figure 2. Left: yields of strange hadrons (normalised to the number of participant nucleons) as a function of centrality, expressed by the number of participants [4]. The abscissa is normalised to the value measured in p+Pb collision ($N_{\mathrm{part}} = 2$). Right: Strangeness enhancement for hyperons as a function of volume, calculated with the canonical formulation of the hadron gas model [6].

The original perception of strangeness enhancement underwent a shift in interpretation when it was shown that all observed hadron abundances at top SPS energy, including those of strange hadrons, can be reproduced by a hadron resonance gas in chemical equilibrium [5]. This formally purely hadronic description uses only three parameters – volume, temperature, and baryo-chemical potential – to fit particle yields or yield ratios. The temperature obtained from these fits is about 160 MeV, stunningly close to both the Hagedorn temperature and the critical temperature as obtained from lattice QCD calculations.

In the context of thermal models, the difference in the relative strangeness content in nuclear and elementary collisions is understood as an effect of exact strangeness conservation, which suppresses strangeness production in small systems like resulting from p + p reactions [6]. Strangeness conservation is accounted for by the canonical formulation of the thermal model w.r.t. strangeness production, which shows a strong volume effect. For large systems like those produced in central Pb + Pb collisions, the grand-canonical formulation, which is technically easier to solve, gives a sufficiently precise approximation. The thermal model in its canonical formulation also reproduces the hierarchy of strangeness enhancement as observed experimentally (see Fig. 2). So, "strangeness enhancement" has become "canonical suppression" in small systems.

The question remains how the apparent chemical equilibrium is obtained. A-priori calculations [2] as well as microscopic hadronic transport simulations like UrQMD show that inelastic hadronic two-body collisions are not efficient enough to equilibrate strange hadrons – in particular not heavy hyperons like Ξ or Ω – within the finite lifetime of the fireball. Two explanations were brought forward. The first argues that the transition from the deconfined to the confined state, i.e., from the QGP to the hadron gas, taking place when the system expands and cools below the critical temperature, must populate the hadronic phase space statistically, whatever the detailed mechanisms of hadronisation may be [7]. The phase transition thus creates a hadronic state of maximum entropy, i.e., an equilibrium state, which in this view is not the result of a hadronic relaxation process, but a consequence of the nature of hadronisation.

An alternative explanation of the apparent chemical equilibrium took into account the production of strange particles in collisions with more than two hadrons in the entrance channel, e.g., $2\pi + 3K \to \bar{N}\Omega$ [8]. Such processes require three or more particles to be close in space-time and, hence, show a very strong dependence on temperature and density. They are thus only effective very close to the critical temperature, i.e., near the phase transition. There, however, they are sufficient to equilibrate even Ω baryons within a few fm.

The two pictures outlined above agree in the opinion that a phase transition from a QGP to a hadron gas is prerequisite for a hadro-chemical equilibrium state, and that the hadron abundances do not change significantly after hadronisation, i.e., hadronisation and chemical freeze-out coincide. Consequently, the observed chemical equilibrium is taken as an indirect proof of the transition to a deconfined state in the course of the collision.

Strange hadron yields measured in nuclear collisions at much higher energies as available at BNL-RHIC and CERN-LHC are also in very good agreement with a thermal description. Strong evidence for the creation of a QGP here comes also from very different observables like jet quenching and flow [9–12]. Strangeness at top SPS and higher energies thus seems to be understood.

3 The onset of deconfinement

If a deconfined state is formed in heavy-ion collisions at top SPS energy, the question arises at which collision energy the deconfinement transition is first achieved. Following the argument that strangeness equilibration is indicative for the formation of a QGP, it seems natural to search for the onset of deconfinement by testing the applicability of the hadron gas model at lower collision energies. The thermal model is able to describe data obtained at lower SPS and at AGS energies; here, however, only a small number of hadron species was experimentally accessible up to now. In particular, data on multi-strange hyperons are quite scarce, owing to their low multiplicity at moderate energies.

At very low energy, the HADES collaboration at GSI-SIS18 reported a strong deviation – by a factor of about 15 – of the Ξ^- yield from the thermal fit to the hadron yields measured in Ar + Cl collisions at 1.76A GeV [13]. This is the first indication that the statistical description of strange hadrons yields does not hold at low energies. It should be noted, however, that at this energy, Ξ^- is produced deep sub-threshold, presumably by secondary collisions involving previously produced K and Λ, e.g., $\Lambda + K^- \to \pi^0 + \Xi^-$ or $\Lambda + \Lambda \to p + \Xi^-$.

A systematic investigation of strangeness production at lower SPS energies was performed by the NA49 collaboration in the years 1999 - 2002, with apparently intriguing results: both the K^+/π^+ and

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the Λ/π^- ratios show a narrow maximum at a beam energy of 30A GeV [14, 15]. Such a maximum was predicted by a the so-called Statistical Model of the Early Stage (SMES) [16], assuming the deconfinement to set in at this energy. The association of the observed maximum in relative strangeness production to the onset of deconfinement, however, was heavily debated subsequently. In particular, it was shown that the hadron gas model, with the parameters T and μ_B smoothly parametrised as function of collision energy, also results in a strangeness maximum at 30A GeV, which is attributed to the transition from a baryon-dominated to a meson-dominated hadronic final state [17]. Still, the original description of the energy dependence of the K^+/π^+ ratio by the hadron gas model was rather poor [18], but it was improved by including high-mass resonances into the model [19]. The situation remains unclear (see Figure). The deviation of the K^+/π^+ and Λ/π^- ratios from the statistical description does not appear sufficient for a strong claim for "new physics"; the Ξ^- measurements lacks precision, and for the Ω^-, only one data point at 40A GeV exists.

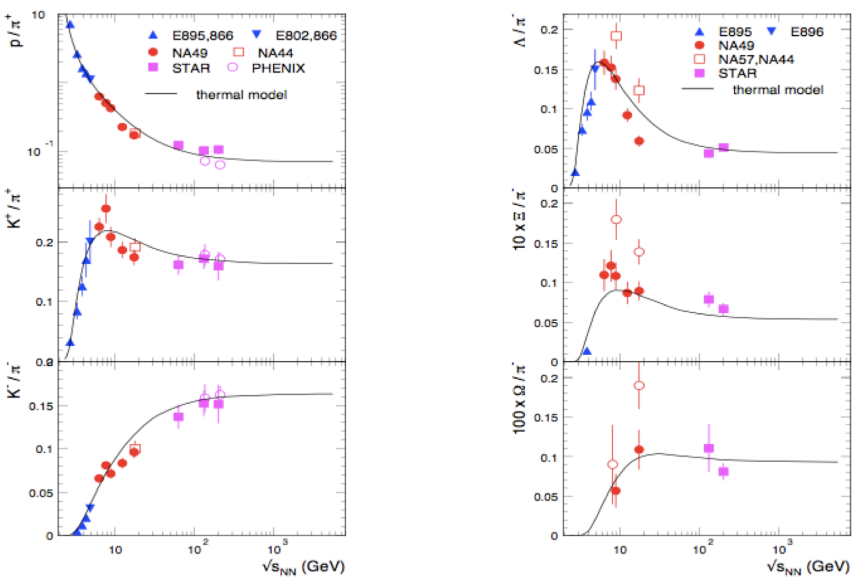

Figure 3. Energy dependence of the relative yield of strange hadrons. The full line shows the parametrisation by the the hadron gas model. (Courtesy NA49 collaboration)

The predictions of the hadron gas model and the Statistical Model of the Early Stage are quite different: in the hadron gas model, the strangeness maximum is due to the maximum in net-baryon density. The effect thus diminishes with increasing strangeness content: the maximum for Ω/π is shallower than that for Ξ/π, which is shallower than Λ/π. Moreover, the position of the maximum shifts to higher energies with increasing strangeness content [20]. In the SMES, the situation is the opposite: the effect is due to the overall strangeness production and thus more pronounced for Ω than for Λ or K; and the maxima are predicted to be at the same energy. So, yields of multi-strange hyperons are discriminative, and precision data on the Ξ and Ω yields as function of collision energy can be expected to lead to a definite conclusion on the issue. Such data can be expected from future experiments at NICA and FAIR-SIS300.

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4 The ϕ meson

In the general context of strangeness production, the ϕ meson plays a particular role owing to its valence quark content $s\bar{s}$, which makes it strangeness-neutral as a hadron, but sensitive to partonic strangeness production scenarios. In particular, strongly enhanced ϕ production (w.r.t. proton-proton reactions) was suggested as indicator for the QGP [22]. The respective measurements at SIS-18, AGS, and RHIC energies, however, do not reveal a spectacular behaviour; they are again well described by the statistical hadronisation scenario. In the SPS energy range, in contrast, the description of the hadron gas model fails considerably, and so do the results of microscopic transport simulations (Fig. 4). ϕ production in this energy range, hosting the maximum in net-baryon density and, possibly, the onset of deconfinement, still lacks a sound interpretation. In contrast to multi-strange hyperons, the data on ϕ yields are rather precise, such that future measurements will not help elucidate the situation. The ball here is surely on the theory side.

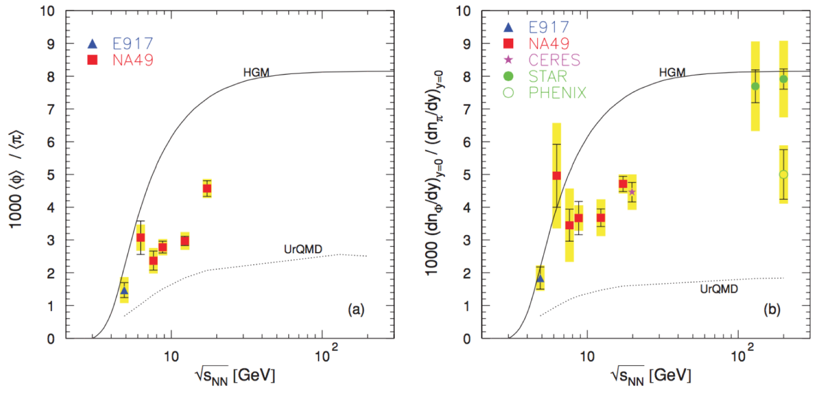

Figure 4. ϕ/π ratio in full phase space (left) and at mid-rapidity (right) measured in central Pb+Pb (Au+Au) collisions, as function of collision energy. The full line shows the prediction of the hadron gas model, the dotted line that of the UrQMD model. (Taken from [21].)

5 Strange anti-baryons

In the energy range under discussion here, the measurement of anti-baryons is notoriously difficult, since their yield is very low – the production of anti-baryons is strongly suppressed in a baryon-dense environment. Consequently, the current data situation is scarce. In particular, data on mutli-strange anti-baryons do not exist below top SPS energy. Still, strange anti-baryons might be a very sensitive probe of the matter produced in heavy-ion collisions. The reason is that the suppression of their production is released in a deconfined medium. This was demonstrated by the microscopic transport model pHSD, which switches to partonic production mechanisms in regions of the fireball where a critical energy density is exceeded [23]. The volume fraction of deconfined to confined matter is a function of collision energy; it is very small at e.g., 5A GeV, but close to unity at top SPS energy (158A GeV). The effect of the deconfined medium on the production of Ω^- and $\bar{\Omega}^+$ is shown in Fig. 5 by comparison to the results obtained with HSD, without any partonic phase, in the FAIR energy range. While the yield of Ω^- is only slightly affected, its anti-particle appears very sensitive, and the effect is most pronounced at the lower energies, where it amounts to more than an order of magnitude. The reason for the Ω not being affected appreciably is that the fraction of QGP is very low and does not significantly add to the hadronic production. This changes at higher energies, where partonic production eventually becomes dominant. The hadronic anti-Ω production, in contrast, is so low that event a tiny amount of deconfined medium suffices to enhance it by factors. This microscopic picture is quite different from the concept of an onset of deconfinement as discussed in section 3; it rather predicts a gradual increase of the fraction of deconfined medium until the entire fireball consists of QGP.

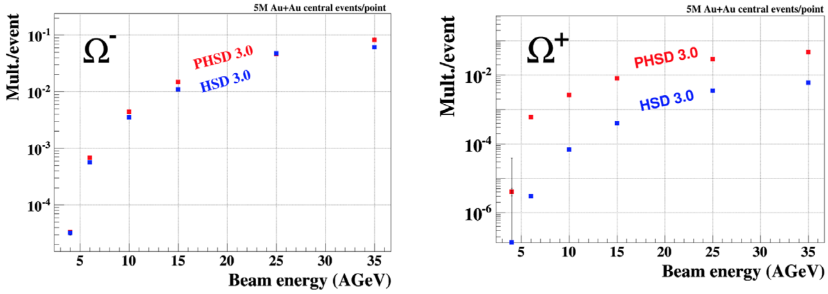

Figure 5. Multiplicity of Ω^- (left) and $\bar{\Omega}^+$ in central Au+Au collisions as predicted by the HSD (blue) and the pHSD (red) models. The latter includes a partonic production scenario in fireball regions exceeding a critical energy density. (Courtesy CBM collaboration)

Following this model prediction, the measurement of the yield of multi-strange anti-hyperons is most promising for the study of deconfinement even (or in particular) at low energies as will become available with the FAIR facility. Experimentally, the very low expected anti-hyperon yields necessitate extreme event statistics, which seem only feasible with the CBM experiment [24].

6 Summary

Strangeness production below top SPS energy still poses a number of open questions: Does thermalisation hold even at low energies? Can the "horn" in the K/π ratio be understood in terms of the hadron gas model? What happens at maximal net-baryon density (30A GeV)? What are the production mechanisms near or below the threshold in elementary collisions? Why can the ϕ yield at SPS energies neither be described by the hadron gas model nor by microscopic transport? What is the energy dependence of the production of multi-strange (anti-)hyperons?

Strangeness continues to be one of the most important probes for the study of the QCD phase diagram at high net-baryon densities and in particular for the search for the first-order phase transition. Many new data will become available in the near future by ongoing activities at RHIC and SPS, and in the next decade by the new experimental programmes CBM at FAIR and MPD at NICA. The latter two promise to decisively improve the data situation on multi-strange hyperons and, in particular, anti-hyperons. Such data are likely one of the prime keys to the understanding of deconfinement in dense QCD matter.

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