

## Summary talk: Experiments at low energies

**Yvonne Leifels**

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt,  
Planckstr. 1, 64291 Darmstadt, Germany

E-mail: [y.leifels@gsi.de](mailto:y.leifels@gsi.de)

### Abstract.

In heavy-ion collisions at beam energies  $\sqrt{s_{NN}}$  between 1 and 150A GeV highest baryonic densities are reached at rather moderate temperatures. By varying the beam energy and the system size a broad range of the QCD phase diagram is scanned where several interesting phenomena are predicted by theoretical models. Apart from possible phase transitions and existence of a critical point in this regime, the production of strangeness and the interaction of strange particles with the surrounding hot and dense nuclear medium constitutes a prominent probe not only to address the underlying reaction mechanisms and production processes but in particular to constrain densities and temperatures reached in the course of the collision.

Recent results on heavy-ion collisions in this beam energy regime obtained by various experimental collaborations are summarized, with special emphasis on strangeness production, rare probes, and critical phenomena. The importance of data on elementary reactions (i.e., pp, p+nucleus, and  $\pi$ +nucleus) as a bench mark for theoretical models and their relevance for understanding the underlying mechanisms of heavy-ion collisions are being discussed. Several interesting observables have been presented in various contributions, which give further motivation for the construction of high-rate experiments at new accelerator facilities.

### 1. Introduction

The conjectured phase diagram of QCD, usually presented in terms of temperature  $T$  and baryonic chemical potential  $\mu_B$ , is of fundamental interest. At small baryonic chemical potential, the hadronic phase is assumed to be separated from the quark-gluon phase by a cross-over transition. At the critical point the cross over transition is expected to evolve with rising baryonic chemical potential into a supposedly first-order phase transition. Super-conducting phases might appear at even higher baryonic potential and low temperature [1, 2]. Theoretical predictions of the properties of both the critical point and the phase boundary at high baryon chemical potential are still lacking experimental verification and/or constraints.

The relevant regime in the QCD phase diagram of high baryonic potential and moderate temperature can be accessed experimentally with heavy-ion collisions in the beam energy regime  $\sqrt{s_{NN}} < (20 - 100)$  GeV. During the course of these reactions densities up to several times normal nuclear matter density  $\rho_0$  are reached. Such collisions of heavy-ions have been studied at SPS/CERN, AGS/BNL and in the low-energy scan of RHIC/BNL, and—in the lowest energy regime—at the accelerators of GSI and formerly at Berkeley. Several observables have been suggested to give access to the properties of the phase boundary and the critical point (i.e., the K/ $\pi$  ratio as a function of beam energy, fluctuations as a measure of critical phenomena etc.). Experimental findings, like the enhancement in the K<sup>+</sup>/ $\pi$ <sup>+</sup> ratio at  $\sqrt{s_{NN}} \approx 10$  GeV,



have motivated various efforts to understand the origin of these observations and to characterize heavy-ion collisions in this energy regime with a very high degree of precision.

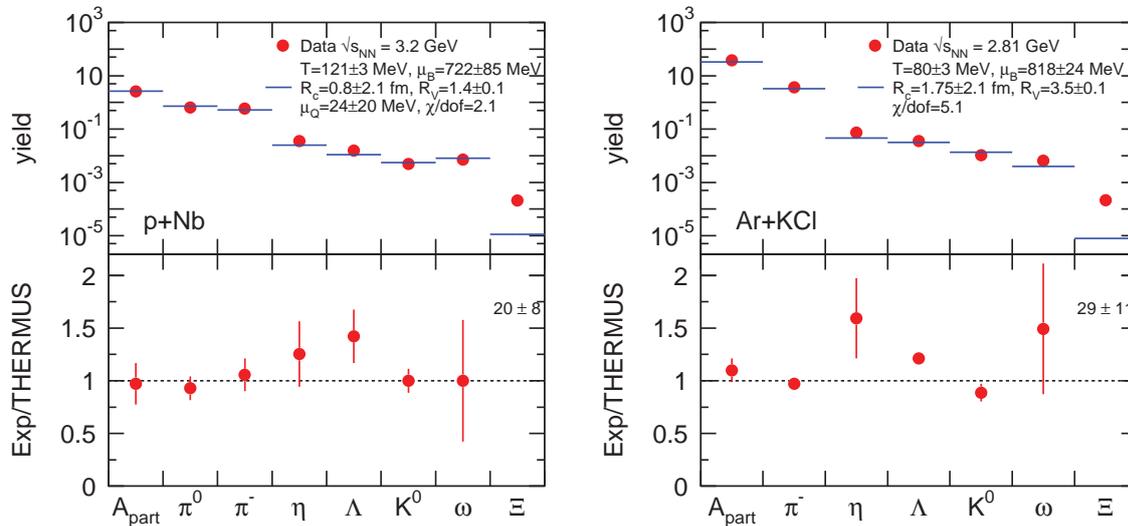
In addition, the study of heavy-ion collisions at low energies offers unique opportunities to investigate particle production, strangeness production in particular, in a high-density and moderate temperature environment. The high density phase is baryon dominated and rather long lived. Most of the particles are produced below or close to their production thresholds in NN collisions. Hence, the production rates are very sensitive to density fluctuations and in-medium effects. Despite low production yields modern detector set-ups capable to sustain high event rates are able to accumulate enough statistics even on very rare probes. Relying now on a broad range of particle species, the chemical freeze-out can be more reliably characterized in the framework of thermal models.

Another interesting aspect is the formation of hyper-nuclei in heavy-ion collisions by coalescence of nucleons with hyperons, which is—according to thermal model predictions—highest at these moderate beam energies [3]. Measuring yields and phase-space distributions will give hints on the underlying production mechanisms and the interaction of hyperons with nucleons in a dense medium. From the astrophysical side, the precise knowledge of the hyperon-nucleon interaction is of crucial importance, since  $\Lambda$ -hyperons are supposed to be stable in neutron stars and might form an important constituent of neutron star matter.

## 2. Strangeness production at SIS energies

The HADES experiment at GSI has measured strangeness production in Ar+KCl reactions at 1.8A GeV [4]. It was possible not only to reconstruct  $\Phi$ -mesons—their production in elementary processes is inhibited by the OZI rule—via their decay into charged kaons but also double strange  $\Xi^-$ -hyperons ( $\Xi(1315)^-$ ) by measuring their decay into  $\Lambda + \pi^-$ . Rather high production yields have been deduced for both particles. A  $\Phi/K^-$  ratio of  $0.37 \pm 0.13$  was measured [5]. Such a high ratio means that the  $K^-$  spectra might be affected by the decay of  $\Phi$ -mesons substantially. After an upgrade of the HADES detector, it was possible to investigate Au+Au collisions at  $E_{beam} = 1.25A$  GeV with an event rate of 50 kHz, thus enabling to collect enough statistics to measure not only kaon production yields and spectra but also to access rare probes like the  $\Phi$ -meson with a production threshold in  $E_{NN} = 2.59$  GeV in NN collisions. The  $\Phi/K^-$  ratio is even higher than in the 2A GeV region. Interestingly, this experimental data can be described within the framework of a thermal model [6], when the  $\Phi$ -Meson is included without strangeness suppression; strangeness is conserved only in a radius smaller  $R_C$  than the system radius  $R_V$ . In a first attempt describing Au+Au results (not including systematical errors),  $T_{chem} = 47 \pm 5$  MeV,  $\mu_B = 799 \pm 34$  MeV, and  $R_C/R_V = 0.3 \pm 0.2$  have been extracted.

Generally, all particle yields in heavy-ion reactions at SIS energies can be described within thermal models with the exception of the  $\Xi^-$  data. However, it was found that the chemical freeze-out temperature  $T_{chem}$  is equal or slightly smaller than the kinetic temperature  $T_{kin}$ , which is extracted from the particle spectra at mid-rapidity [5, 7]. This is unexpected, because the kinetic freeze-out should occur after the chemical one at a lower temperature. Variant findings were reported for p+Nb reactions at 3.5 GeV [5]. Thermal model fits agree with the experimental particle yields, except—again—for the  $\Xi^-$  production. Particle yields for p+Nb and Ar+KCl collisions including the thermal model fits are presented in 1. Such a result is rather remarkable. since thermal equilibration is not readily expected for proton induced reactions at such low energies. Of particular interest is, however, that for p-induced reactions chemical temperatures  $T_{chem}$  are *larger* than the kinetic temperatures  $T_{kin}$ . One might speculate whether the larger flow contribution in collisions of heavy-ions is responsible for the high kinetic temperatures observed in this data. But similar findings have also been reported for a rather small heavy-ion system (Al+Al), where essentially no flow exists [7]. These results certainly call for more systematic measurements varying energy and system size.



**Figure 1.** Preliminary HADES data on particle production in p+Nb at 3.5 GeV (left) and Ar+KCl collisions at 1.85A GeV (right) in comparison to THERMUS fits [6], as presented by [5].

It has been shown that the particle ratios measured in heavy-ion collisions can be reproduced by models like UrQMD [8]. If microscopic transport models also reproduce the difference between kinetic and chemical temperatures (including the gross properties of the reactions like stopping and flow), one might investigate the mechanisms leading to the apparent thermal equilibration in heavy-ion reactions within those models.

### 3. Strangeness production at SIS energies and the role of heavy resonances

Several theoretical attempts to describe strangeness production at SIS energies based on microscopic transport models have been presented [8, 9] during this conference. In one of them [8], high mass resonances are contributing to the strangeness production, in particular to the production of  $\Phi$ -mesons and the double strange  $\Xi^-$ . It is possible to reproduce not only the  $\Phi$  yields with such an assumption but also the production rates of  $\Xi^-$ -hyperons. Such conjectures have to be verified by experimental data. Proton-induced reactions deliver information on elementary production mechanisms of strange particles, form a normalization for heavy-ion reaction data, and yield bench mark information for microscopic transport models.

Data on proton-induced reaction in the SIS energy regime measured by the HADES collaboration have been presented [10]. Data of p+p at  $E_{beam} = 3.5$  GeV are used to extract a complete cross section data base of channels relevant for  $K^0$  production and now can serve as reference measurement for the  $K^0$  in p+A data, where the interaction between Kaons and nucleons is studied.

It was possible to study the role of heavy resonances in the production of strange particles with the reaction channel  $p+p \rightarrow \Sigma(1382)^+ + K^+ + n$ . Angular distributions of the  $\Sigma(1385)^+$  in different reference frames are found to be compatible with the hypothesis that 33% of the  $\Sigma(1385)^+$  result from the decay of an intermediate broad  $\Delta^{++}$  excitation at about 2000 MeV/ $c^2$ .

Those two examples corroborate the necessity of measuring elementary reactions in conjunction with heavy-ion reactions. At low energies strangeness production is a complex process, which is not completely understood, and additional information on elementary processes is definitely needed.

#### 4. Production of nuclei and hyper matter

Nuclei are formed in heavy-ion collisions essentially at all energies. At SIS energies a substantial part of the colliding nuclei matter is emitted from the hot and dense zone is bound into fragments even in the most central collisions. The number of formed nuclei is dramatically decreased at LHC energies. But on the other hand, the energy is high enough that nuclei and anti-nuclei are formed with essentially the same rates, with a penalty factor of  $\sim 300$  for each additional nucleon [11].

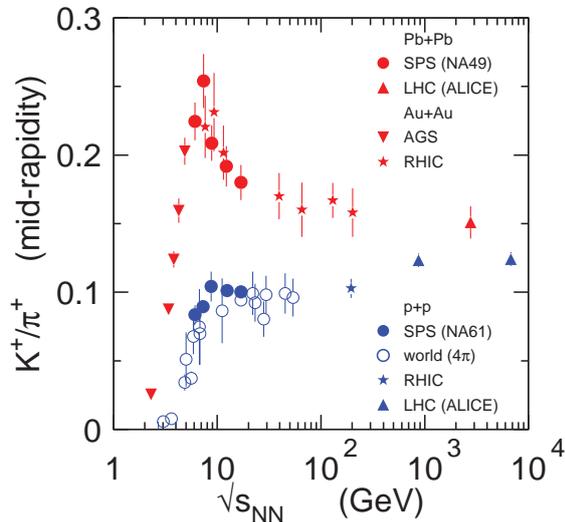
One or more of the nucleons are replaced by a hyperon in hyper-nuclei. Study of hyper-nuclei in heavy-ion collisions has several advantages over production in elementary reactions: the momentum transfer is large, which allows determining lifetimes with a high-degree of precision; one could produce hyper-nuclei with an exotic n/p ratio by employing radioactive nuclei; or one might observe multi-strange objects at higher incident energies and study the properties of the EOS of hyper matter. Hyper-nuclei are supposedly formed by coalescence. At least at higher energies their production yields are compatible with thermal-model predictions [11]. At lower incident energies other processes are discussed. Hyper-nuclei might be formed by re-scattering hyperons into the spectator matter and subsequent capture within the residues. Such a mechanism requires that the spectator matter is moving not too fast to ensure that the phase space distribution of the hyperons, which are produced in the hot and dense collision zone, overlaps with that of the spectator matter. Scattering of pions into the spectator matter followed by strangeness production via the reaction  $\pi + N \rightarrow K^+ + Y$  is an alternative mechanism to form hyper-nuclei in the spectator residues. Heavier (and more exotic) hyper-nuclei could be formed much more easily by such processes than by coalescence [12].

The HYPHI collaboration has investigated hyper-nuclei production at SIS energies in the spectator region. In  ${}^6\text{Li} + {}^{12}\text{C}$  collisions at  $E_{beam} = 2A \text{ GeV}$   ${}^3_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{H}$  have been reconstructed by their weak decays into  $\pi^-$  and  ${}^3\text{He}$  or  $\alpha$ , respectively. An interesting finding, which is also reported by other experiments (STAR and ALICE [11]), is that the  ${}^3_{\Lambda}\text{H}$  lifetime is much shorter than previously measured [13] and significantly shorter than the lifetime of the  $\Lambda$ -hyperon (263 ps). How the  $\Lambda N$  interaction and the hyper-triton lifetime are connected is still unresolved.

Cross sections as well as phase space distributions of  ${}^3_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{H}$  hyper-nuclei have been reconstructed by the HYPHI collaboration for the first time at such low incident energies [13]. These results have been compared to predictions of a microscopic transport code in combination with a specific clusterization algorithm [14]. Since usually only nucleons are transported in microscopic models of heavy-ion reactions, additional codes are needed to form clusters. The FRIGA code calculates binding energies (including a  $\Lambda N$  potential and quantum effects like shell and pairing energies) and searches the most probable clusters with a simulated annealing mechanism. The model results describe the experimental data of the HYPHI reasonably well.

#### 5. Search for the critical point

Theoretical attempts to predict the existence and location of the critical point in the phase diagram of  $T$  versus  $\mu_B$  lead to conflicting results. A scan of the phase diagram by varying the sizes of colliding nuclei (change of rescattering probability) and energies of the collisions (change of  $\mu_B$ ) is a promising experimental search strategy, which is being pursued at different accelerators and setups. A study of hadron production in central Pb+Pb collisions by NA49 at SPS, revealed structures in the energy dependence of the  $\langle K^+ \rangle / \langle \pi^+ \rangle$  ratio at mid-rapidity (see Fig. 2), a sudden change in the number of pions per participant, and a plateau in the energy dependence of the inverse slope parameter. Such structures have been predicted to be an onset of the phase transition to the QGP. Non-monotonic behaviour of the energy dependence of certain observables and a coinciding maximum of several fluctuation measures, like particle multiplicities or average transverse momenta of produced particles, would indicate the existence and the location of the critical point. Amongst others, such a program was started by the NA49



**Figure 2.** Data sets from different experiments for  $K^+/\pi^+$  ratio of Au+Au/Pb+Pb and p+p collisions as a function of  $\sqrt{s_{NN}}$ .

collaboration [16] and is now followed systematically by the NA61/SHINE experiment and the low energy scan program pursued by the STAR collaboration at RHIC.

New high precision p+p and Be+Be data was presented by the SHINE collaboration [15], which serves as bench mark and normalization of the heavy-ion data. There are indications that the structures observed in Pb+Pb are already present in p+p but on a much smaller level as can be seen in Fig. 2. Theoretical models do not describe all features of the p+p data. The search for maxima in fluctuation observables has been deemed to not be conclusive enough. In medium size systems there is an indication of a maximum observed, but, for heavier systems, high statistical data must still be obtained in future experimental campaigns.

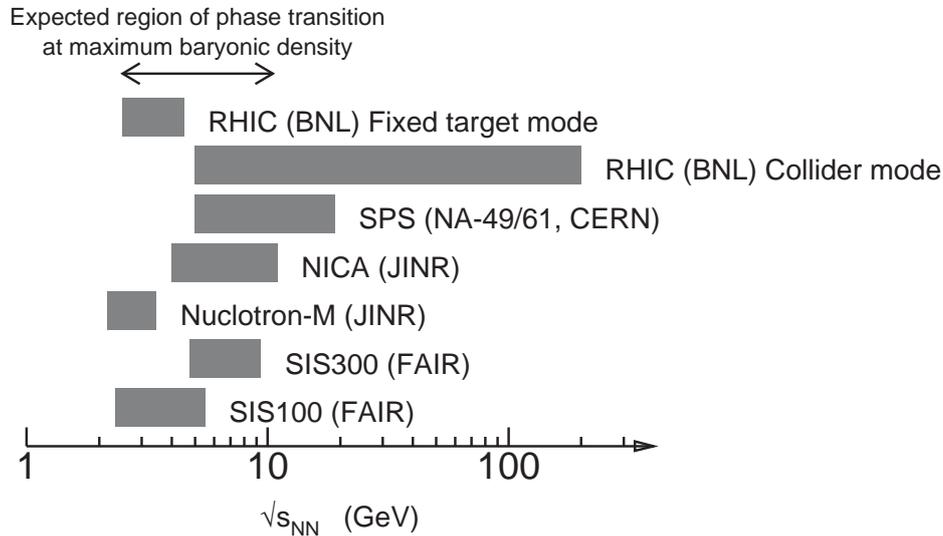
## 6. Outlook

High rate experiments to investigate heavy-ion collisions are undertaken at SIS18 energies employing detectors, which are able to withstand high intensity beams. The large statistics allows investigating strangeness production and the search for rare probes like  $\Phi$ -mesons, double strange  $\Xi^-$  [5], as well as hyper-nuclei [13]. Parallel to the measurements of heavy-ion reactions, proton induced reactions are studied to understand reactions channels for strangeness production at threshold energies. Partial wave analysis (PWA) was discussed [10] as another important tool to unravel the role of high mass resonances in the strangeness production. But still more data is needed to disentangle the possible processes.

The search for the critical point was continued with measurements in p+p and Be+Be systems at SPS energies. Hints were found in the energy and system size dependence fluctuation observables, which are sensitive to the critical point and the experiments will be continued with heavier systems to complete these systematic efforts.

The STAR detector will extend the available data set to the lowest possible energies available at RHIC in the near future by making the beam collide with a fixed target. This method will enhance the luminosity at those beam energies and reduce the available energy in the center-of-mass system (compare Fig. 3).

The renewed interest in the high density, moderate temperature region of the QCD phase diagram is one of the important research lines at the two accelerator projects currently pursued in Europe: FAIR and NICA. The first stage of the FAIR accelerator will come into operation in 2021 with the SIS100. SIS100 will deliver high intensity beam upto 11A GeV for Au ions and 29



**Figure 3.** Energy ranges in terms of  $\sqrt{s_{NN}}$  accessible by existing and future accelerators in the region of the QCD phase diagram of high  $\mu_B$  and moderate  $T$  after [17].

GeV for protons; NICA will offer experiments at a collider with heavy-ions at  $\sqrt{s_{NN}} = 3.5$  GeV with average luminosity of  $10^{27}$  starting in 2019. An overview on the future accelerator ranges in  $\sqrt{s_{NN}}$  is shown in Fig. 3. Plans for new experiments aiming on the investigation of the QCD phase diagram at high baryonic densities have been presented during this conference; CBM at FAIR [18], and BM@N and MPD at the accelerators in Dubna [17]. BM@N (Baryonic Matter at Nuclotron) is a fixed target experiment at the Nuclotron (JINR) to study A+A collisions by measuring a variety of observables, i.e., particle yields, ratios, transverse momentum spectra, rapidity, and angular distributions, as well as fluctuations and correlations of hadrons, whereas the Multi-Purpose Detector MPD will be an experiment at the NICA collider at the JINR. The Compressed Baryonic Matter experiment (CBM) is laid out as a fixed-target experiment at the heavy-ion synchrotrons SIS-100/300 at the FAIR facility. The detector will record both pA and AA collisions at beam energies between 10 and 45 AGeV with interaction rates of 10 MHz. Hence, it will be possible to study extremely rare probes, which are not accessible by any other accelerator and/or detector setup operating in this energy regime.

Many measurements have been undertaken at SPS, AGS, and lately at RHIC investigating  $J/\Psi$  suppression, strangeness production, elliptic and directed flow, HBT (femtoscopy), event-by-event fluctuations, and many more to understand the QCD phase diagram in the region of high baryonic densities and moderate temperatures. Several interesting non-monotonic behaviours of observables have been found, which motivated the development of the new detector and accelerator concepts. During the next years data will become available, which will shed new light on this highly interesting and exciting region of the QCD phase diagram.

Finally, I want to express my gratitude to the organizers and all participants for the interesting and fruitful conference, the stimulating discussions and the inspiring atmosphere.

## 7. References

- [1] Weise W 2012 *Progress in Nuclear and Particle Physics* **67** 299-311
- [2] Fukushima K and Hatsuda T 2010 *Reports on Progress in Physics* **67** 014001
- [3] Andronic A et al 2011 *Phys. Lett. B* **697** 203-207
- [4] Schmah A 2010 *J. Phys. G* **37** 094004

- [5] Lorenz M *contribution to this conference*
- [6] Wheaton S, Cleymans J, Hauer M 2009 *Comp. Phys. Commun.* **180** 84
- [7] Lopez X et al. 2008 *J. Phys.* **G** 044020
- [8] Bleicher M 2015 *contribution to this conference*
- [9] Cabrera D 2015 *contribution to this conference*
- [10] Fabbietti L 2015 *contribution to this conference*
- [11] Chinellato D 2015 *contribution to this conference*
- [12] Botvina A 2015 *contribution to this conference*
- [13] Rappold C 2015 *contribution to this conference*
- [14] Le Fèvre A 2015 *contribution to this conference*
- [15] Larsen D 2015 *contribution to this conference*
- [16] Seyboth P 2015 *contribution to this conference*
- [17] Kekelidze V 2015 *contribution to this conference*
- [18] Friese V 2015 *contribution to this conference*