Hyperons at CBM-FAIR

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Abstract. The CBM experiment is one of the four scientific pillars of the Facility for Antiprotons and Ion Research (FAIR) in Darmstadt, Germany. Its discovery potential – complementary to heavy-ion experiments at colliders – is based on high-luminosity ion beams. This enables access to extremely rare probes such as charmed particles, vector mesons or multi-strange hyperons with high statistics. However, 3rd generations readout systems and detectors are required to handle the large interaction rates (up to 10 MHz for Au+Au) with sufficient precision and bandwidth. In this contribution we will outline the unique CBM physics program focusing onto hyperons.

1. Introduction
The observation of a mass \((1.97 \pm 0.04) M_\odot\) neutron star [1] has spurred interest into models of nuclear matter capable to stabilize nuclear matter at high densities [2,3,4], i.e., to prevent the collapse of heavy neutron stars into black holes. The relevant degrees of freedom in nuclear matter at high densities are nucleons and hyperons; as well as quarks in the case of the onset of a deconfinement transition.

The future experiments at FAIR (Darmstadt) or at NICA (Dubna) will employ high intensity heavy-ion beams in the range 2-35 AGeV (\(\sqrt{s_{NN}} = 2.7 - 8.3 GeV\)) and \(\sqrt{s_{NN}} = 4 - 11 GeV\), respectively. These experiments will allow to investigate rather exotic matter at baryon densities up to \(7 \times \rho_0\) with good statistics for the first time. This will enable to explore yet uncharted territory with rare probes, such as charmed particles, di-leptons, double hypernuclei or multi-strange hyperons [5,6].

2. Rare Probes
Rare probes such as low mass di-leptons, charmonium and open charm will allow to characterize the medium at high net baryon densities much more detailed then previously possible. While bulk observables (flow, spectra of proton and pions) as well as correlations and fluctuations are accessible to all experiments (STAR/PHENIX@RHIC, NA61@SPS, MPD@NICA) at the relevant low beam energies (\(\sqrt{s_{NN}} \sim 8 GeV\)), the above mentioned rare probes can only be measured at CBM@FAIR.

In this paper, however, we will not further focus on leptons and charm. Instead, we will discuss (multi-)strangeness as probes of dense matter: flow and excitation functions, subthreshold production of multi-strange hyperons, double-strange hypernuclei and strange di-baryons, the latter also called MEMOs (metastable exotic multi-hypernuclear objects).
2.1. Flow

The experimental investigation of flow has basically ceased in the last century with the decommissioning of the FOPI experiment at the GSI SIS18 and the E877/895 experiments at the BNL AGS. One of the central topics of flow physics is the quest for the nuclear equation of state. Besides being interesting in itself as describing the property of nuclear matter the knowledge of the nuclear EoS is of outmost importance to understand the stability of heavy neutron stars.

As can be seen from Figure 1 the description of flow data by simulations is unsatisfactory: no single EoS describes all types of anisotropies at all energies. At the same time the experimental errors allow for an uncertainty in the incompressibility parameter $K$ of up to 150 MeV. However, protons represent only a small part of the flowing species. The CBM experiment will dramatically improve the data situation by measuring the flow of identified particles in the relevant energy range, including multi-strange hyperons and dileptons. Of particular interest is the flow of particles not suffering from rescattering like $\Xi$ hyperons or $\phi$ mesons, for which no experimental data exist. These measurements will significantly contribute to our understanding of the QCD-matter equation-of-state at neutron star core densities.

![Figure 1](image.png)

**Figure 1.** Excitation function of sideward (left) and elliptic flow (right) of protons for Au+Au collisions. The symbols represent experimental data, while the line are simulations assuming different equations of state.

2.2. Multi-strange Hyperons

The yields and phase-space distributions of multi-strange hyperons ($\Xi, \Omega$) are promising tools to study the properties and the degrees of freedom of QCD matter at extreme nuclear densities. In particular, these particles may serve as unambiguous messengers of a high-density phase: for hyperon production binary reactions proceeds like $pp \rightarrow \Xi^-K^+K^-p$ or $pp \rightarrow \Omega^-K^+K^0p$ and have accordingly high thresholds of 3.7 and 7.0 GeV, respectively. In dense baryonic matter, however, $\Xi^-$ and $\Omega^-$ can also be created via strangeness exchange reactions like $\Lambda\Lambda \rightarrow \Xi^-p$ and $\Lambda\Xi^- \rightarrow \Omega^-n$ or $\Lambda K^\pi \rightarrow \Xi^-\pi^0$, with the $\Lambda$ and the $K^-$ previously produced in independent reactions such as $pp \rightarrow K^+\Lambda p$ and $pp \rightarrow K^+K^-pp$, which require only 1.6 and 2.5 GeV, respectively. Alternatively, three-body collisions involving $\Lambda$’s or kaons open new production channels for $\Sigma$ and $\Omega$ with respect to $pp$ reactions. The production of multi-strange hyperons is thus expected to be enhanced at high densities, and their yield to be sensitive to the baryon density reached in the fireball. Moreover, the energy distributions of
multi-strange hyperons provide information on the fireball temperature and the radial flow at the time, when they are emitted. Therefore, systematic measurements of $\Xi^-$ and $\Omega^-$ production as function of beam energy and size of the colliding nuclei offer the possibility to study the nuclear matter equation of state, or baryon density fluctuations as they are expected to occur when the system undergoes a first-order phase transition or approaches the QCD critical endpoint.

Existing data on the production of multi-strange hyperons in nuclear collisions at SIS-100 beam energies are scarce [7]. In particular, no data on production below 40 AGeV ($\sqrt{s_{NN}} = 8.8$ AGeV) exist, except for $31 \Xi^-$ measured at 6 AGeV at the AGS [8]. A systematic measurement of multi-strange hyperons as diagnostic probes of dense nuclear matter at SIS-100 energies has thus a substantial discovery potential.

| Energy [AGeV] | $\Sigma^-$ | $\Omega^-$ | $\Lambda^-$ | $\Xi^-$ | $\bar{\Omega}^+$ |
|---------------|------------|------------|------------|--------|-----------------|
| 4.0           | $9.0 \times 10^6$ | $1.8 \times 10^5$ | $3.6 \times 10^3$ | $5.3 \times 10^3$ | $9.0 \times 10^2$ |
| 6.0           | $2.6 \times 10^7$ | $5.0 \times 10^5$ | $2.4 \times 10^5$ | $1.4 \times 10^4$ | $2.8 \times 10^3$ |
| 8.0           | $4.0 \times 10^7$ | $1.4 \times 10^6$ | $3.6 \times 10^6$ | $2.0 \times 10^5$ | $6.0 \times 10^4$ |
| 10.7          | $5.4 \times 10^8$ | $2.2 \times 10^6$ | $6.8 \times 10^6$ | $3.8 \times 10^5$ | $1.2 \times 10^4$ |

**Table 1.** Expected hyperon yields [9] measured per week at a minimum-bias interaction rate of $2 \times 10^4 s^{-1}$. The minimum bias multiplicity is assumed to be 25% of the one in central collisions.

A prerequisite for these measurements is sufficient statistics in finite time. Table 1 shows that already at $2 \times 10^4$ minimum-bias interactions the accumulated data exceed previous measurements in terms of yield.

2.3. **Search for Double Hypernuclei**

Up to now, only a handful double hypernuclei have been seen, mostly in emulsion experiments. Hypernuclei, i.e., nuclei containing at least one hyperon in addition to nucleons, offer the fascinating perspective to explore the third, strange dimension of the chart of nuclei. Their investigation provides information on the hyperon-nucleon and even on the hyperon-hyperon interactions, which play an important role in neutron star models.

The conventional production mechanism is rather complicated, e.g., via the following chain reaction employing a kaon beam: $K^- + N \rightarrow K^+ + \Xi^-, \Xi^- + ^{12}C \rightarrow ^{\Lambda \Xi}He + ^4He + t$. Hence the production cross sections are exceedingly small. On the other hand, heavy-ion collisions offer the possibility to produce (double) hypernuclei via coalescence of $\Lambda$’s with nucleons or light fragments in the final state of the reaction. In high-energy nucleus-nucleus collisions, $\Lambda$ hyperons are produced abundantly. Their maximum yield is observed at beam energies between 30 and 40 AGeV (about 50 in central Pb + Pb collisions). At 10 AGeV still 15 $\Lambda$’s are produced. The coalescence probability of $\Lambda$ with light nuclei is highest at low energies yielding, according to hadron gas model calculations [10, see also 14], $2 \times 10^{-2} \, ^{\Lambda_6He}, \, 10^{-6} \, ^{\Lambda_6He}$ and $3 \times 10^{-8} \, ^{\Lambda_6He}$ per central collision at $8 \sim 10$ AGeV (cf. **Figure 2**). This would give, with the foreseen CBM interactions rates about $120 \, ^{\Lambda_6He/week}$ and still $3.6 \, ^{\Lambda_6He/week}$. For the detection of the double hypernuclei, the decay chain has to be reconstructed in the tracking detectors, e.g., $^{\Lambda_6He} \rightarrow ^{\Lambda_5He} + \pi^- \rightarrow ^4He + p + \pi^-$. Such measurements would represent a breakthrough in hypernucleus physics, as up to now only 6 candidates for double-lambda hypernuclei events have been found, and only one $^{\Lambda_6He}$ event has been unambiguously identified.
Figure 2. Energy dependence of hypernuclei yields at mid-rapidity for $10^6$ central $Au + Au$ events as calculated with the statistical model [10]. The predicted yields of $^3He$ and $^4He$ are included for comparison.

2.4. Search for Meta-Stable Multi-Strange Objects

Metastable objects with strangeness, e.g. strangelets and (strange) di-baryons, were proposed long ago as collapsed states of matter, consisting of either baryons or quarks [11,12]. Up to date, none of these objects have been observed. Their existence or absence is an open issue in high-energy physics (cf. [13]).

High-energy nuclear collisions, with kaons and $\Lambda'$s being abundantly produced in a single event, could provide a tool to create such composites objects with multiple units of strangeness. Recent calculations within a hybrid (microscopic transport + hydrodynamics) model predict multiplicities/event of about $3 \cdot 10^{-2}$ for the $(\Xi^0\Lambda)_b$ in central collisions at 35A GeV [14]. Owing to the finite lifetime of such an object its decay, e.g., $(\Xi^0\Lambda)_b \rightarrow \Lambda\Lambda$, should be detectable via displaced vertices ($ct \approx 1 - 5\ cm$) [15]. Indeed, simulations (cf. Figure 3) show that $(\Xi^0\Lambda)_b'$s can be reconstructed with a signal-to-background ratio above 200 for $10^{12}$ central events [16,17].

Most of the strange di-baryon searches were done via the ($K^+, K^-$) reaction (cf. [18], and Refs. therein), which is not directly comparable with the production of di-baryons in heavy-ion collisions. The nearest equivalent to heavy-ion reactions is a result reported by the KTeV collaboration [19] at Fermilab, were lightly bound $H^0$-dibaryons produced in $pN$-collisions were searched for. However, the acceptance of the experimental apparatus was optimal for a decay length $ct = 160\ cm$, and thus the reported limit are not applicable for the search range of $ct \approx 1 - 5\ cm$ accessible in the CBM experiment.
Figure 3. Reconstructed invariant-mass distribution of $\Lambda\Lambda$ candidates

3. Experimental Setup
The experimental setup of the CBM experiment is shown in Figure 4. From left to right one has the CBM superconducting magnet with the silicon spectrometer inside, which consists of the Micro Vertex detector (MVD) and the Silicon Tracking System (STS). It is followed by a Ring Imaging Cherenkov (RICH, light blue), four layers of Transition Radiation Detector (TRD, blue) and a Time-of-Flight (TOF, yellow) wall. Downstream of the experiment is a Projectile Spectator Detector (PSD). The muon spectrometer (MuCh) is in its parking position. For the observables discussed above primarily the STS in combination with the TOF wall is relevant.

Figure 4. View of the CBM experimental setup. For details see text.
3.1. STS

The silicon tracking system is intended for the reconstruction of the trajectories of charged particles produced in the interaction and the measurement of their momenta. It is installed between the yokes of a superconducting dipole magnet, providing a field integral of $1 \text{Tm}$ and an aperture of $140 \text{cm}$ in vertical and $280 \text{cm}$ in horizontal direction.

![Image](image_url)

**Figure 5.** Left: conceptual design of the Silicon Tracking System, showing a cut through the detector in the dipole magnet. Right: engineering model of the STS, with the eight tracking stations to be mounted on the main support frame.

The STS is realized as an array of eight tracking stations constructed from thin double-sided silicon micro-strip detectors. The roughly 1,200 sensors will be mounted on a light-weight carbon structure, the signals from the inner part being routed to the front-end electronics at the periphery of the station by ultra-thin cables. The aim is to keep the material budget below 1% radiation length per station. **Figure 5** shows the conceptual design of the detector system and the current engineering model.

3.2. TOF

The identification of hadrons in CBM is achieved through the measurements of their time-of-flight. The TOF detector is based on the technology of resistive plate chambers (RPC), providing a time resolution of about $60 \text{ps}$. RPC modules will be assembled in a wall with an active area of about $120 \text{m}^2$, the granularity being adapted to cope with the variation of hit rates, which range from $2 \text{kHz/cm}^2$ at the periphery to $25 \text{kHz/cm}^2$ in the inner sections.

4. Status of Preparations

The development of detector and technical systems for CBM is in an advanced stage [20] and will be largely completed by the end of 2016. For most of the systems Technical Design Reports are approved or under evaluation. Series production of detector components will start 2016/17 and is planned to be completed 2019/20, followed by the installation in the CBM cave and commissioning without beam.

First beams from SIS-100 into the CBM cave are not expected before 2022. In view of this delay, the CBM collaboration is investigating possibilities to install and commission parts of detector systems at other experimental facilities. Examples are the installation of a part of the TOF wall at the STAR experiment at RHIC or the co-operation of CBM with BM@N at NICA in the construction of the silicon detectors. Furthermore, CBM intends to install a reduced set-up at a beam line at the SIS-18 accelerator at GSI in order to test the interplay of systems and the full data chain including data processing in real-time.
5. Summary

Heavy-ion collisions in the SIS-100/300 energy range are an ideal tool for the production of hadronic matter at neutron star core densities, and hence offer the unique opportunity to investigate fundamental properties of strongly interacting systems and its constituents: the nuclear matter equation of state, exotic new phases such as quarkyonic matter, in-medium modifications of hadrons as a signature for chiral symmetry restoration, hypernuclei and multi-strange objects, charm production at threshold beam energies, and charm propagation in nuclear matter.

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