Status and Challenges of the Compressed Baryonic Matter (CBM) Experiment at FAIR

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Status and Challenges of the Compressed Baryonic Matter (CBM) Experiment at 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 rare probes.

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 hadrons) 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 more exotic probes of dense matter: strangeness in the form of multi-strange hyperons, double-strange hypernuclei and multi-strange di-baryon, the latter also called MEMOs (metastable exotic multi-hypernuclear objects).

2.1. Multi-strange Hyperons

The yields and phase-space distributions of multi-strange hyperons (Ξ, Ω) 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 $pp \rightarrow \Omega^- K^+ K^+ K^0 p$ and have accordingly high thresholds of 3.7 and 7.0 GeV, respectively. In dense baryonic matter, however, Ξ^- and Ω^- can also be created via strangeness exchange reactions like $\Lambda\Lambda \rightarrow \Xi^- p$ and $\Lambda\Xi^- \rightarrow \Omega^- n$ or $\Lambda K^- \rightarrow \Xi^- \pi^0$, with the Λ 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 Σ and Ω 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 Ξ^- and Ω^- 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 $40A\ GeV$ ($\sqrt{s_{NN}} = 8.8\ AGeV$) exist, except for 312 Ξ^- 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]	Σ^-	Ω^-	$\bar{\Lambda}^-$	$\bar{\Sigma}^-$	$\bar{\Omega}^+$
4.0	9.0×10^6	1.8×10^5	3.6×10^3	5.3×10^3	9.0×10^2
6.0	2.6×10^7	5.0×10^5	2.4×10^5	1.4×10^{34}	2.8×10^3
8.0	4.0×10^7	1.4×10^6	3.6×10^6	2.0×10^5	6.0×10^4
10.7	5.4×10^8	2.2×10^6	6.8×10^6	3.8×10^5	1.2×10^4

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 2×10^4 minimum-bias interactions the accumulated data exceed previous measurements in terms of yield.

2.2. 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: $K^- + N \rightarrow K^+ + \Xi^-, \Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$. 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, Λ 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 Λ with light nuclei is highest at low energies yielding, according to hadron gas model calculations [10, see also 14], 2×10^{-2} $^3_\Lambda He$, 10^{-6} $^5_{\Lambda\Lambda} He$ and 3×10^{-8} $^6_{\Lambda\Lambda} He$ per central collision at $8 - 10\, AGeV$. This would give, with the foreseen CBM interactions rates about 120 $^5_{\Lambda\Lambda} He/week$ and still 3.6 $^6_{\Lambda\Lambda} He/week$. For the detection of the double hypernuclei, the decay chain has to be reconstruction in the tracking detectors, e.g., $^5_{\Lambda\Lambda} He \rightarrow {}^5_\Lambda He + \pi^- \rightarrow {}^4 He + p + \pi^-$.

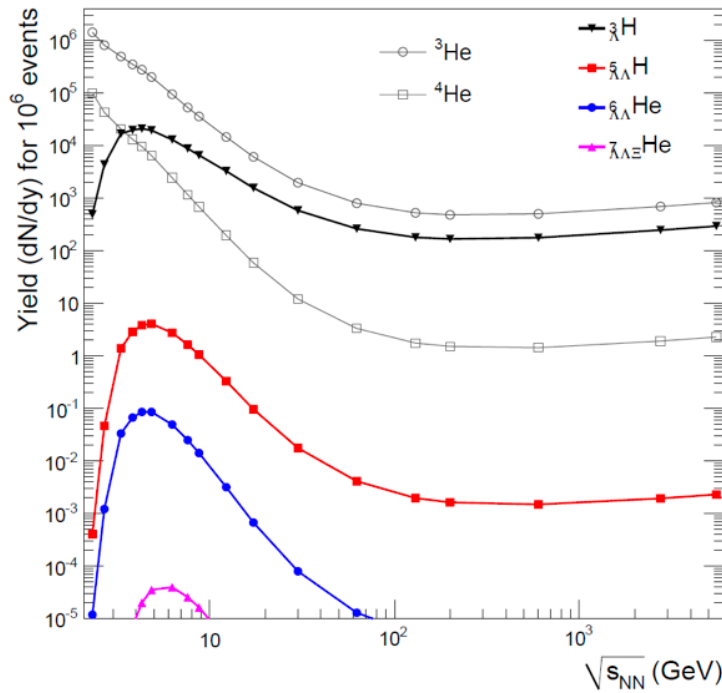**Figure 1:**   Energy dependence of hypernuclei yields at mid-rapidity for 10^6 central $Au + Au$ events as calculated with the statistical model [10]. The predicted yields of $^3 He$ and $^4 He$ are included for comparison.

2.3. 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 ($c\tau \approx 1 - 5\, cm$) [15]. Indeed, simulations 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 $c\tau = 160\, cm$, and thus the reported limit are not applicable for the search range of $c\tau \approx 1 - 5\, cm$ accessible in the CBM experiment.
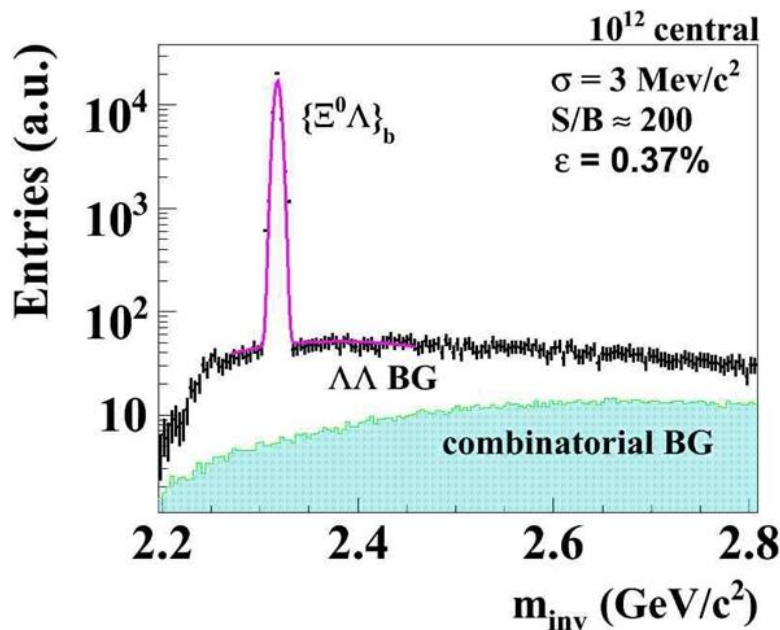
Figure 2:   Reconstructed invariant-mass distribution of $\Lambda\Lambda$ candidates

3. 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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