Physics with the CBM Experiment

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on behalf of the CBM Collaboration

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FAIR Accelerator Complex

Primary Beams
- $10^9$/s Au up to 11 GeV/u
- $10^9$/s C, Ca, ... up to 14 GeV/u
- $10^{11}$/s p up to 29 GeV
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What We Are After

The quest: study properties of QCD matter at high net-baryon densities
• Equation-of-state
• Onset of deconfinement / chiral restoration
• Nature of transition (first-order?)
• Critical end-point

General experimental strategy: stay as open and flexible as possible; measure as many observables as you reasonably can.
CBM: Experiment Systems

- Large acceptance: 2.5° – 25°
- Identify:
  - Hadrons (TOF)
  - Electrons (RICH, TRD)
  - Muon (MUCH)
  - Neutral probes (ECAL)
  - Open charm (MVD)
- High rates: up to $10^7$ events/s
SIS-100 and SIS-300

- SIS-100 and CBM are part of the FAIR Modularised Start Version (MSV)
- SIS-300 is agreed-on part of FAIR, but not of the start version; timeline is unclear
- we concentrate here on CBM@SIS-100
  - Au: 2A – 11A GeV
  - Ni: 2A – 15A GeV
  - p: up to 30 GeV
- staying open for SIS-300 as later upgrade
CBM Physics: Strangeness

• One of the “classical” observables: strangeness enhancement / canonical suppression
• Strangeness yields from are well described by the statistical model: strong argument for phase transition (no hadronic mechanism to equilibrate e.g. Omega)
• Model fits describe data at lower SPS and at AGS
  – But with a limited amount of particle species
  – Data on multi-strange baryons are scarce
• Following this: measuring strange baryon abundances at lower energies.
  – Down to which collision energies does the hadron gas model hold?
Breakdown of strangeness thermalisation?

HADES result for $\Xi^-$ at SIS-18 (1.76A GeV): $\Xi^-$ yield is off by an order of magnitude from the statistical model.

N.b.: This is deep sub-threshold.
Production through multi-step processes

$$\Lambda K \rightarrow \Xi \pi \quad \Lambda \Lambda \rightarrow \Xi^- p \quad \Xi K \rightarrow \Omega \pi$$

$R.~Holzmann$, CBM Physics Workshop, April 2010
The need for data on multi-strange baryons

A long-lasting debate: pure hadronic description or signal of drastic change in matter properties? Data on multi-strange baryons will be decisive!

- "Onset" scenario: effect is due to increase in strangeness; sharp maximum at same location as K/π; size of peak increases with strangeness content
- Hadron Gas Model: effect is due to net-baryon density; broad maximum; size of maximum decreases with strangeness content; position of maximum shifts
Strange anti-baryons at FAIR/NICA energies

Microscopic models (including partonic production) predict the anti-hyperons to be very sensitive to partonic production mechanisms (hyperons much less)
CBM Performance for Hyperons

Input: UrQMD, central Au+Au, 10A GeV
Reconstruction from fully simulated detector response
CBM Performance: Anti-Hyperons

Input: central Au+Au, 10A GeV UrQMD (PHSD for Ω⁺)

Very rare probes; require high interaction rates and online selection!
### Hyperons: Expected Statistics

<table>
<thead>
<tr>
<th>Au+Au 10 AGeV</th>
<th>$\Lambda$</th>
<th>$\Xi^-$</th>
<th>$\Omega^-$</th>
<th>$\Omega^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>decay channel</td>
<td>$p\pi^-$</td>
<td>$\pi^-p\pi^-$</td>
<td>$K^-p\pi^-$</td>
<td>$K^+\bar{p}\pi^+$</td>
</tr>
<tr>
<td>$M_{\text{UrQMD} 3.3}$</td>
<td>17.4</td>
<td>0.22</td>
<td>5.5E-3</td>
<td>6.7E-5</td>
</tr>
<tr>
<td>BR(%)</td>
<td>63.9</td>
<td>~100</td>
<td>67.8</td>
<td>67.8</td>
</tr>
<tr>
<td>total eff. (%)</td>
<td>25.7</td>
<td>8.5</td>
<td>5.4</td>
<td>2.3</td>
</tr>
<tr>
<td>$S/B_{2\sigma}$</td>
<td>.3</td>
<td>17.8</td>
<td>1.0</td>
<td>~10</td>
</tr>
<tr>
<td>Reco yield/sec. $\sim$ 1MHz</td>
<td>4.5M</td>
<td>20k</td>
<td>280</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Will allow systematic, differential studies also of rare particles!
Hyperons: Acceptance and Efficiency
CBM Physics: Hyper-Matter

In heavy-ion collisions: produced through capture of $\Lambda$ in light nuclei

Thermal model: maximum production at CBM energies

Transport: sensitive to medium properties (correlation of strangeness and baryon number)

A. Andronic et al., PLB 697 (2011) 203

S. Zhang et al., PLB 684 (2010) 224
CBM Physics: Hyper-Matter

CBM Simulation
central Au+Au, 10A GeV
$10^{12}$ events (3 weeks beamtime)

Prospects are good;
double-strange hyper-nuclei require
maximal interaction rate
A multitude of particles will become accessible. Real-time reconstruction allows online selection of rare probes. Software becomes the key to the physics output.
CBM Physics: Flow

- The prime tool to study the equation-of-state
- Results at lower energies not understood in terms of transport models

CBM will add flow data, also for weakly rescattering particles like $\varphi$ or $\Omega$

A. Kugler, this conference

STAR, PRL 112 (2014) 162301
CBM Physics: Fluctuations

Should signal the critical point...

...or spinodial decomposition of a mixed phase?

STAR, NPA 956 (2016) 320c

M. Lorentz, QM 2017
CBM Physics: Lepton Pairs

Emitted throughout the lifetime of the fireball: probe its space-time evolution

Low mass (< 1 GeV): in-medium properties of rho meson; excess yield (over vacuum hadronic cocktail) is sensitive to the lifetime of the system

Intermediate mass (1 – 2.5 GeV): no hadronic sources; measure directly the temperature of the fireball.

\( \text{NA60, EPJC 59 (2009) 607} \)
No di-lepton data exist between HADES and NA60!

CBM will provide di-lepton mass spectra and measure the caloric curve in the FAIR energy range. Interpretation almost model-independent!

Extracted temperature at intermediate masses; violet: speculated signature of a mixed phase
CBM Physics: Charm

• Important (if not decisive) probe of the created medium
  – that holds at all energies!

• Fraction of charm hadronising in J/psi is sensitive to the medium properties (e.g. suppression in QGP)

• Particular at lower energies (below top SPS):
  – $N_{c\bar{c}} \ll 1$ -> no regeneration, ”clean” probe
  – Softer J/psi, longer-lived fireball: charm has a chance to see the medium

• Proper interpretation of data requires the measurement of both open and hidden charm
  – Important part of the CBM physics programme

CBM Simulation, Au+Au @ 25A GeV
CBM Physics: Charm at SIS-100

- The CBM charm programme is tailored for SIS-300 energies
- At SIS-100:
  - charmonium at top energy: Au+Au, 10A GeV (sub-threshold, extremely challenging)
  - $Z/A = 0.5$ (e.g., Ni+Ni) @ 15A GeV (slightly above threshold)
  - open and hidden charm in $p+A$ up to 30 GeV (c-cbar cross section, cold matter effects)

central Au + Au, 10A GeV

$p + C$, 30 GeV
CBM Physics: Open Charm at SIS-100

D mesons:
Interaction rate 0.1 MHz
260 $D^0$ and 45 $D^0$ in 2 weeks

Acceptance down to zero $p_t$

Charmonium (muon channel):
Interaction 1 MHz
3300 $J/\Psi$ in 2 weeks
Sub-threshold production through heavy baryonic resonances:

\[ N^* \rightarrow \Lambda_c + D \text{ and } N^* \rightarrow N + J/\psi \]
CBM and MPD

**CBM:** fixed-target
- Extreme rates (large range of observables) but restricted energy range (in particular in the first years)

**MPD:** collider
- Larger energy range
- Limited in rate

A lot of complementarity;
Some competition where physics programmes overlap.
Summary

• The ambitious design of CBM, combining very high interaction rates with large acceptance and precision reconstruction, will allow the measurement of a multitude of particles originating from heavy-ion collision
  – At SIS-100 (AGS energy range) up to 10A GeV from 2024 on
  – After the installation of the second (booster) synchrotron up to 35A GeV (45 for symmetric nuclei)

• Systematic measurements (collision energy, system size) will address the nature of QCD matter at high net-baryon density:
  – Particle yields and spectra
  – Flow
  – Fluctuations
  – Lepton pairs
  – Charm