QCD matter physics at FAIR
The CBM experiment

Outline:

- The status of FAIR
- The CBM physics case
- The CBM experiment

BES workshop, INT Seattle, October 3 – 7, 2016
On Sept. 13, 2016 BMBF gave green light and 203 M€ to start civil construction.

1st call for tender on Sept. 22: water management and excavation

2nd call for tender in Nov.: shell construction ‘north area’, includes SIS100 and CBM cave

Start of construction mid of 2017
The CBM cave

CBM will take first beam from SIS100
4000 tons of steel plates transported from KIT to FAIR for the CBM beam dump
Exploring the QCD phase diagram

Quark-Gluon Plasma

Hadronic Phase

Critical Point

Chiral Density-Wave

Gas-Liquid

Nuclear Superfluid

Quarkyonic Matter

Color Supercritical Phases

sQGP

CFL

2SC

Crystalline CSC States

~ $2 \rho_0$

~ $5 \rho_0$

Courtesy of K. Fukushima & T. Hatsuda

Baryon Chemical Potential $\mu_B$

(3-body)

courtesy Toru Kojo (CCNU)
Exploring the QCD phase diagram

Au beam energies:

FAIR SIS100: $\sqrt{s_{NN}} = 2.7 - 4.9$ GeV
FAIR SIS300: $\sqrt{s_{NN}} = 4.9 - 8.3$ GeV
NICA: $\sqrt{s_{NN}} = 4.5 - 11$ GeV
Experiments exploring dense QCD matter

high net-baryon densities

![Graph showing interaction rate vs. collision energy](image)
Baryon densities in central Au+Au collisions

5 A GeV

10 A GeV
**CBM physics case and observables**

The QCD matter equation-of-state at neutron star core densities

- collective flow of identified particles ($\pi, K, p, \Lambda, \Xi, \Omega, ...$)
  driven by the pressure gradient in the early fireball

AGS: proton flow in Au+Au collisions

Azimuthal angle distribution:
\[
dN/d\phi = C (1 + v_1 \cos(\phi) + v_2 \cos(2\phi) + ...)
\]

The QCD matter equation-of-state at neutron star core densities

- collective flow of identified particles (π,K,p,Λ,Ξ,Ω,...)
  driven by the pressure gradient in the early fireball
- particle production at (sub)threshold energies via multi-step processes (multi-strange hyperons, charm)

Direct multi-strange hyperon production:

\[
\begin{align*}
\text{pp} & \rightarrow \Xi^{-} K^{+} K^{0} p \quad (E_{\text{thr}} = 3.7 \text{ GeV}) \\
\text{pp} & \rightarrow \Omega^{-} K^{+} K^{0} p \quad (E_{\text{thr}} = 7.0 \text{ GeV}) \\
\text{pp} & \rightarrow \Lambda^{0} \bar{\Lambda}^{0} \text{pp} \quad (E_{\text{thr}} = 7.1 \text{ GeV}) \\
\text{pp} & \rightarrow \Xi^{+} \Xi^{-} \text{pp} \quad (E_{\text{thr}} = 9.0 \text{ GeV}) \\
\text{pp} & \rightarrow \Omega^{+} \Omega^{-} \text{pp} \quad (E_{\text{thr}} = 12.7 \text{ GeV})
\end{align*}
\]

Hyperon production via multiple collisions

1. \( \text{pp} \rightarrow K^{+} \Lambda^{0} p \), \( \text{pp} \rightarrow K^{+} K^{-} \text{pp} \),
2. \( p \Lambda^{0} \rightarrow K^{+} \Xi^{-} p \), \( \pi \Lambda^{0} \rightarrow K^{+} \Xi^{-} \pi \),
   \( \Lambda^{0} \Lambda^{0} \rightarrow \Xi^{-} p \), \( \Lambda^{0} K^{-} \rightarrow \Xi^{-} \pi^{0} \)
3. \( \Lambda^{0} \Xi^{-} \rightarrow \Omega^{-} n \), \( \Xi^{-} K^{-} \rightarrow \Omega^{-} \pi^{-} \)

Antihyperons

1. \( \bar{\Lambda}^{0} K^{+} \rightarrow \Xi^{+} \pi^{0} \),
2. \( \Xi^{+} K^{+} \rightarrow \Omega^{+} \pi^{+} \).
The QCD matter equation-of-state at neutron star core densities

- collective flow of identified particles (\(\pi, K, p, \Lambda, \Xi, \Omega, \ldots\))
  driven by the pressure gradient in the early fireball
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Direct multi-strange hyperon production:

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pp &\rightarrow \Xi^- K^+ K^+ p \quad (E_{\text{thr}} = 3.7 \text{ GeV}) \\
pp &\rightarrow \Omega^- K^+ K^+ K^0 p \quad (E_{\text{thr}} = 7.0 \text{ GeV}) \\
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pp &\rightarrow \Omega^+ \Omega^- pp \quad (E_{\text{thr}} = 12.7 \text{ GeV})
\end{align*}
\]

Hyperon production via multiple collisions

1. \(pp \rightarrow K^+ \Lambda^0 p, \quad pp \rightarrow K^+ K^- pp,\)
2. \(p \Lambda^0 \rightarrow K^+ \Xi^- p, \quad \pi \Lambda^0 \rightarrow K^+ \Xi^- \pi,\)
3. \(\Lambda^0 \bar{\Lambda}^0 \rightarrow \Xi^- p, \quad \Lambda^0 K^- \rightarrow \Xi^- \pi^0\)
4. \(\Lambda^0 \Xi^- \rightarrow \Omega^- n, \quad \Xi^- K^- \rightarrow \Omega^- \pi^-\)

Antihyperons

1. \(\bar{\Lambda}^0 K^+ \rightarrow \Xi^+ \pi^0,\)
2. \(\Xi^+ K^+ \rightarrow \Omega^+ \pi^+.\)
Phase transitions from partonic to hadronic matter

- excitation function of strangeness: $\Xi^-(dss), \Xi^+(dss), \Omega^-(sss), \Omega^+(sss)$
- chemical equilibration at the phase boundary
CBM physics case and observables

Phase transitions from partonic to hadronic matter

- excitation function of strangeness: \( \Xi^{-}(dss), \Xi^{+}(\bar{d}\bar{s}s), \Omega^{-}(s\bar{s}s), \Omega^{+}(\bar{s}s\bar{s}) \)

\[ \rightarrow \text{chemical equilibration at the phase boundary} \]

Particle yields and thermal model fits

HADES: Ar + KCl 1.76 A GeV

G. Agakishiev et al., arXiv:1512.07070

Very few data at FAIR energies
CBM physics case and observables

Phase transitions from partonic to hadronic matter, phase coexistence

- excitation function of strangeness: $\Xi^-(dss), \Xi^+(\bar{d}s), \Omega^-(sss), \Omega^+(\bar{s}s)$
  → chemical equilibration at the phase boundary
- excitation function (invariant mass) of lepton pairs:
  thermal radiation from QGP, caloric curve

Invariant mass distribution of lepton pairs

Slope of dilepton invariant mass spectrum
1 GeV/c$^2$ < $M_{inv}$ < 2.5 GeV/c$^2$

No data at FAIR energies
CBM physics case and observables

Phase transitions from partonic to hadronic matter, phase coexistence

- excitation function of strangeness: $\Xi^-(dss), \Xi^+(\bar{d}s\bar{s}), \Omega^-(sss), \Omega^+(\bar{s}s\bar{s})$
  $\rightarrow$ chemical equilibration at the phase boundary

- excitation function (invariant mass) of lepton pairs:
  thermal radiation from QGP, caloric curve

- anisotropic azimuthal angle distributions: “spinodal decomposition”

Spinodal decomposition of the mixed phase

Slope of dilepton invariant mass spectrum
$1 \text{ GeV}/c^2 < M_{inv} < 2.5 \text{ GeV}/c^2$
CBM physics case and observables

Phase transitions from partonic to hadronic matter, phase coexistence, critical point

- excitation function of strangeness: $\Xi^-(dss), \Xi^+(\overline{dss}), \Omega^-(sss), \Omega^+(\overline{sss})$
  
  $\rightarrow$ chemical equilibration at the phase boundary

- excitation function (invariant mass) of lepton pairs:
  Thermal radiation from QGP, caloric curve

- anisotropic azimuthal angle distributions: “spinodal decomposition”

- event-by-event fluctuations of conserved quantities ($B, S, Q$)

$4^{th}$ moment of net-proton multiplicity distribution: critical fluctuations

![Graph showing statistical fluctuations and critical point](image)

No data at FAIR energies
Onset of chiral symmetry restoration at high $\rho_B$

- In-medium modifications of hadrons: $\rho, \omega, \phi \to e^+e^- (\mu^+\mu^-)$
- Dileptons at intermediate invariant masses: $4\pi \to \rho - a_1$ chiral mixing
CBM physics case and observables

N-Λ, Λ-Λ interaction, strange matter?
- (double-) lambda hypernuclei
- meta-stable objects (e.g. strange dibaryons)

CBM physics case and observables

N-Λ, Λ-Λ interaction, strange matter?
- (double-) lambda hypernuclei
- meta-stable objects (e.g. strange dibaryons)

Double lambda hypernuclei production in central Au+Au collisions at 10 A GeV:

<table>
<thead>
<tr>
<th></th>
<th>Multiplicity</th>
<th>Yield in 1 week</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^5\Lambda\Lambda H$</td>
<td>$5 \cdot 10^{-6}$</td>
<td>3000</td>
</tr>
<tr>
<td>$^6\Lambda\Lambda He$</td>
<td>$1 \cdot 10^{-7}$</td>
<td>60</td>
</tr>
</tbody>
</table>

Assumption for yield calculation:
Reaction Rate 1 MHz
BR 10% (2 sequential weak decays)
Efficiency 1%

CBM physics case and observables

Charm production at threshold energies in cold and dense matter

- excitation function of charm production in p+A and A+A (J/ψ, D⁰, D±)

HSD calculation

Central coll. Au+Au 10 A GeV:

\[ M_{J/\psi} = 1.7 \cdot 10^{-7} \]

W. Cassing, E. Bratkovskaya, A. Sibirtsev,

UrQMD calculation including subthreshold charm production via

\[ N^* \rightarrow \Lambda_c + D \] and \[ N^* \rightarrow N + J/\psi \]

Central Au+Au collisions 10 A GeV:

\[ M_{J/\psi} = 5 \cdot 10^{-6} \]

J. Steinheimer, A. Botvina, M. Bleicher, arXiv:1605.03439v1
Highly appreciated: support from theory

- Realistic description of heavy-ion collisions at high net-baryon densities (energies of 4 – 40 A GeV)
- Quantitative relation between physics case and observables

<table>
<thead>
<tr>
<th>Physics case</th>
<th>Diagnostic probe</th>
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<td>Equation-of-state</td>
<td>Flow, Particle production</td>
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<tr>
<td>Phase transition</td>
<td>Chemical equilibration of $\varphi, \Xi, \Omega, ...$?</td>
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<tr>
<td></td>
<td>Open and hidden charm</td>
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<td>First order phase transition:</td>
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<td>- Spinodal decomposition</td>
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<td>- Caloric curve</td>
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<tr>
<td>- Critical point</td>
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<td>Fluids, flow power spectrum</td>
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<td>Intermediate mass dileptons?</td>
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<td></td>
<td>E-b-e fluctuations of B, S, Q</td>
</tr>
<tr>
<td>Chiral symmetry restoration</td>
<td>Dilepton invariant mass spectra?</td>
</tr>
<tr>
<td>NΛ and ΛΛ interaction</td>
<td>Hypernuclei (yield, lifetime)</td>
</tr>
</tbody>
</table>
Experimental requirements

- $10^5 - 10^7$ Au+Au reactions/sec
- determination of displaced vertices ($\sigma \approx 50 \, \mu m$)
- identification of leptons and hadrons
- fast and radiation hard detectors and FEE
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction
Experimental requirements

HADES

p+p, p+A
A+A (low mult.)

Dipol Magnet
Silicon Tracking System
Micro Vertex Detector
Ring Imaging Cherenkov
Muon Detector

Transition Radiation Detector
Time of Flight Detector

DAQ/FLES HPC cluster

Projectile Spectator Detector
Particle Identification

Detectors used: STS, TOF, TRD
p reconstruction efficiency
π⁺, K⁺, and p reconstruction efficiency
Strange hadrons in central Au+Au 10 AGeV

\[ K_s^0 \rightarrow \pi^+\pi^- \]

\[ \Lambda \rightarrow p\pi^- \]

\[ \bar{\Lambda} \rightarrow \bar{p}\pi^+ \]

\[ \Xi^- \rightarrow \Lambda\pi^- \]

\[ \Xi^+ \rightarrow \bar{\Lambda}\pi^+ \]

\[ \Omega^- \rightarrow \Lambda K^- \]
Hyperons in Au+Au 10 AGeV

missing mass analysis

STS + MVD

\[ \Sigma^- \rightarrow n\pi^- \]

\[ \Sigma^+ \rightarrow n\pi^+ \]

\[ \Sigma^+ \rightarrow p\pi^0 \]
Simulations

Elliptic flow measurements in Au+Au collisions at 10 A GeV at b = 6 – 8 fm

1 day: $10^6$ min. bias events/s $\times 8.6 \cdot 10^4$ s = $8.6 \cdot 10^{10}$ events

Yield of p, Λ, and Ω$^{-}$ vs. $p_T$  

Relative statistical error of $v_2$ for p, Λ, and Ω$^{-}$
Hypernuclei in central Au+Au 10 AGeV
Simulations

Dileptons in central Au+Au collisions at 8 A GeV

**Electrons**

Simulation STS, RICH, TRD, TOF: RICH with mechanical structure Hit smearing in TRD (4 layers)

**Muons**

Simulation STS, MUCH with TRD, TOF: Clustering in all detectors (3 GEM stations + 4 layers TRD)
Simulations

Dileptons in central Au+Au collisions at 8 A GeV

Electrons + Muons
Open and hidden charm in CBM at SIS100

Ni + Ni central collisions at 15 A GeV

260 $\bar{D}^0$ and 45 $D^0$ in 2 weeks at IR = 0.1 MHz

Au + Au central collisions at 10 A GeV

6480 $J/\psi$ in 2 weeks at IR = 10 MHz

$10^{11}$ Ni+Ni 15A GeV
IR = 0.1 MHz
$\varepsilon = 1.74\%$
$S/Bg = 0.8(0.4)$

$\epsilon_{J/\psi} = 0.9\%$
$S/B$ ratio = 1.0

$UrQMD$ multiplicity* $\sim 5 \times 10^{-6}$

*Sub-threshold charm production in nuclear collisions J.
Steinheimer, A. Botvina, M. Bleicher arXiv:1605.03439
Online particle identification in CBM: The KF Particle Finder

Tracks: e^+, μ^+, π^+, K^+, p^+, d^+, 3He^+, 4He^+

primary and secondary

Dileptons

Charmonium
J/ψ → e^+e^-
J/ψ → μ^+μ^-

Low mass vector mesons
ρ → e^+e^-
ρ → μ^+μ^-
ω → e^+e^-
ω → μ^+μ^-
ϕ → e^+e^-
ϕ → μ^+μ^-

Gamma
γ → e^+e^-
γ → μ^+μ^-

Gamma-decays
π^0 → γγ
η → γγ

Open-charm

Open-charm particles
D^0 → K^-π^+
D^0 → K^-π^+π^0
\bar{D}^0 → K^+π^-
\bar{D}^0 → K^+π^-π^0
D^+ → K^+π^+π^-
D^- → K^-π^-π^0
D_s^+ → K^+π^-π^0
D_s^- → K^-π^+π^-
Λ_c^+ → p K^-π^+
Λ_c^- → \bar{p} K^+π^-

Open-charm resonances
D_s^{*0} → D^+π^-
\bar{D}_s^{*0} → D^0π^-
D_s^{*+} → D^0π^+π^0
D_s^{*-} → D^0π^-π^0
D_s^{*0} → D^0π^0

Strange particles

Σ^0 → Λπ^+
Σ^+ → Λπ^+
Σ^- → Λπ^-
Ω^- → ΛK^-
\bar{Ω}^+ → \Λ K^+

Σ^0 → Λγ
Σ^0 → Λγ
Σ^+ → pπ^0
Σ^- → \bar{p}π^0
\bar{Σ}^0 → Λπ^0
\bar{Σ}^0 → Λπ^0

Strange resonances

Σ^{*0} → Σ^{*+}π^-
Σ^{*+} → Σ^{*0}π^+
Σ^{*0} → Σ^{*+}π^0
Σ^{*+} → Σ^{*0}π^+

Hypermatter

Hypermultiplets
\{Λn\} → d^+π^-
\{Λp\} → d^-π^+
3ΛH → 3ΛHeπ^-
3ΛH → 3ΛHeπ^+
4ΛH → 4ΛHeπ^-
4ΛH → 4ΛHeπ^+
4ΛHe → 4ΛHeπ^-
4ΛHe → 4ΛHeπ^+
5ΛHe → 4ΛHeπ^-
5ΛHe → 4ΛHeπ^+

Heavy multistrange objects
\{Σ^0Λ\} → ΛΛ

successfully used online in the STAR experiment
FAIR Phase 0 experiments

1. Install, commission and use 430 out of 1100 CBM RICH multi-anode photo-multipliers (MAPMT) in HADES RICH photon detector.
FAIR Phase 0 experiments

1. Install, commission and use 430 out of 1100 CBM RICH multi-anode photomultipliers (MAPMT) in HADES RICH photon detector

2. Install, commission and use 10% of the CBM TOF modules including read-out chain at STAR/RHIC (BES II 2019/2020)
FAIR Phase 0 experiments

3. Install, commission and use 4 Silicon tracking layers and the Project Spectator Detector at the BM@N experiment at the Nuclotron in JINR/Dubna (Au-beams up to 4.5 A GeV in 2018/19)
FAIR Phase 0 experiments

3. Install, commission and use 4 Silicon tracking layers and the Project Spectator Detector at the BM@N experiment at the Nuclotron in JINR/Dubna (Au-beams up to 4.5 A GeV in 2018/19)

4. Build mCBM at GSI/SIS18 for a full system test with high-rate nucleus-nucleus collisions from 2018 - 2020
The CBM Collaboration: 59 institutions, 530 members

Croatia:
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang

Czech Republic:
CAS, Rez
Techn. Univ. Prague

France:
IPHC Strasbourg

Germany:
Darmstadt TU
FAIR
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
Frankfurt Univ. ICS
GSI Darmstadt
Giessen Univ.
Heidelberg Univ. P.I.
Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
KIT Karlsruhe
Münster Univ.
Tübingen Univ.
Wuppertal Univ.
ZIB Berlin

India:
Aligarh Muslim Univ.
Bose Inst. Kolkata
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
IOP Bhubaneswar
IIT Kharagpur
IIT Indore
Gauhati Univ.

Korea:
Pusan Nat. Univ.

Poland:
AGH Krakow
Jag. Univ. Krakow
Silesia Univ. Katowice
Warsaw Univ.
Warsaw TU

Romania:
NIPNE Bucharest
Univ. Bucharest

Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
Kurchatov Inst., Moscow
LHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
PNPI Gatchina
SINP MSU, Moscow
St. Petersburg P. Univ.

Ukraine:
T. Shevchenko Univ. Kiev
Kiev Inst. Nucl. Research

26th CBM Collaboration meeting in Prague, CZ
14 -18 Sept. 2015
Summary

• CBM scientific program at SIS100: Exploration of the QCD phase diagram in the region of neutron star core densities → large discovery potential.

• First measurements with CBM: High-precision multi-differential measurements of hadrons incl. multistrange hyperons, hypernuclei and dileptons for different beam energies and collision systems → terra incognita.

• Status of experiment preparation: Prototype detector performances fulfill CBM requirements. 7 TDRs approved, 4 TDRs in preparation.

• Funding: CBM start version is financed by about 2/3 (+ EoI).

• FAIR Phase 0: HADES with CBM RICH photon detector, use CBM detectors at STAR/BNL and BM@N/JINR