The CBM Experiment: Program and Status

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Dense Baryonic Matter

**Neutron stars**
- Temperature: \( T < 20 \text{ MeV} \)
- Density: \( \rho < 10 \rho_0 \)
- Lifetime: \( T \sim \text{infinity} \)

**Neutron star merger**
- Temperature: \( T < 70 \text{ MeV} \)
- Density: \( \rho < 3\rho_0 \)
- Reaction time: \( (GW170817) \) \( T \sim 10^{\text{s}} \)

**Heavy ion collisions at SIS100**
- Temperature: \( T < 120 \text{ MeV} \)
- Density: \( \rho < 8\rho_0 \)
- Reaction time: \( t \sim 10^{-23} \text{ s} \)

Compressed Baryonic Matter

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Mission:
Systematically explore QCD matter at large baryon densities with high accuracy and rare probes.

Outline:
Current experimental knowledge
Experimental and theoretical expectations / speculations
Experiment setup
Status of developments
Planned Fair Phase-0 and Phase-1 measurements
Baryon densities at SIS100

Baryon densities in central Au+Au collisions

5 A GeV

10 A GeV


5 \rho_0

8 \rho_0

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Hard probes (initial state)

Penetrating probes (integrate over collision history)
Relicts (produced in dense phase)

Freeze-out (final state particles)
Thermalized (?) hadrons

\[ \bar{\rho}, \bar{\Lambda}, \Xi^+, \Omega^+, J/\psi \]
\[ \Xi^-, \Omega^-, \phi \]
\[ e^+e^-, \mu^+\mu^- \]

\[ \pi, K, \Lambda, \ldots \]

resonance decays
Chemical Freeze-out data

Analyses in framework of Statistical Hadronisation Model

High energies:
grandcanonical ensemble

\[ n_i(\mu, T) = \frac{N_i}{V} = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int \frac{p^2 dp}{e^{\frac{E_i - \mu_i}{T}} + 1} \]

\[ \mu_i = \mu_B B_i + \mu_S S_i + \mu_I I_{3,i} \]

Lower energies / small systems:
canonical ensemble,
strangeness suppression factor \( \gamma_s \)

Equilibrium achieved in small systems?

Equilibrium as signature for phase transition?

Freeze-out line at large baryon densities as phase boundary to quarkyonic matter?

A. Andronic et al.,

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HADES: Sub-threshold $\Xi^-$ - production

Ar+KCl reactions at 1.76A GeV

- $\Xi^-$ yield by appr. factor 25 higher than thermal yield
Strong sensitivity to Equation Of State
due to multistep production
(formation of nucleon resonances)
=> soft EOS (K=200 MeV)
Soft EOS (Skyrme, $K = 200$ MeV) is not repulsive enough to allow for a neutron star with 2 solar masses.

DBHF BONN A corresponds to AP4, however, does not contain strange baryons.

Stiffening of EOS must occur in the range of densities up to $4 \rho_0$ (SIS100 energy range).
Strange and charmed particle production thresholds in pp - collisions

<table>
<thead>
<tr>
<th>reaction</th>
<th>( \sqrt{s} ) (GeV)</th>
<th>( T_{\text{lab}} ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pp \rightarrow K^+ \Lambda p )</td>
<td>2.548</td>
<td>1.6</td>
</tr>
<tr>
<td>( pp \rightarrow K^+ K^- pp )</td>
<td>2.864</td>
<td>2.5</td>
</tr>
<tr>
<td>( pp \rightarrow K^+ K^+ \Xi^- p )</td>
<td>3.247</td>
<td>3.7</td>
</tr>
<tr>
<td>( pp \rightarrow K^+ K^+ \Omega^- n )</td>
<td>4.092</td>
<td>7.0</td>
</tr>
<tr>
<td>( pp \rightarrow \Lambda \bar{\Lambda} pp )</td>
<td>4.108</td>
<td>7.1</td>
</tr>
<tr>
<td>( pp \rightarrow \Xi^- \Xi^+ pp )</td>
<td>4.520</td>
<td>9.0</td>
</tr>
<tr>
<td>( pp \rightarrow \Omega^- \bar{\Omega}^+ pp )</td>
<td>5.222</td>
<td>12.7</td>
</tr>
<tr>
<td>( pp \rightarrow J/\Psi \ pp )</td>
<td>4.973</td>
<td>12.2</td>
</tr>
</tbody>
</table>
Hyperons as probes of dense matter

PHSD interpretation of $\Xi^-$ production


Predicted sensitivities of production yields:

- strong dependence on Chiral Symmetry Restoration (CSR)
- Measurable dependence on Equation of State (NL1, NL3)
Antihyperon – production

Prediction of PHSD transport model
(E. Bratkovskaya, W. Cassing)

I. Vassiliev, CBM, private communication

Large sensitivity to
partonic degrees of freedom
in SIS100 energy range
(deconfinement phase transition)

Mapping out the phase structure requires systematic measurements.
• Tracking acceptance: $2^\circ < \theta_{\text{lab}} < 25^\circ$

• Free streaming DAQ

$R_{\text{int}} = 10 \text{ MHz (Au+Au)}$

with

$R_{\text{int}} (\text{MVD}) = 0.1 \text{ MHz}$

• Software based event selection
CBM – Strategy

Exploration of QCD phase diagram as international effort:

- NA61 @ SPS / CERN
- BM@N @ Nuclotron/JINR
- STAR (F.t.) @ RHIC/BNL
- MPD @ NICA / JINR

CBM’s unique feature
High statistics measurement of rare probes
Main features:

- radiation tolerant detectors and front-end electronics
- no hardware trigger of events,
- free streaming (triggerless) data,
- all detector hits with time stamps,
- software based event selection

Reaction rate:  \( \text{Au + Au, } 10^7 \text{ collisions per second} \)

Data rate: ~1 TB/s
CBM physics and observables

QCD equation-of-state
- collective flow of identified particles
- particle production at threshold energies

Phase transition
- excitation function of hyperons
- excitation function of LM lepton pairs

Critical point
- event-by-event fluctuations of conserved quantities

Chiral symmetry restoration at large $\rho_B$
- in-medium modifications of hadrons
- dileptons at intermediate invariant masses

Strange matter
- (double-) lambda hypernuclei
- Search for meta-stable objects (e.g. strange dibaryons)

Heavy flavour in cold and dense matter
- excitation function of charm production
CBM experimental setup (day-1)

- Tracking acceptance: $2^\circ < \theta_{lab} < 25^\circ$
- Free streaming DAQ
  \[ R_{int} \approx 0.5 \text{ MHz (Au+Au)} \]
  
  full bandwidth:
  - Det. – Entry nodes
  - reduced bandwidth
  - Entry nodes – Comp. farm

  with
  \[ R_{int} \text{ (MVD)=0.1 MHz} \]

- Software based event selection

Day-1 setup = MSV setup – Compute Performance - ECAL
Phase-1 = Day1 with full Compute Performance + ECAL

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Observables: Strangeness and Dileptons

Excitation function of yields and phase-space distributions of multi-strange hyperons and lepton pairs in AA (C+C, Au+Au) collisions from 2-11 A GeV.

Search for hypernuclei (no data available in this energy range).

multi-strange hyperons

hypernuclei

dilepton invariant mass
Dileptons as probes for dense matter

LMR: ρ – chiral symmetry restoration
fireball space – time extension

IMR: access to fireball temperature
ρ-a_1 chiral mixing

Measurement program:
e.g. excitation function of IMR - slope

- 1M Au+Au (b=0 fm), 8 AGeV
- IMR: S/B > 1/100
- Statistical accuracy of 10% requires
  ~1 week of beamtime

Figure:
T. Galatyuk

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Di-electron measurement
Full performance, uses MVD, limited to 100 kHz

Hyperon measurements, e.g. Au+Au at 10A GeV:

Hypernuclei measurement, e.g. Au + Au at 10A GeV

Di-Muon
LM measurement at 8A GeV
1. Install, commission and use 430 out of 1100 CBM RICH multi-anode photo-multipliers (MAPMT) including FEE 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)

3. Upgrade BM@N experiment with 4 Silicon stations of CBM/STS design in the BM@N experiment at the Nuclotron JINR/Dubna (Au-beams in late 2020)

4. Install, commission and use the Project Spectator Detector at the BM@N experiment

5. mini CBM (mCBM@SIS18) demonstrator for full CBM data taking and analysis chain

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CBM FAIR Phase 0 project at SIS18: mCBM

Demonstrator for full CBM data taking and analysis chain

The mCBM test-setup (“mini-CBM”) will focus on

- test of final detector prototypes
- free streaming data transport to a computer farm
- online reconstruction and event selection
- offline data analysis

under full load conditions (Au + Au, $10^7$ interactions/s)


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mCBM performance benchmark

(Sub)threshold $\Lambda$ – baryon reconstruction.

Event based MC simulation of $10^8$ events
(measurement time: 10 s)

$\Lambda \to p + \pi^-$

Acceptance & Efficiency
mCBM Cave (HTD)

FLUKA calculations:
$10^8$ Au ions s$^{-1}$, 1.24 AGeV, 2.5 mm Au target ($P_{int} = 10\%$)
vertical section: beam level

- Modified switching magnet (HTD – MU1)
- New beam dump
- Additional shielding

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Status of the cave reconstruction

Nov. 24, 2017

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## Schedule of mCBM construction

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/2017</td>
<td>cave &amp; beam line: reconstruction started, procurement started</td>
</tr>
<tr>
<td>11/2017</td>
<td>mDAQ test stand @ Heidelberg operational</td>
</tr>
<tr>
<td>12/2017</td>
<td>beam dump mounted</td>
</tr>
<tr>
<td>03/2018</td>
<td>cave reconstruction completed</td>
</tr>
<tr>
<td>04/2018</td>
<td>mFLES cluster @ Green IT Cube installed</td>
</tr>
<tr>
<td>05/2018</td>
<td>beam line installed and commissioned</td>
</tr>
<tr>
<td>05/2018</td>
<td>installation of detector stations</td>
</tr>
<tr>
<td>06/2018</td>
<td>start commissioning w/o beam</td>
</tr>
<tr>
<td>08/2018</td>
<td>start commissioning with beam</td>
</tr>
</tbody>
</table>

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eTOF & HPC software in STAR at RHIC (BNL)

Participating CBM groups:
• Tsinghua Univ. Beijing
• GSI Darmstadt
• TU Darmstadt
• Univ. Frankfurt
• Univ. Heidelberg
• USTC Hefei
• CCNU Wuhan

CBM eTOF prototype module (2016)

Test module installed (Oct. 2016),
Module is operational (Oct. 2016),
STAR DAQ interface (Jan. 2017),
Full sector test (Spring 2018),
Wheel installation (Summer 2018),
BES II data taking (2019/2020),
Transfer of modules to FAIR (2021/22).

Time to trigger for hits in trigger window gIPB 00

DAQ integration accomplished (Spring ‘17)
64 M production events recorded

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Physics Program for the STAR/CBM eTOF Upgrade

The STAR Collaboration
The CBM Collaboration eTOF Group
(Dated: September 19, 2016)

Example: kaon acceptance

Topics to be studied with extended acceptance in energy range $\sqrt{s_{NN}} = 3 – 62$ GeV:

- Excitation function and phase-space distributions of hyperons, hypernuclei, anti-protons, ...
  → Equilibration, phase transitions

- Collective Flow ($v_1$, $v_2$)
  → Equation-of-State, phase transitions

- Fluctuations of conserved quantum numbers (baryon, charge, strangeness)
  → Critical point

- Dilepton yields
  → Chiral symmetry restoration

arXiv:1609.05102v1 [nucl-ex]
STS & PSD in BM@N (JINR)

Silicon Tracking Stations

dipole magnet

GEM tracker

Au beams up to 4.5 GeV/u

PSD calorimeter


- 2018: Installation of PSD detector (MoU signed)
- 2020: Installation of 4 Si tracking stations (MoU signed)
- 2020: Au beams from Nuclotron

Improvement in efficiency & signal / background

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CBM – Collaboration: 55 institutions, 470 members

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang
Chongqing Univ.

Czech Republic:
CAS, Rez
Techn. Univ. Prague

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.
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
Warsaw Univ.
Warsaw TU

Romania:
NIPNE Bucharest
Univ. Bucharest

Hungary:
KFKI Budapest
Eötvös Univ.

Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
Kurchatov Inst., Moscow
VBLHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
PNPI Gatchina
SINP MSU, Moscow

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

30th CBM Collaboration meeting in Wuhan
24-28 September 2017

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CBM scientific program at SIS100 is unique
- explore QCD matter at neutron star core densities
- employ high statistics capability
  to achieve high-precision of multi-differential observables
  to enable rare processes as sensitive probes

CBM day-1 setup allows start of program with significant discovery potential
- excitation function of hyperons production
- excitation function of di-lepton production
- study of hypernuclei

CBM Phase 0 activities targeted towards usage and understanding of major components & production of visible physics results with CBM devices
- CBM – RICH sensors & readout in HADES at SIS18
- CBM – TOF and HPC software in STAR at RHIC/BNL
- CBM – PSD and CBM - STS in BM@N at Nuclotron/JINR
- Integration of all subsystems & FLES in mCBM at SIS18