The CBM physics program

Christian Sturm, GSI
for the CBM Collaboration

Outline

CBM physics at SIS100

Outlook to FAIR phase 2

Experiment preparation and activities during FAIR phase 0
Compressed baryonic matter – neutron stars

Crab-Nebula (Supernova 1054)

Crab pulsar
Rotation period $T = 33.4$ ms
Slowing down rate $\Delta T/\Delta t = 3 \cdot 10^{-8}$ s/a
Mass $\sim 1.5 M_\odot$
Radius $\sim 15$ km
Density $3 - 10 \rho_0$

Pseudo-color image (NASA)
- infrared – Spitzer Space Telescope
- optical – Hubble Space Telescope
- x-ray – Chandra X-ray Observatory (space)

Slow motion

Non-equilibrium Dynamics, April 2018
C.Sturm, GSI
Compressed baryonic matter – collision of neutron stars

**Neutron star merger**

Temperature
\[ T < 70 \text{ MeV} \]

Density
\[ \rho < 2 - 6 \rho_0 \]

Reaction time
\[ \Delta t \sim 10 \text{ ms} \]

numerical simulation, GW170817
T. Dietrich (Max Planck Institute for Gravitational Physics)
Compressed baryonic matter – collision of (heavy) nuclei

Equation 1:
\[ \rho_{\text{max}} \approx 3 \rho_0 \]

Note: System not necessarily equilibrated.
Messengers at FAIR energies

Non-equilibrium Dynamics, April 2018 C.Sturm, GSI 4

UrQMD transport calculation  U+U 23 AGeV

charm

Φ, Ξ, Ω

K, π, Λ, η

ρ → e^+ e^−  μ^+ μ^−

ρ → e^+ e^−  μ^+ μ^−

prompt γ

thermal γ

decay γ

resonance decays
Exploring the QCD phase diagram

At very high temperature:
N of baryons $\approx$ N of antibaryons $\rightarrow$ situation similar to early universe
Lattice QCD: crossover transition Hadronic Matter $\rightarrow$ Quark-Gluon Plasma

Experiments:
ALICE, ATLAS and CMS at LHC & STAR and PHENIX at RHIC
Exploring the QCD phase diagram

At high baryon density:
N of baryons $\gg$ N of antibaryons, densities like in neutron star cores
→ Lattice QCD not (yet) applicable
→ Models predict first order phase transition with mixed or exotic phases

Experiments:
BES at RHIC, NA61 at CERN SPS, NICA at JINR and CBM at FAIR
Mission:
Systematically explore QCD matter at large baryon densities with high accuracy and rare probes.

Fundamental questions:
- Equation-of-state of QCD matter at neutron star core densities
- Phase structure of QCD matter
- Chiral symmetry restoration at large densities
- Bound states with strangeness

Field driven by experimental data!
The Facility for Antiproton and Ion Research

FAIR SIS100 energies
(Au ions)

<table>
<thead>
<tr>
<th>$E_{\text{lab}}^{\text{kin}}$ [A·GeV]</th>
<th>$\sqrt{s_{NN}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.7</td>
</tr>
<tr>
<td>4</td>
<td>3.3</td>
</tr>
<tr>
<td>8</td>
<td>4.3</td>
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<td>11</td>
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<tr>
<td>14 (Ca)</td>
<td>5.5</td>
</tr>
<tr>
<td>29 (p)</td>
<td>7.6</td>
</tr>
</tbody>
</table>
Strangeness at FAIR energies

Particle yields from central Au + Au collisions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( \sqrt{s} ) (GeV)</th>
<th>( T_{\text{lab}} ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pp \to K^+ \Lambda p )</td>
<td>2.548</td>
<td>1.6</td>
</tr>
<tr>
<td>( pp \to K^+ K^- pp )</td>
<td>2.864</td>
<td>2.5</td>
</tr>
<tr>
<td>( pp \to K^+ K^+ K^- p )</td>
<td>3.247</td>
<td>3.7</td>
</tr>
<tr>
<td>( pp \to K^+ K^+ K^- p )</td>
<td>4.092</td>
<td>7.0</td>
</tr>
<tr>
<td>( pp \to \Lambda \bar{\Lambda} pp )</td>
<td>4.108</td>
<td>7.1</td>
</tr>
<tr>
<td>( pp \to \Xi^- \Xi^+ pp )</td>
<td>4.520</td>
<td>9.0</td>
</tr>
<tr>
<td>( pp \to \Omega^- \bar{\Omega}^+ pp )</td>
<td>5.222</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Little knowledge on **multi-strange hyperons** at energies \( T_{\text{lab}} < 10 \text{ AGeV} \)

→ multi-step production ?
→ production via strangeness exchange channels ?
→ enhanced production in dense medium ?
Multi-strange hyperons and hypernuclei at FAIR energies

**HADES data**

Ar + KCl 1.76 A GeV


**Statistical hadronisation model:**

production of light nuclei and hypernuclei

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker

Strangeness
Multi-strange (anti-) hyperons at FAIR energies

PHSD: Transport code with partonic phase ($\varepsilon > 1$ GeV/fm$^3$)
HSD: Hadronic transport code

I. Vassiliev, E. Bratkovskaya, preliminary results

Non-equilibrium Dynamics, April 2018
C.Sturm, GSI
In transport code included effective NN potential (Skyrme):

\[ U(\rho) = \alpha \left( \frac{\rho}{\rho_0} \right) + \beta \left( \frac{\rho}{\rho_0} \right)^\gamma \]

Constraints for the parameters of the potential:

\[ \varepsilon(\rho = \rho_0, T = 0) = -16 MeV \]

\[ \left( \frac{\partial \varepsilon(\rho, T = 0)}{\partial \rho} \right)_{\rho = \rho_0} = 0 \]

<table>
<thead>
<tr>
<th>Corresponding EoS with</th>
<th>( \alpha ) [MeV]</th>
<th>( \beta ) [MeV]</th>
<th>( \gamma )</th>
</tr>
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<tbody>
<tr>
<td>( \kappa = 380 \text{ MeV} )</td>
<td>-124</td>
<td>70.5</td>
<td>2</td>
</tr>
<tr>
<td>( \kappa = 200 \text{ MeV} )</td>
<td>-356</td>
<td>303</td>
<td>7/6</td>
</tr>
</tbody>
</table>

Au+Au 1.5 AGeV
W. Reisdorf et al. (FOPI), Nucl. Phys. A 876 (2012) 1

consistent picture at SIS18 energies (1.5 < \( \rho / \rho_0 < 3.0 \))
inconclusive at AGS energies
Nuclear equation-of-state at FAIR energies

DBHF: E. N. E. van Dalen, C. Fuchs, A. Faessler
EPJ. A 31,29 (2007)

→ (sub-threshold) production
of $\Omega^+ (\bar{s}\bar{s}\bar{s}\bar{s})$ at FAIR energies
- refined to the high-density phase
- small final-state interaction
Dileptons
Electromagnetic radiation from the fireball

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

LOW MASS REGION (LMR):
\[ \rho \] – chiral symmetry restoration

INTERMEDIATE MASS REGION (IMR):
access to fireball temperature
\[ \rho - a_1 \] chiral mixing


Fig. by T. Galatyuk & EPJA 52 (2016) 131

Non-equilibrium Dynamics, April 2018 C. Sturm, GSI
Di-electron reconstruction

Input:
UrQMD 3.2
Au+Au 8 AGeV
central collision

$\rho \rightarrow e^+ e^-$

mc lepton tracks

Non-equilibrium Dynamics, April 2018
C.Sturm, GSI
Charm cross section in elementary collisions:


Sub-threshold production through heavy baryonic resonances:

\[ N^* \rightarrow \Lambda_c + D \] and \[ N^* \rightarrow N + J/\psi \]
Summary: unique measurements with CBM at day 1

**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
= complementary measurement to $e^+e^-$
with different systematic errors
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
Using beams from two synchrotrons for parallel operation!

### FAIR energies (Au ions)

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<tr>
<td>30</td>
<td>7.7</td>
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<tr>
<td>35</td>
<td>8.3</td>
</tr>
<tr>
<td>44 (Ca @ SIS300)</td>
<td>9.3</td>
</tr>
<tr>
<td>89 (p @ SIS300)</td>
<td>13.0</td>
</tr>
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</table>
Maximum in K/π at 30 AGeV

Plateau in apparent temperature above 30 AGeV
indication of 1st order phase transition (latent heat)?
CBM physics: Charm @ FAIR phase 2

CERN/SPS experiments:
- In-In 158 GeV (NA60)
- Pb-Pb 158 GeV (NA50)

Excitation function of $J/\psi$ production at FAIR energies

→ production mechanism ?
→ $J/\psi$ suppression ?

No data available below top SPS energies!
Excitation function of $J/\psi$ production at FAIR energies

$\rightarrow$ production mechanism ?
$\rightarrow$ $J/\psi$ suppression ?

HSD “hadronic”
O. Linnyk et al.,

SHM “partonic”
A. Andronic et al.,
active absorber system with tracking detectors (GEM / straw tubes) sandwiched between absorber slices

CBM Simulation
Au+Au @ 25 AGeV
### Experimental challenges

Non-equilibrium Dynamics, April 2018  
C. Sturm, GSI

#### Particle multiplicity x branching ratio

- **HSD or Statistical model**
- **Au+Au** 25 A GeV (min. bias)
- **SPS Pb+Pb** 30 A GeV
- **STAR Au+Au** $\sqrt{s_{NN}}=7.7$ GeV

#### Rare probes

- $e^+e^-$
- $\mu^+\mu^-$

- **AGS**

- **Au+Au** 4 A GeV (central)

**Note:**

- Rare probes → extremely high interaction rates required!
CBM strategy

Exploration of the 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:
ultimate rate capability for
high statistics measurement of rare probes

→ fast and radiation tolerant detectors
→ free-streaming read-out electronics
→ high speed data acquisition and
  high performance computer farm
  for online event reconstruction and selection
HADES

p+p, p+A
A+A (low mult.)
large acceptance
low material budget

data transport to a DAQ/FLES HPC cluster

CBM
hadrons

Time of Flight

s.c. Dipol Magnet

Silicon Tracking System

Projectile Spectator Detector
CBM dileptons

- Micro Vertex Detector
- s.c. Dipol Magnet
- Time of Flight
- Silicon Tracking System
- Transition Radiation Detector (4/10)
- Muon Detector (SIS100 version)
- Data transport to DAQ/FLES HPC cluster
- Projectile Spectator Detector

Non-equilibrium Dynamics, April 2018 C.Sturm, GSI
The high-performance free-streaming DAQ system of CBM

Main features:
- radiation tolerant detectors and front-end electronics
- free-streaming DAQ system
  - all detector hits with time stamps,
  - software based event selection

DAQ room: data pre-processing on FLES input cluster

Green IT Cube: online time slice building and event selection

1 TB/s

μ-slices

~80m

~800m
Start of CBM experiments in 2024
Status of the FAIR construction
A CBM full-system test-setup at GSI/FAIR: mCBM@SIS18

concept:
A permanent test-setup at the host lab
- detector prototypes at $\theta_{\text{lab}} \approx 20^\circ$
- collision rates up to 10 MHz
- compact setup (< 5m)
- no B-field $\rightarrow$ straight tracks
- high resolution TOF ($T_0$ – TOF stop wall)

Topics to be addressed
- free streaming read-out and data transport to the mFLES
- online reconstruction
- offline data analysis
- controls
- detector tests of final detector prototypes

Non-equilibrium Dynamics, April 2018
C.Sturm, GSI
Design of the mCBM test-setup

Non-equilibrium Dynamics, April 2018
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mCBM Cave (HTD @ SIS18 facility)

- modified switching magnet (HTD MU1)
- new beam dump
- additional shielding

FLUKA calculations (right fig.):
10⁸ Au ions s⁻¹, 1.24 AGeV,
2.5 mm Au target (P_{int} = 10%)
vertical section: beam level

requirement: \( \bar{D} \leq 0.5 \mu\text{Sv/h} \)
Status of the cave reconstruction

December 20, 2017

Non-equilibrium Dynamics, April 2018

C.Sturm, GSI
mCBM benchmark observable: Λ reconstruction

Simulation input: $10^8$ UrQMD events, min. bias

Acceptance

Efficiency

Ni+Ni 1.93AGeV

S/B = 8.4

Au+Au 1.24AGeV

S/B = 0.24

$\Lambda \rightarrow p + \pi^-$
Λ production at SIS18 energies – mCBM reference data

Ni + Ni 1.93 AGeV
M. Merschmeyer et al. (FOPI), PRC 76, 024906 (2007)

Au + Au 1.23 AGeV
H. Schuldes et al. (HADES)
EPJ Web of Conferences 171, 01001 (2018), SQM2017

midrapidity

H. Schuldes et al. (HADES)
EPJ Web of Conferences 171, 01001 (2018), SQM2017
## mCBM data taking

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
</table>
| 2018 | development & commissioning  
data transport, data analysis, detector tests |
| 2019 | approaching full performance  
subsystems completed, high-rate data transport / processing  
→ online reconstruction |
| 2020 | 1\textsuperscript{st} benchmark run  
Λ reconstruction production runs  
benchmark coll. systems: Ni+Ni 1.93AGeV & Au+Au 1.24AGeV |
| 2021 | 2\textsuperscript{nd} benchmark run  
Λ reconstruction in Ni+Ni and Au+Au collisions  
at various projectile energies → Λ production excitation function |

### Λ - slope parameter:
- smaller than proton
- not explained by transport models

Reason unclear:
- rescattering cross section ?
- repulsive potential ?

requested beamtime was fully granted by GSI/FAIR G-PAC

proposal to be submitted in 2019
CBM Collaboration: 55 institutions, 470 members

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

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.
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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