THE COMPRESSED BARYONIC MATTER (CBM) EXPERIMENT AT FAIR

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- For the CBM Collaboration -

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SIS-100 Capabilities

<table>
<thead>
<tr>
<th>Beam</th>
<th>Z</th>
<th>A</th>
<th>E [AGeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>1</td>
<td>1</td>
<td>29</td>
</tr>
<tr>
<td>d</td>
<td>1</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>Ca</td>
<td>20</td>
<td>40</td>
<td>14</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>79</td>
<td>197</td>
<td>11</td>
</tr>
<tr>
<td>U</td>
<td>92</td>
<td>238</td>
<td>10.7</td>
</tr>
</tbody>
</table>

- Intensity gain: $x \times 100 - 1000$ ($\sim 10^{13}/s$ for $p$; $\sim 10^{10}/s$ for $Au$)
- 10 x energy (compared to SIS-18@GSI)
- Antimatter: antiproton beams
- Precision: System of storage and cooler rings

• FAIR is progressing well towards strategic objectives
• CBM Building’s construction progressing well on schedule
• Ready for ‘Heavy Installation’ from mid-2022
• CBM integration to be completed by 2025
• Updates on construction available at: GSI Webpage | YouTube | ...
CBM Physics Case & Observables
CBM PHYSICS GOALS

Unanswered fundamental questions for QCD at high densities

- Equation of State (EoS) of symmetric nuclear (and asymmetric neutron) matter at neutron star core densities
- Phase structure of QCD matter (phase trans.? critical point?)
- Chiral symmetry restoration at large $\mu_B$
- Bound states with strangeness
- Charm in cold and dense matter

The CBM research program can decipher dense QCD matter properties

Microscopic (CBM) + Macroscopic Collisions (Astro) = True Multi-Messenger Physics
Physics Case 1: Equation of State and Neutron Star Properties

Heavy-Ion Collisions

P. Ray et al., STROBE: X-ray Timing and Spectroscopy on Dynamical Timescales from Microseconds to Years, arXiv:1903.03035
**ANISOTRPIIC FLOW**

Nucelar EoS \( \propto '\text{(In)Compressibility}' \) of the nuclei \( \propto '\text{Flow}' \) direction of participants and spectators

\[
\frac{dN}{d\phi} \propto 1 + (2 \cdot v_1 \cdot \cos \phi) + (2 \cdot v_2 \cdot \cos 2\phi) + \cdots
\]

**SUB-THRESHOLD STRANGENESS PRODUCTION**

Nucelar EoS \( \propto '\text{(In)Compressibility}' \) of the nuclei \( \propto '\text{Flow}' \)

Density \( \propto '\text{Strangeness Yield}' \)
**PHYSICS CASE 1: EQUATION OF STATE AND NEUTRON STAR PROPERTIES**

CBM, with its capability with observables like particle flow and sub-threshold particle production, is in pole position to push our understanding of SNM and PNM at higher densities, thereby enhancing HIC’s compatibility with astrophysical observations.

**HIC PRESENT (@SIS-18)**
- HIC constraints the EoS only where its sensitivity is highest (~1.5$n_{\text{sat}}$), where it favours stiffer EoS
- Constraints are consistent between HIC and astro

**HIC FUTURE (@SIS-18, SIS-100, …)**
- Higher density constraints are currently driven by Astro (which are limited in statistics)
- HIC has the potential to limit the constraints at higher densities

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**SIS-18**
- SNM: FOPI + KaoS
- PNM: ASY-EoS-I/II

**SIS-100**
- CBM

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**FOPI:** Nucl. Phys. A 945, 112 (2016)
**AGS, BEVALAC:** Science 298, 1592 (2002)
**KaoS:** Phys. Rev. Lett. 86, 39 (2001)

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**SnRIT:** Phys. Rev. Lett. 126, 162701 (2021)
Non-monotonic behaviour of the caloric curve potentially signals phase transition

Dileptons, being electromagnetic probes, act as a thermometer of the strong-interacting fireball medium

\[
\frac{dN}{dM} \sim M^{3/2} \cdot \exp \left( -\frac{M}{T_S} \right)
\]

CBM will be the first experiment to use di-leptons for systematic measurements in both production channels (e^+e^- and \(\mu^+\mu^-\)) in the same coverage.
**Physics Case 3: QCD Critical End Point**

Based on the recent fRG and L-QCD results, there are no signs of criticality for $\mu_B/T \leq 4$

Most promising range for finding the Critical End Point (CEP):

$(135, 450)$MeV $\lesssim (T_{\text{CEP}}, \mu_{B_{\text{CEP}}}) \lesssim (100, 650)$MeV

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F. Karsch, RHIC Beam Energy Scan and Beyond 2021
A. Lahiri, LATTICE 2021
J.M. Pawlowski, CPOD 2021

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**EVENT-BY-EVENT FLUCTUATIONS**
Based on the recent fRG and L-QCD results, there are no signs of criticality for $\mu_B/T \lesssim 4$.

Most promising range for finding the Critical End Point (CEP): $(135, 450)\text{MeV} \lesssim (T_{\text{CEP}}, \mu_{B,\text{CEP}}) \lesssim (100, 650)\text{MeV}$

Higher-order cumulants and ratios of conserved quantities ($B$, $Q$, $S$) are sensitive to QCD CEP.

CBM can systematically study the higher-order cumulants and ratios to contribute significantly to the search of QCD-CEP.

F. Karsch, RHIC Beam Energy Scan and Beyond 2021
J. M. Pawlowski, CPOD 2021
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 $\mu_B$
- in-medium modifications of hadrons
- meson-baryon coupling
- dileptons at intermediate invariant masses

Strange matter
- (double-) lambda hyper-nuclei
- search for meta-stable objects (e.g., strange dibaryons)

Heavy flavor in cold and dense matter
- excitation function of charm production

DOI: 10.1007/978-3-642-13293-3

DOI: 10.1140/epja/i2017-12248-y
CBM SIMULATED PHYSICS PERFORMANCE
**Beam-Target Interaction Rates and Rare Probes’ Yields**

The CBM research program comprises a comprehensive scan of observables, beam energies and collision systems at up to 10 MHz beam-target interaction rates giving an unprecedented access to the ‘rare probes’

<table>
<thead>
<tr>
<th>Particle (mass MeV/c²)</th>
<th>Yield at 0.1 MHz I.R. (Day-1) in 90 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 AGeV</td>
</tr>
<tr>
<td>( \Lambda ) (1115)</td>
<td>1.2 x 10⁸</td>
</tr>
<tr>
<td>( \Xi^- ) (1321)</td>
<td>2.0 x 10⁹</td>
</tr>
<tr>
<td>( \Xi^+ ) (1321)</td>
<td>3.0 x 10⁷</td>
</tr>
<tr>
<td>( \Omega^- ) (1672)</td>
<td>4.0 x 10⁶</td>
</tr>
</tbody>
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<tr>
<td></td>
<td>6 AGeV</td>
</tr>
<tr>
<td>( \Omega^+ ) (1672)</td>
<td>7.0 x 10⁴</td>
</tr>
<tr>
<td>( \Lambda^4 \mathrm{He} ) (2993)</td>
<td>2.7 x 10⁸</td>
</tr>
<tr>
<td>( \Lambda^4 \mathrm{He} ) (3930)</td>
<td>1.7 x 10⁷</td>
</tr>
<tr>
<td>( \Lambda^4 \mathrm{He} ) (5047)</td>
<td>15</td>
</tr>
</tbody>
</table>

P. Senger, Phys.Scripta 96 (2021) 5, 054002

Y. Vassiliev (GSI)
The Compressed Baryonic Matter Experiment at FAIR

**Projectile Spectator Detector (PSD)**

**Dipole Magnet**

**Micro-Vertex Detector (MVD)**

**Silicon Tracking System (STS)**

**MUon CHamber (MUCH); or Ring Image Cherenkov (RICH)**

**Transition Radiation Detector (TRD)**

**Time-Of-Flight (TOF)**
CBM Simulations, central Au-Au@10AGeV

Clear separation between charged protons, pions and kaons

Clear separation between pions and electrons, and light nuclei

ToF - Hadron Identification

RICH - Electron ID

TRD + ToF - Electron, Light Nuclei, Heavy Fragments
Anisotropic Flow

- Input model $v_1$ is recovered using data-driven methods with projectile spectators
- Procedures for centrality determination, particle identification and corrections for effects of detector’s azimuthal non-uniformity are applied
- Results for $v_1$ of $\pi^+, \Lambda$ also available

O. Lubynets et al., Particles 2021, 4(2), 288-295
O. Golosov, CPOD 2021

Ongoing – Higher harmonics ($v_2$, $\ldots$)

(Multi-) Strangeness Production

- Tools for the multi-differential physics analysis are prepared for strange hadrons
- Reconstruction is based on the dedicated KFParticleFinder package
- Magnetic field scaling and multi-strange hyperon reconstruction performance also studied at lowest SIS-100 energies
  I. Vassiliev et al., CBM Progress Report 2020
- Possible improvements by using Machine Learning are ongoing
  S. Khan, SQM 2021
Physics Performance – [II]

- Clear peaks for the low mass vector mesons in both production channels, with 5M Au-Au collisions
- Negligible contribution from Drell-Yan and open charm decay
- Access to thermal signal is feasible with good background description
- Statistical accuracy for $T_{\text{slope}}$ of 10% requires $\sim 10^{11}$ events, $\sim 20$ days of beamtime @ 0.1 MHz I.R.

Di-lepton Distribution

Net-Proton Multiplicities and Cumulants

- The centrality dependence of cumulants of net-proton up to order four is under investigation
- Plans to analyze cumulants up to order six with large statistics and other SIS-100 energies
- Analysis ongoing for the net-charge and net-kaon
Experimental Challenges
**Recent Achievements In Detector Projects — [I]**

**Magnet (GSI, BINP Novosibirsk, JINR Dubna)**
- Progress in design of coils, branch box, transfer line, cryostat.
- Successful Yoke and Power Supply Production Readiness Review in February 2021
- Hall at BINP prepared for Factory Acceptance Tests

**Beam monitor and start detectors (TU Darmstadt, GSI)**
- Endorsed as an independent project
- Start detector Concept for Day-1 based on pcCVD high purity diamond sensors
- A concept of the beam abort system being worked out

**MVD (U Frankfurt, GSI, IKF Frankfurt, IPHC Strasbourg, Pusan Nat’l Univ.)**
- MIMOSIS-1: first full size sensor prototype available! First tests successful, systematic studies ongoing
- TDR submitted to ECE/ECG in May 2021
- MIMOSIS-2 submission in H2.2021

**STS (GSI Darmstadt, JINR Dubna, KIT Karlsruhe, JU Krakow, AGH Crakow, KINR Kiev, Univ. Tübingen, Warsaw UT)**
- All sensors delivered, QA done
- Successful Module and Ladder assembly EDR in Dec. 2020
- New ASICS available (STS-XYter2.2)
- Preproduction in Q2/Q3.2021
RECENT ACHIEVEMENTS IN DETECTOR PROJECTS – [II]

MUCH (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, NISER Bhubaneswar, IIT Kharagpur, IIT Indore, Gauhati Univ., PNPI Gatchina )

- CDRs accepted for LV, GEM, Mechanics and Gas systems
- 2nd GEM station assembled and tested with cosmic rays using MUCH/STS-XYTER
- mCBM with mMUCH couldn’t be attended due to covid, planning for the next campaign

RICH (Univ. Giessen, Univ. Wuppertal, PNPI Gatchina, GSI Darmstadt )

- Mechanics CDR accepted, EDR in 09.2021
- Camera design EDR completed; pre-production (demonstrator incl. cooling) launch in 2021
- Mirrors EDR/PRR in Q1.2021 followed by start of mirror production

TRD (NIPNE Bucharest, Univ. Frankfurt, Univ. Heidelberg, Univ. Münster, IRI Frankfurt)

- Outer modules PRR completed, first of series production (5 modules ) in H1.2021
- Inner modules TDR Addendum submitted to ECE/ECSG in 05.2021
- SPADIC 2.3 ASIC test submission in Dec. 2020

TOF (THU Beijing, NIPNE Bucharest, GSI Darmstadt, TU Darmstadt, USTC Hefei, Univ. Heidelberg, ITEP Moscow, HZDR Rossendorf, CCNU Wuhan)

- New ASIC PADI XI successfully tested – PRR in 06.2021
- Particle fluxes > 10 kHz/cm² reached
- Ageing studies ongoing in Bucharest (ISRAM facility);

PSD (INR Moscow, TU Darmstadt, CTU Prague, NPI Rez)

- All modules produced, Upper support structure arrived at FAIR in 09.2020
FAIR PHASE 0 – AVOIDING RISKS AND SPECTACULAR FAILURES...

However, we can save 700 lira and two months by not taking soil tests.

mCBM @ SIS-18

- mCBM - Pre-series and prototype detectors under realistic conditions with SIS18 beams
- First results show time and spatial correlations between the synchronized data streams of the detector subsystems demonstrating for the first time a conceptual verification of the triggerless-streaming read-out and data transport of CBM
- Charged particle fluxes up to 20 kHz/cm² at 3m from the target → Detailed high-rate tests for TOF and MVD, LGADs, SMX FEB, STS LV with Pb and Xe beams → validated radiation tolerance
CBM CONTRIBUTION TO FAIR PHASE 0

HADES-RICH: Already 1/2 (430 MAPMTs + FEE) of CBM-RICH

STAR-eTOF: 10% (108 MRPCs) of CBM-TOF

BM@N-STS: 1/3 (300 Si-sensors; 4 tracking layers) of CBM-STS
BM@N-FHCal & NA61-PSD: 20 and 13 modules, respectively, of CBM-PSD

CBM Online Reconstruction Software for STAR-BES

BM@N FHCal

BM@N STS

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

BES-II Run 2020

\[ \sqrt{s_{NN}} = 3 \text{ GeV} \]

\[ M = 494.2 \text{ MeV/c}^2 \]

\[ \sigma = 5.9 \text{ MeV/c}^2 \]

\[ S = 16978.4 \]

\[ S/B = 2.05 \]

\[ \text{SIF/S} + B = 104 \]

K\(^+\) → \(\pi^+\pi^0\)

BES-II Run 2020
CBM@SIS-100 (2 – 11 AGeV Au-Au) provides unique conditions in lab to probe QCD matter properties at neutron star core densities, including the high-density EOS, and the search for new phases at higher densities.

FAIR (Intermediate Objective) is secured and on track
- to start operation in 2026+
- employ high statistics capability
  - to achieve high precision of multi differential observables
  - to enable rare processes as sensitive probes

CBM day-1 setup already has significant discovery potential
- excitation function of hyperon production
- excitation function of di lepton production
- study of light hyper-nuclei

CBM Phase 0 activities (HADES, STAR, BM@N, NA61, mCBM)
- understanding of major components
- production of physics results with CBM devices

MOVING TOWARDS A TRULY MULTI-MESSENGER PHYSICS ERA
THANK YOU
(A) Chiral effective field theory:

(B) Multi-messenger astrophysics:

(C) HIC experiments:

(D) HIC and Astro combined:

(E)

(F)