The phase diagram of strongly interacting matter

\[ \frac{1}{V} \left( n_q - n_{\bar{q}} \right) \]

How to scan the phase diagram?
→ Nucleus-nucleus collisions at various beam energies!

data taken at:
RHIC/LHC  SPS  AGS  SIS

P. Braun-Munzinger et al. PLB 518 (2001)
F. Becattini et al. PRC 96 (2004)
R. Averbeck et al. nucl-ex/9803001
Outline

Part I Nuclear Matter in (or close to) ground state

Part II Exploring compressed nuclear matter in “nature”

Part III Exploring dense nuclear matter in the laboratory

Part IV Exploring the early universe in the laboratory

Part V Exploring the highest baryon densities in the laboratory
Part I
Nuclear Matter in (or close to) ground state
Nuclear matter in ground state: the Nuclear Shell Model

Woods-Saxon Potential

\[ V(r) = \frac{-V_0}{1 + \exp \left( \frac{r-R}{a} \right)} \]

Density distribution of nucleons inside (heavy) nuclei

Solving the Schrödinger equation

\[ \left\{ \frac{\hbar^2}{2m} \Delta + [E - V(r)] \right\} \Psi = 0 \]

Splitting of shells due to the spin-orbit coupling has to be taken into account!

Observed magic numbers

<table>
<thead>
<tr>
<th>( N )</th>
<th>2</th>
<th>8</th>
<th>20</th>
<th>28</th>
<th>50</th>
<th>82</th>
<th>126</th>
<th>(184)</th>
<th>(196)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z )</td>
<td>2</td>
<td>8</td>
<td>20</td>
<td>28</td>
<td>50</td>
<td>82</td>
<td>(114)</td>
<td>(164)</td>
<td></td>
</tr>
</tbody>
</table>
Effective nucleon-nucleon interaction

The meson exchange is a model to describe the effective nucleon-nucleon-interaction.

- Pion (π-meson): 
  - pseudo-scalar particle \( J^P = 0^- \)
  - \( m_\pi \approx 140 \text{ MeV} \)

- ρ-, ω-meson: 
  - vector particle \( J^P = 1^- \)
  - \( m_\rho,\omega \approx 780 \text{ MeV} \)

Range \( R \) of the interaction is determined by the uncertainty principle:

\[
R = c\Delta t = \frac{\hbar c}{m_\chi c^2} = \frac{197 \text{ MeV} \cdot \text{fm}}{m_\chi c^2}
\]

- Hard-core repulsion for \( r \leq 0.4 \text{ fm} \)
- Long-range attraction
- \((\pi/\omega \text{ exchange, Pauli principle, quark d.o.f.})\)
- \((\pi \text{ exchange})\)
- Binding around \( \sim 0.8 \text{ fm} \)

Note: In QCD one important contribution to the description of the nucleon-nucleon interaction is given by color neutral quark-antiquark exchange (sea quarks) which can be understood as a meson exchange between nucleons.
The equation-of-state of nuclear matter

\[ \varepsilon(\rho, T) = \varepsilon_T(\rho, T) + \varepsilon_C(\rho, T = 0) + \varepsilon_0 \]

\( (\varepsilon = E / A) \) thermal compression mod\( \text{ul} \) ground state energy

thermodynamical concept

nuclear equation-of-state at \( T = 0 \): the "compressional" energy

\[ E/A(\rho, T = 0) = \frac{1}{\rho} \int U(\rho) \, d\rho \]

\( U(\rho) \): density dependent local potential

--- \( \kappa = 380 \) MeV
--- \( \kappa = 200 \) MeV

stiff EoS

soft EoS

compression modulus

\[ \kappa = \left( 9\rho^2 \frac{\partial^2 E/A(\rho, T = 0)}{\partial \rho^2} \right)_{\rho = \rho_0} \]
The nuclear equation-of-state (EoS)

\[ E/A(\rho, T = 0) = \frac{1}{\rho} \int U(\rho) \, d\rho \]

**effective NN-Potential**

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

**constraints for the parameters of the potential:**

\[ \varepsilon(\rho = \rho_0, T = 0) = -16\text{MeV} \]
\[ \left( \frac{\partial \varepsilon(\rho, T = 0)}{\partial \rho} \right)_{\rho = \rho_0} = 0 \]

<table>
<thead>
<tr>
<th>( \kappa = 380 \text{ MeV} )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[MeV]</td>
<td>[MeV]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-124</td>
<td>70.5</td>
<td></td>
<td>2</td>
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</table>

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

compression modulus
Collective excitation of nuclei: Giant Resonances

- **Monopole vibration:** "breathing mode" of the nucleus
- **Dipole vibration:** "protons and neutrons oscillate against each other"
- **Quadruple vibrations**
Excitation of the giant monopole resonance

*Excitation of the giant monopole resonance*

**inelastic scattering of α particles on nuclei**

\[ \alpha \rightarrow ^{90}\text{Zr} \rightarrow \alpha \]

\[ E_{\text{kin}} = 240 \text{ MeV} \]

Measure of the total energy of the outgoing α particle → \(E_x\)

"resonance phenomenon"

The energy loss of the α particle of about 15 – 25 MeV excites slight density oscillations with elongations of about \(1/100 \rho_0\) (around saturation density \(\rho_0\)). It is a collective excitation of the nucleus and calls the Giant Monopole Resonance or the "breathing mode" of nuclei.

From the measured excitation energy distribution \(E_x\):

→ frequency

→ restoring force (potential) of the oscillation

→ "spring constant" \(\kappa = \) compression modulus
"Excitation of the **Giant Monopole Resonance** by inelastic scattering of $\alpha$ particles on nuclei"


\[ \kappa = 231 \pm 5 \text{ MeV} \]
The bonds between nucleons inside the nucleus are relatively "weak". The average distance is much larger than the hard core radius of the nucleon.

Nucleons are not localized inside the nucleus - they can move almost free inside the nucleus $\rightarrow p_f = 250 \text{ MeV/c}$.

The effective NN-potential has an attractive and a repulsive component.

The equation-of-state of nuclear matter:

\[ \kappa = 231 \pm 5 \text{ MeV at saturation density } \rho_0 \]

Link to QCD?

Quarks and gluons are not the relevant degree of freedom (in this regime). The largest fraction of the interaction strength is shielded because quarks and gluons are bound to color neutral hadrons.
QCD: running coupling constant $\alpha_s$

**Coupling strength between two quarks**

- **perturbative** QCD: $a_s \ll 1$
- **non-perturbative** QCD: $a_s \cong 1$

Asymptotic freedom
(Frank Wilczek - Physics Nobel prize 2004)

**Quarks are confined!**

$$ V(r) = -\frac{4\alpha_s \hbar c}{3r} + Kr $$

~1 fm
Results of the ALADIN collaboration show evidence for a transition from a liquid to a vapor phase of nuclear matter.
Part II
Exploring compressed nuclear matter in “nature”

Late stages of heavy stars

\[ T \approx 0, \rho \rightarrow 5-10 \rho_0 \]
Stellar evolution

M < 8 M\(_{\odot}\)  \quad \text{M \geq 8 M\(_{\odot}\)}

white dwarf  \quad \text{red giant}  \quad \text{neutron star}  \quad \text{black hole}

\text{note: } M\odot \equiv M_{\odot}
Observed neutron star masses


PSR J1614-2230
Green Bank Radio Observatory (2010)
Mass: \( (1.976 \pm 0.04) \, M_\odot \)
Distance: \( \sim 1 \, \text{kPc} \, (~3200 \, \text{Ly}) \)
Pulsar spin period: \( 3.1508076534271(6) \, \text{ms} \)
Companion mass: \( 0.5 \, M_\odot \)
Orbital period: \( 8.6866194196(2) \, \text{d} \)
Neutron star mass-radius relation

constraints to EoSs
- nucleons
- nucleons + exotic matter
- strange matter

Pressure balance
Fermi pressure
Gravity
Repulsive core

doi:10.1038/nature09466
Composition of a neutron star

Each arrow indicates a different model for the neutron star.

Each model is based on assumptions on nuclear matter properties!


ICNFP 2014 Christian Sturm, GSI
Equation-of-state: Non-local SU(3) NJL with vector coupling

Quark matter in massive neutron stars?
Part III
Exploring dense nuclear matter in the laboratory

Nucleus-nucleus collisions at SIS18
Relativistic nucleus-nucleus collisions at SIS18

\( \text{Au} + \text{Au} \)

high density phase

transport models: \( \rho_{\text{max}} \approx 3 \rho_0 \)

\( \rho, T \)

\( \approx 10^{-22} \text{ s} = 100 \text{ fm/c} \)

\( \approx 10 \text{ fm/c} \)

at SIS18 (max. 2 AGeV in A+A):

\( \rho_B \approx 1 - 3 \rho_0 \)

\( T \approx 70 - 100 \text{ MeV} \)

note:

system not necessarily equilibrated
The creation of strange mesons in elementary reactions

**K^+ mesons**

\[ m = 493.7 \text{ MeV/c}^2 \]

production threshold

\[ E_{lab} = 1.58 \text{ GeV} \]

**K^- mesons**

\[ m = 493.7 \text{ MeV/c}^2 \]

production threshold

\[ E_{lab} = 2.5 \text{ GeV} \]
Additional channels in A+A collisions

e.g.

\[ N N \rightarrow N \Delta \]
\[ N \Delta \rightarrow N K^+ Y \]
\[ \pi N \rightarrow K^+ Y \quad (Y=\Lambda,\Sigma) \]

multi step processes!

... and final state interaction!

![Graph](image)
The compression modulus of nuclear matter ($\rho > \rho_0$)


Figure by C. Fuchs

soft nuclear equation-of-state: $\kappa \approx 200$ MeV
Azimuthal particle emission

semi central collisions

Fourier expansion of the $dN/d\phi$ distribution:

$$\frac{dN}{d\phi} \sim \left[ 1 + 2v_1 \cdot \cos(\phi) + 2v_2 \cdot \cos(2\phi) \right]$$

the coefficients quantify:
- $v_1$ the in-plane and
- $v_2$ the elliptic emission pattern

mid rapidity

$p,d,t,\alpha$

$E_{\text{beam}} / A$ (GeV)

- 1.2
- 0.8
- 0.4
- 0.15
- 0.09

Au+Au, M3, Z=1+2

$\phi$ (deg.)

0 90 180 270 360

0 5 10 15 20 25 30
Elliptic flow and the Nuclear EoS

FOPI Collaboration

BUU transport models:

“soft” / “stiff” EoS

c) in-medium NN cross section

d) Asymmetric Colliding Nuclear Matter approximation
onset of chiral transition visible at SIS18? → generation of mass?

• antikaon production
• dileptons
The strong interaction and the origin of hadron masses

Quarks (R < 10^{-4} fm; M ≈ 10 MeV)

Nucleus (R ≈ 1-10 fm; M ≈ A x GeV)

Theory the strong interaction:
Quantum Chromo Dynamics (QCD)

\[ M \approx \sum m_i \]

\[ 1 \text{ GeV} >> 20 \text{ MeV} \]

atom

nucleus

nucleon

**nucleon:**

mass not determined by sum of current quark masses !!!

Simple minded view:

mass given by energy stored in motion of quarks and by energy of gluon fields \((m = E/c^2)\)
The strong interaction and the origin of hadron masses

Constituent quark masses

Proton
The strong interaction and the origin of hadron masses

$\pi^+$: $uud$

$K^+$: $uus \bar{s}$

$\eta$: $\frac{(u\bar{u} + d\bar{d} - 2s\bar{s})}{\sqrt{6}}$

$K^+(494)$: $u\bar{s}$

$p$: $uud$

$\rho^+(770)$: $u\bar{d}$

$\Delta^+(1232)$: $uud$

$\pi^+(140)$: $u\bar{d}$
Chiral symmetry in a nutshell

Chiral symmetry = fundamental symmetry of QCD

In case of mass less quarks:
the chirality corresponds to the (conserved) helicity,
left- and right-handed quarks decouple

Chirally symmetric world: chiral partners with same spin but opposite parity degenerate in mass.

The QCD Lagrangian is chirally symmetric but in "nature" chiral symmetry is broken!
Mass split is large, comparable to hadron masses.

- explicit breaking by small but finite quark masses
- spontaneously broken due to the existence of a mass less mode ("Goldstone-boson"): the pion
Chiral symmetry restoration

According to theoretical predictions (i.e. by Lattice QCD), chiral symmetry can be (partially) restored:

- At high temperature
- At large baryon density
e^+e^- pairs – penetrating probes!
Di-lepton sources

<table>
<thead>
<tr>
<th>mass [MeV/c^2]</th>
<th>cτ [fm]</th>
<th>dominating decay</th>
<th>e^+e^- branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ 768</td>
<td>1.3</td>
<td>ππ</td>
<td>4.4 x 10^{-5}</td>
</tr>
<tr>
<td>ω 782</td>
<td>23.4</td>
<td>π^+π^--π^0</td>
<td>7.2 x 10^{-5}</td>
</tr>
<tr>
<td>Φ 1019</td>
<td>44.4</td>
<td>K^+K^-</td>
<td>3.1 x 10^{-4}</td>
</tr>
</tbody>
</table>

E_{thr} (NN)
1.7 GeV
1.8 GeV
2.6 GeV
C+C vs. N+N results

Comparison of C+C data to average of pp and np collisions:

- C+C data reproduced (within 20%) by superposition of pp and np data
- Pair “excess” observed in C+C data can be traced back to enhanced pair production in n+p collisions (DLS puzzle solved)

PLB 690 (2010) 118
PL.B 663 (2008) 43
η mass region: strong overshoot above the cocktail of long-lived sources!

ρ/ω mass region: strength of ρ meson?
Part V
Exploring the highest baryon densities in the laboratory

Nucleus-nucleus collisions
• at the Nucletron-M with BM (1 – 4 AGeV)
• at NICA with MPD
• at SPS with NA61/Shine and NA60’
• at RHIC/BES
• at FAIR with CBM & HADES (2 – 45 AGeV)
Exploring the QCD phase diagram at FAIR energies

Open questions at high net baryon densities:
• Phase transition from hadronic matter to quarkyonic or partonic matter?
• Chiral phase transition? Chiral restoration?
• In-medium modification of hadrons?
• Nuclear Equation-of-State at neutron star core densities?

→ substantial discovery potential at SIS100 / 300

Field driven by experimental data!
Messengers from the dense fireball

UrQMD transport calculation  U+U 23 AGeV

charm

prompt $\gamma$

thermal $\gamma$

decay $\gamma$

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

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

$\Phi, \Xi, \Omega$

$K, \pi, \Lambda, \eta$

resonance decays
Experimental challenges

Particle multiplicity x branching ratio (from HSD and thermal model)

Au+Au 25 A GeV min. bias

SPS Pb+Pb 30 A GeV
STAR Au+Au \( \sqrt{s_{NN}} = 7.7 \) GeV

CBM experimental program
Systematic measurement of excitation functions of (rare) probes with full event characterization for a variety of beam energies and collision systems
\( \pi^+, \eta, \rho, \omega, \varphi, K^{+0}, p, \bar{p}, \Lambda, \bar{\Lambda}, \Sigma^*, \Xi^+, \Omega^-, \Omega^{+0}, J/\psi, \psi' \).
Charmonium (J/ψ)

1974: J/ψ discovery at SLAC and BNL

- bound state of heavy quarks: c̅c
- quantum numbers as the photon: Jp = 1-
- J/ψ mass: 3.1 GeV
- c mass: ~1.3 GeV
- binding energy ~600 MeV
- width: 93 keV (life time: 10^{-20}s)
J/ψ production in nucleus-nucleus collisions

signature of deconfinement?

J/ψ suppression

J/ψ regeneration
CBM physics observables: Charmonium (J/ψ)

CERN/SPS experiments

No data available below top SPS energies!

Excitation function of J/ψ production at SIS100/300 energies
→ production mechanism?
→ J/ψ suppression?


CERN/SPS experiments

In-In 158 GeV (NA60)
Pb-Pb 158 GeV (NA50)

B. Alessandro et al., EPJC39 (2005) 335
CBM physics observables
Charmonium ($J/\psi$) and open charm ($D\bar{D}$) production

HSD “hadronic”
O. Linnyk et al.,

SHM “partonic”
A. Andronic et al.,
CBM physics observables
Electromagnetic radiation from the dense fireball

\[ \frac{1}{2} (pp+np) \ 1.25 \text{ A GeV} \]

\[ 1/N_{\pi^0} dN/dM_{ee} [(\text{GeV/c}^2)^{-1}] \]

\[ 0.1 < p_e < 1.1 \text{ GeV/c} \]
\[ \eta \text{ comp. subtracted} \]

\[ M_{ee} \ [\text{GeV/c}^2] \]

No data available in SIS100 / SIS300 energy range!

Excitation function of lepton pair production (2 – 45 A GeV)
\[ \rightarrow \text{excess?} \]

In-medium mass distributions of light vector mesons (2 – 45 A GeV)
\[ \rightarrow \text{in-medium modification of light vector mesons?} \]
CBM physics observables
Production excitation function of multi-strange baryons

Knowledge about multi-strange baryons at energies below 10 AGeV very limited

→ multi-step production ?
→ production via strangeness exchange channels ?
→ enhanced production in dense medium ?

direct production:

\( pp \rightarrow \Xi^- K^+ K^+ p \quad E_{\text{thr}} = 3.7 \text{ GeV} \)
\( pp \rightarrow \Omega^- K^+ K^0 p \quad E_{\text{thr}} = 7.0 \text{ GeV} \)
CBM physics observables
Excitation function of collective flow

Present data sets are not conclusive due to large uncertainties

High precision collective flow excitation function at SIS100/300
→ equation-of-state at neutron star core densities
CBM physics observables
Hypernuclei, strange dibaryons and massive strange objects

Single and double hypernuclei in nucleus-nucleus collisions
Search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects

→ Production of hypernuclei via coalescence of hyperons and light nuclei


Summary: CBM physics case and observables

The equation-of-state at neutron star core densities
- collective flow of hadrons
- particle production at threshold energies
  (multi-strange hyperons)

Onset of chiral symmetry restoration at high $\rho_B$
- in-medium modifications of hadrons ($\rho, \omega, \phi \rightarrow e^+e^-(\mu^+\mu^-)$)

New phases of strongly-interacting matter
- excitation function and flow of lepton pairs
- excitation function and flow of strangeness ($K, \Lambda, \Sigma, \Xi, \Omega$)

Deconfinement phase transition at high $\rho_B$
- excitation function and flow of charm ($J/\psi, \psi', D^0, D^\pm, \Lambda_c$)
- anomalous charmonium suppression

Strange matter
- (double-) lambda hypernuclei
- strange meta-stable objects
  (e.g. strange dibaryons)
CBM experimental challenges

Perform measurements at unprecedented reaction rates
$10^5 - 10^7$ Au+Au reactions/sec
→ fast and radiation hard detectors
→ free-streaming read-out electronics
→ high speed data acquisition and
   high performance computer farm for online event selection
→ 4-D event reconstruction

Identification of leptons and hadrons

Determination of (displaced) vertices ($\sigma \approx 50 \, \mu m$)

Central Au+Au at 25 A GeV / UrQMD+GEANT4 : 160 p, 400 $\pi^+$, 400 $\pi^+$, 44 K$^+$, 13 K$^-$
The CBM cave at FAIR

Magnet + STS  RICH  TRD  TOF  PSD  + MVD

beam

MUCH parking pos.
Performance of hyperon identification

Simulations:
- STS with realistic geometry, material budget, and detector response
- TOF at 10 m, time resolution 80 ps

$5 \times 10^6$ Au+Au central
10 AGeV

$5 \times 10^6$ Au+Au central
25 AGeV
Performance of open charm identification

$p+C$

30 GeV

$Au+Au$

25 AGeV

no particle identification by time-of-flight

$p+C$

30 GeV

$Au+Au$

25 AGeV

$D^0 \rightarrow K\pi\pi\pi$

$D^\pm \rightarrow K\pi\pi$

$D^0 \rightarrow K\pi\pi\pi$

$D^\pm \rightarrow K\pi\pi$

$\frac{S}{B} = 2.5(1.24)$

$\text{eff} = 4.75\%$
central Au+Au collisions at 25 A GeV

Detector systems: STS, RICH+TRD or MUCH, ToF

Di-lepton invariant mass spectra

$\omega$, $\phi$, $e^+e^-$, $J/\psi$, $\mu^+\mu^-$
CBM physics observables

Production excitation function in nucleus-nucleus collisions at SIS100/300 of multi-strange baryons, anti-protons and anti-hyperons, single and double hypernuclei.

Search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects.

High precision collective flow excitation function at SIS100/300.

Excitation function of J/ψ production at SIS100/300 energies.

Excitation function of lepton pair production and in-medium mass distributions of light vector mesons (2 – 35 A GeV).

(not complete)