Heavy-Ion Physics at High Baryon Densities

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The Phase Diagram of Heavy-Ion Experiments

$\sqrt{s_{NN}}$ (GeV)

Year of first experiments

hadronic

phase transition

QGP

experimental programmes at lower beam energies

ICNFP 2014, Kolymbari, 31 July 2014
V. Friese
RHIC Beam Energy Scan

- STAR (and PHENIX) experiments @ RHIC
- phase 1: 2010 – 2014
- phase 2 planned for 2018 - 2019

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<th>Energy (GeV)</th>
<th>Events (Millions)</th>
<th>Time (Weeks)</th>
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NA61

- upgrade of the NA49 detector at CERN-SPS; recently first ion data (Be+Be)
- 2-d scan: beam energy and system size
CBM

• next-generation fixed-target experiment at the FAIR centre, Darmstadt (under construction)
• hadron, lepton and photon detector with large acceptance
• beam energy range 2A – 45A GeV
• programme includes HADES at the new beam line
• operation from 2019 on
MPD

- collider experiment at the NICA accelerator complex at JINR / Dubna (under construction)
- hadronic and leptonic probes
- collision energies: $\sqrt{s_{NN}} = 4 – 11$ GeV
- operation from 2019 on
NA60+

- dedicated fixed-target muon experiment proposed for CERN-SPS
- detector concept similar to NA60 (two spectrometers before and after the absorber), but adapted to conditions at lower energies
- low- and intermediate-mass di-muons down to 20A GeV, charmonium down to 60A GeV
- letter of intent in preparation

G. Usai, FAIR Workshop, this conference
Motivation – in a Nutshell

• Assuming a deconfined state is created in nuclear collisions at top SPS energy and above:
  – when (at which beam energy) is such a state first reached (onset of deconfinement)?
  – of what nature is the phase transition?

• This calls for a systematic study in terms of collision energy (and, also, system size) – at energies below top SPS (158A GeV ≈ 17.3 GeV)
  – looking for discontinuities / non-monotonic behaviour in the energy dependence of observables

• Why does that mean “high baryon density”? 
Finally: The QCD Phase Diagram

Features:
• deconfined at high \( T / \mu_B \)
• at \( \mu_B = 0 \): no phase transition (cross-over)
• at high \( \mu_B \): first-order phase transition
• both domains separated by a critical point
• potentially rich structure near \( T=0 \) axis
The hadronic final state resembles a hadron gas in equilibrium.

Different collision energies probe different regions of the phase diagram.

Microscopic models confirm to reach a high-density state with medium energies.
Probing Highest Net-Baryon Densities

J. Randrup & J. Cleymans
• Results of the beam energy scan by NA49 (1999-2002)
  – maximum in K/π at 30A GeV
    • explained by statistical model (?)
  – plateau in apparent temperature above 30A GeV
    • indicative of 1st order phase transition (latent heat) ?
• might be an interesting energy region to look further into
• Number of measured hadron species decreases when going to lower energies.
• Does the statistical model still work here, also with rare species?
• Puzzling observations:
  • \( \phi \) well described at SIS-18 (sub-threshold!) and RHIC, but not so at SPS
  • \( \Xi \) at SIS-18 (also deep sub-threshold) off by factor of 20 from SHM.
• Is strangeness production really understood?
Multi-Strange (Anti-)Hyperons

• Particularly interesting near threshold ($\Xi$: 3.7 GeV, $\Omega$: 7.0 GeV)

• Can be produced in nuclear collisions also sub-threshold:
  – multi-step processes like $\Lambda K \rightarrow \Xi \pi$ $\Xi K \rightarrow \Omega \pi$
  – many-body collisions with $K$ or $\Lambda$ in entry channel

• Sensitive to both strangeness and baryon density

• Quantitative predictions: need microscopic models
Multi-Strange (Anti-)Hyperons

• Predictions from pHSD: anti-Hyperons are particularly sensitive to the production scenario
  – much easier to be produced in QGP: relaxes strong constraints due to high baryon density

• Very recent high-statistics calculations: \( \Omega^+ \) is enhanced by a factor of 8 in pHSD (partonic) compared to HSD (hadronic) in Au+Au at 25A GeV
Anti-Hyperons: Experimental Prospects

Needs very high statistics and good secondary vertexing to identify (anti-)cascade decays

- CBM/FAIR: 4A - 45A GeV
- MPD/NICA: √s = 4A – 11A GeV (E = 6A – 60A GeV)
- BM@N (NICA fixed target): 2A – 5.5A GeV
The Search for the Critical Point

• Criticality would express in non-statistical event-by-event fluctuation of conserved quantities: e.g., net charge, net baryon

• Beautiful data delivered by STAR: but no conclusive indication of a critical point yet
  – n.b.: theory gives little guidance as to how close to the critical point fluctuations should be observable
    • finite size and lifetime of system
  – data at lower energies suffer from low statistics
    • improvement to be expected from BES phase II (improved beam, detector upgrade)
Vector Mesons and the Generation of Mass

- Hadrons are expected to change their properties (mass / width) in presence of dense medium
  - vanishing of chiral condensate; restoration of chiral symmetry (?)
- Experimental access: short-lived vector mesons (ρ)
  - decay inside the fireball -> retain information on dense environment
  - decay into lepton pairs: no strong interaction, carry information out of the medium

The Melting of the $\rho$

- Observation of excess over spectrum expected from hadronic cocktail was observed at SPS by CERES ($e^+e^-$) and NA50/NA60 ($\mu^+\mu^-$)
- Landmark measurement: NA60 (In+In): consistent with broadening of the $\rho$ meson

Data: NA60, EPJC 59 (2009) 607
Messages from HADES

- Excess already present at beam energies as low as 1.76A GeV and systems as small as Ar+KCl! Can this have to do with chiral symmetry restoration?
  - Need the proper baseline: p+p is not enough.
  - Can coupling of ρ to baryons explain everything?
  - Newest results: excess of factor of 8 in Au+Au at 1.23A GeV!
- Data in the high density region utterly desirable!
The Intermediate Mass Region

- Between $\phi$ and $J/\psi$: no hadronic sources
  - processes: Drell-Yan, thermal radiation (QGP / hadron gas)
- Apparent temperature of excess yield (through transverse spectra) as function of mass:
  - rise for $m < 1$ GeV: hadronic sources, radial flow
  - constant for $m > 1$ GeV: early source with low flow -> direct radiation from the QGP?
- Calls for systematic investigation at lower energies!
Low-Mass Lepton Pairs: Experimental Prospects

- HADES/FAIR: $e^+e^-$, up to 4A GeV (Au+Au), 8A GeV (Ni+Ni)
- CBM/FAIR: $e^+e^-$ and $\mu^+\mu^-$, 4A - 45A GeV
- MPD/NICA: $e^+e^-$, $\sqrt{s} = 4A – 11A$ GeV ($E = 6A – 60A$ GeV)
- NA60+/SPS: $\mu^+\mu^-$, 20A - 158A GeV
Charm in Heavy-Ion Collisions

• Unlike lighter quarks, $m_c >> T$
  – thermal production of charm negligible
  – production of charm in first-chance N-N collisions
  – charm probes the produced medium
    • $c$ quark diffusion in QGP
    • $D$ meson / $J/\psi$ propagation in hadronic medium
Charmonium Suppression: The QGP Signal

- Dissociation of charmonium states by free colour charges in a deconfined medium
- observed at SPS (NA50) for very central Pb+Pb collisions (not in In+In / NA60)
- need to control additional effects:
  - absorption in cold nuclear (spectator) matter -> p+A
  - absorption in hot hadronic (co-mover) matter
  - regeneration: only at high collision energies (RHIC, LHC)
Charmonium Below Top SPS Energy

• Can an „onset“ of charmonium suppression be observed below top SPS energy (160A GeV)?

• \(N_{cc\bar{c}} \ll 1\): re-generation negligible

• Many questions:
  – how do quarkonia interact with normal hadrons?
  – what is the effect of nuclear matter on the binding of c-cbar to charmonia?
  – how is the overall c-cbar production rate modified in dense matter?

\[
\begin{array}{c|c|c}
\text{hard} & \text{pre-resonance} & \text{resonance} \\
0.05 \text{ fm} & 0.25 \text{ fm} & \\
\text{c\bar{c} = 1/2m_c} & g=1/\sqrt{2m_c} & \text{qcd}
\end{array}
\]

H. Satz, Heavy-Flavour Workshop, 24 May 2014
Charm Cross Section

• For the interpretation of charmonium data, the total c-cbar production cross section is required: need to measure also open charm.
  – cave: near threshold, N_{J/ψ} << N_D not necessarily true

• Charm cross section close to threshold is experimentally unknown below √s = 20 GeV even in elementary reactions (let alone A+A)!

• pQCD calculations also come with large uncertainties.
Model Predictions for Charm in A+A

HSD: hadronic picture
(based on extrapolation of elementary cross sections to threshold)

Very low predicted rates: experimentally quite challenging!
Charm Predictions for A+A: Partonic Picture

Statistical Model:
• fixed c-cbar multiplicity (e.g., from pQCD)
• statistical hadronisation: implicitly assumes thermalisation of charm quarks in QGP
• works well for RHIC and LHC
The Sensitivity of Charm

- Model predictions (hadronic / partonic) differ significantly: charm production near threshold is sensitive to the production scenario!
- Particularly promising: ratio hidden to open charm (reduces uncertainty due to c-cbar cross section).
Charm in Medium

- Open charm is expected to change properties in dense medium (coupling to light-quark condensate)
- Can have large effect on production cross section!
- Unclear: formation time of open charm vs. life time of dense fireball

Charm at Lower Energies: Experimental Prospects

- exciting physics with many open issues calls for a comprehensive experimental programme including p+p and p+A collisions
- low yields: needs high-rate experiments plus micro-vertexing capabilities for open charm.
- charmonium
  - NA60 down to 60A GeV
  - CBM up to 45A GeV
- open charm
  - NA61: down to ~ 80A GeV
  - CBM: up to 45A GeV
Summary

• Experimental programmes are ongoing or in preparation worldwide to explore strongly interacting matter at highest achievable net-baryon densities.

• The aim is to find and study the structures in the QCD phase diagram:
  – first-order deconfinement phase transition
  – critical point
  – hypothetical new phases at high baryon densities

• These programmes are complementary to the study of the QGP which are performed at top RHIC and LHC.

• New accelerator facilities will become available around 2019.

• The future of heav-ion physics seems bright and promising!