Past and future of heavy ion physics in the CERN SPS energy domain

THE PROBLEM

- Strongly interacting matter: phases and transitions

AND ITS SOLUTIONS:

PAST

- Observation of the onset of deconfinement

AND FUTURE

- Search for the critical point and study properties of the onset of deconfinement
THE PROBLEM

- Strongly interacting matter: phases and transitions

What are the phases of strongly interacting matter?

How do the transitions between them look like?
Phases of water

Phases of strongly interacting matter
Phase diagram of water

critical point

cross-over

1st order phase transition
The phase diagram of water is well established (non-relativistic particles)

The phase diagram of strongly interacting matter is under study (relativistic particles)

Baryochemical potential (MeV)

Temperature (MeV)

Critical point

1st order phase transition

quark gluon plasma

hadrons

color superconductor

M*
In our daily life ...

- Droplets of water
- Droplets of strongly interacting matter
- The properties of strongly interacting matter can be studied only in collisions of nuclei
COLLISIONS OF TWO NUCLEI
-the only tool to study properties of strongly interacting matter in the laboratory

produced particles measured in the NA49 apparatus (scale 10 m)

snapshot of the produced matter after the collision (scale $10^{-14}$ m)

NA49 Pb-Pb
158 GeV/nucleon

UrQMD
Two basic states of strongly interacting matter are expected

Hadron gas at low densities
Quark-gluon plasma at high densities

Collins, Perry
Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry

Department of Applied Mathematics and Theoretical Physics, University of Cambridge,
Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

We first give arguments leading to this idea. It is commonly believed that hadrons consist of quarks\textsuperscript{5−7} despite the apparent nonexistence of free quarks.\textsuperscript{8} There are two main reasons for this belief. First, a quark model explains\textsuperscript{5} many properties of the hadron spectrum, and of strong-interaction decays. Secondly we have Bjorken scaling\textsuperscript{7} in the deep inelastic scattering of leptons by nucleons. Basically, this indicates that hadrons consist of pointlike objects (partons) which interact weakly with each other when close together. Analysis of the data indicates that partons are the fractionally charged spin-$\frac{1}{2}$ Gell-Mann–Zweig quarks. Since free quarks are not observed,\textsuperscript{8} it is assumed that they are permanently bound in hadrons\textsuperscript{9} by a mechanism as yet unknown, but much speculated on.

A neutron has a radius\textsuperscript{10} of about 0.5–1 fm, and so has a density of about $8 \times 10^{14}$ g cm$^{-3}$, whereas the central density of a neutron star\textsuperscript{11–12} can be as much as $10^{16}$–$10^{17}$ g cm$^{-3}$. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.
Hypothetical phase diagram of strongly interacting matter

![Graph showing hypothetical phase diagram of strongly interacting matter. The diagram plots temperature (T, MeV) against chemical potential (μ_B, MeV). The phase transitions from hadrons to quark gluon plasma are indicated.](image-url)
Observation of the onset of deconfinement

Brief history of the CERN SPS ion programs and NA49

Observation of the onset of deconfinement
Brief history of the CERN SPS ion programs and NA49

1986-1991: Pioneering study with O and S beams
Strangeness enhancement and $J/\psi$ suppression
⇒ Simple superposition models do not work

1994-2000: Pb+Pb collisions at the top SPS energy
anomalous $J/\psi$ suppression, statistical properties of hadron production, direct photons
⇒ Is a new state of matter created?

1998-2002: Pb+Pb collisions at low SPS energies
(NA49 energy scan program at the CERN SPS)
Anomalies in energy dependence of hadron production
⇒ Observation of the onset of deconfinement?

Rafelski, Muller
Matsui, Satz

WNM: the basic reference
Bialas, Bleszynski, Czyz

M.G., Gorenstein, Seyboth
NA49 at the CERN SPS

- A large acceptance: \( \approx 50\% \)

- A high momentum resolution:
  \[
  \sigma(p)/p^2 \approx 10^{-4} \quad ((GeV/c)^{-1})
  \]

- A good particle identification:
  \[
  \sigma(\text{TOF}) \approx 60 \text{ ps},
  \sigma(\text{d}E/\text{d}x)/\langle\text{d}E/\text{d}x\rangle \approx 0.04,
  \sigma(m_{\text{inv}}) \approx 5 \text{ MeV}
  \]
Surprising success of statistical models
e.g. the statistical hadronization model:

\[ \langle n_i \rangle = \frac{(2J_i + 1) V}{(2\pi)^3} \int d^3 p \frac{1}{\gamma S_i \exp[(E_i - (\mu_B + \mu_S + \mu_Q))/T]} \pm 1 \]

fit parameters

chemical freeze-out of matter created in A+A collisions

Becattini, Broniowski Florkowski, Gorenstein, Redlich, ...
Freeze-out points of central heavy ion collisions at SPS are close to the phase boundary.

It's possible that the early stage crosses the phase boundary at SPS energies (onset of deconfinement).

HG fits: Becattini et al., Cleymans, Redlich et al.

CP: Fodor, Katz
Onset of deconfinement: the early stage hits the transition line
Onset of deconfinement at the CERN SPS

The basic idea - heating curve of water

Heat used to vaporize water to water vapor

Heating of water vapor

Heating of water

Heat added (each division=4 kJ)

collision energy

hadronic observables
Heating curves of strongly interacting matter

hadrons  mixed  QGP

AGS  SPS  RHIC

collision energy

hadronic observables

AGS  SPS  RHIC

Kink  Horn  Step

collision energy
The kink in pion multiplicity

\[ F \approx \sqrt[2]{s_{NN}} \]

\[ \langle \pi \rangle \text{ - total pion multiplicity} \]

\[ \langle N_W \rangle \text{ - number of interacting nucleons} \]
The horn in strangeness yield

- Deconfinement
  - Decrease of masses of strangeness carriers and the number ratio of strange to non-strange degrees of freedom
  - A sharp maximum in the strangeness to pion ratio

\[
\langle K^+ \rangle / \langle \pi^+ \rangle
\]
A toy model of the horn

\[
\frac{\langle K \rangle}{\langle \pi \rangle} \propto \frac{MT^{3/2}}{T^3} e^{-M/T}
\]

\[
\frac{\langle s \rangle}{\langle u+d+g \rangle} \propto \frac{T^3}{T^3} = \text{const}(T)
\]

\[
\langle n \rangle = \frac{g V}{(2\pi)^3} \int d^3p \frac{1}{e^{E/T} \pm 1}
\]

\[
\approx g V \frac{2\pi^2}{4 \cdot 45} T^3 \quad \text{for light particles}
\]

\[
\approx g V \left(\frac{MT}{2\pi}\right)^{3/2} e^{-M/T} \quad \text{for heavy particles}
\]
**main strangeness carriers**

\[ s \approx s \]

**strangeness conservation**

**isospin symmetry**

\[ K^+ \approx K^0 \]

\[ K^- \approx \bar{K}^0 \]

\[ \bar{\Lambda} \ll \Lambda \]

**high baryon density**

\[ s \] sensitive to strangeness content only

\[ \bar{s} \] sensitive to strangeness content and baryon density
The step in $m_T$ slopes

Deconfinement

Constant temperature and pressure in the mixed phase region

Weaker energy dependence of the shape of transverse mass spectra

$T$ – inverse slope parameter of transverse mass spectra

Shuryak, van Hove
Gorenstein, M.G., Bugaev
The models

Models with the 1^{st} order phase transition reproduce the data

\[ E_S = \left( \langle \Lambda \rangle + \langle K + \bar{K} \rangle \right) / \langle \pi \rangle \]

\( E_S = (\Lambda + K + \bar{K}) / \pi \)

\[ \sqrt{s_{NN}} \text{ (GeV)} \]

\[ F \text{ (GeV}^{1/2}) \]

AGS  SPS  \( F \text{ (GeV}^{1/2}) \)

AGS  SPS  RHIC

Models for A+A:
- Hydro + Phase Transition
- HSD with Cronin effect
- HSD
- UrQMD
- UrQMD 2.0

\( K^+ \)

\( K^+ \)

\( K^- \)

\( K^0 \)

\( p+p (\bar{p}) : \)

\( \text{A}+\text{A}: \)

- AGS
- NA49
- RHIC

25
Summary (I)

1. Several anomalies in hadron production are observed at low SPS energies.
2. The onset of observed anomalies is located at about 30A GeV.
3. The anomalies cannot be reproduced by the models without phase transition.
4. Measured rapid changes are consistent with models assuming 1\textsuperscript{st} order PT.

FUTURE

hadronic observables

collision energy

AGS  SPS  RHIC

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FUTURE

hadronic observables

collision energy

AGS  SPS  RHIC
Search for the critical point and study of the properties of the onset of deconfinement

Physics goals of ...

... new (non-LHC) experimental programs with ions:
- NA61 (=NA49-future) at the CERN SPS (2009)
- STAR/PHENIX at the BNL RHIC (2010)
- MPD at the JINR NICA (2013)
- CBM at the FAIR SIS-300 (2015)
Physics goals

water

strongly interacting matter

quark gluon plasma

future studies

hadrons

critical point

1\textsuperscript{st} order phase transition
Two main events in nucleus-nucleus collisions

Onset of Deconfinement: an early stage hits transition line, observed signals: kink, horn, step

Critical Point: a freeze-out close to critical point, expected signal: a hill in fluctuations

E(OoD) \approx 30A \text{ GeV} \leq E(OoC)
Physics goals

*Discovery potential:*

- search for the critical point of strongly interacting matter
  (← lattice QCD + NA49 results)

*Precision measurements:*

- study the properties of the onset of deconfinement
  (← NA49 results)

- study the properties of hadrons at high energy/baryon density
future experimental programs with ions focus at the CERN SPS energy range.
New (non-LHC) experimental programs with ions

- NA61 (=NA49-future) at the CERN SPS (2009)
- STAR/PHENIX at the BNL RHIC (2010)
- MPD at the JINR NICA (2013)
- CBM at the FAIR SIS-300 (2015)
NA61 at the CERN SPS
NA61 physics goals (I):

**Physics of strongly interacting matter**

*Discovery potential:*

Search for the critical point of strongly interacting matter

*Precision measurements:*

Study the properties of the onset of deconfinement in nucleus-nucleus collisions

Measure hadron production at high transverse momenta in p+p and p+Pb collisions as reference for Pb+Pb results

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**quark-gluon plasma**

**transition**

**hadron gas**
NA61 Physics goals (II):

Data for neutrino and cosmic ray experiments

Precision measurements:

Measure hadron production in the T2K target needed for the T2K (neutrino) physics

Measure hadron production in p+C interactions needed for T2K and cosmic-ray, Pierre Auger Observatory and KASCADE, experiments
NA61 Detector

Upgraded NA49 apparatus

Upgrades: CERN-SPSC-2006-034, SPSC-P-330
NA61 plans a comprehensive scan in the two dimensional plane (energy)-(system size) in the CERN SPS energy domain.

**NA61 ion program**

- **Pb+Pb**
- **In+In**
- **Si+Si**
- **C+C**
- **p+p**

**Energy (A GeV)**: 10, 20, 30, 40, 80, 158

**NA49**

- Energy (A GeV): 10, 20, 30, 40, 80, 158

= $2 \cdot 10^6$ registered collisions
New data registered by NA61 will allow to establish the system size dependence of the anomalies observed in Pb+Pb collisions and thus further test their interpretation as due to the onset of deconfinement.

In particular, it is expected that the "horn" like structure should be the same for S+S and Pb+Pb collisions and then rapidly disappear for smaller systems.

M.G., Gorenstein
New data registered by NA61

In particular the critical point should lead to an increase of multiplicity and transverse momentum fluctuations

**Fluctuations and CP:** Stephanov, Rajagopal, Shuryak, Phys. Rev. D 60, 114028

**Freeze-out points:** Becattini et al., Phys. Rev. C 73, 044905
Test of the performance in the search for the critical point by simulating events in the NA49 detector

Transverse momentum fluctuations in the NA61 acceptance within the UrQMD model

... + an enhancement due to CP added to S+S collisions at 80A GeV

Smooth dependence on energy and system size

Clearly visible maximum (+10 MeV/c) over a smooth background

results from K. Grebieszkow
Central collisions of light and medium size nuclei are required for the proposed fluctuation studies.

Event-by-event fluctuations in the number of interacting (participant) nucleons are the main source of the background in the fluctuation studies.

The fluctuations of the number of projectile participants are suppressed by selecting collisions with fixed number of projectile spectators (in NA49-future measured by PSD).

The fluctuations of the number of target participants can be suppressed only by selection of very central collisions.

Konchakovski et al., Phys. Rev. C 73, 034902
Planed run schedule:

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam</th>
<th>Energy (A GeV)</th>
<th>Days</th>
<th>Physics</th>
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<tr>
<td>2007</td>
<td>protons</td>
<td>30</td>
<td>30</td>
<td>T2K, C-R</td>
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<tr>
<td>2008</td>
<td>protons</td>
<td>30, 40, 50, 158, 400</td>
<td>45</td>
<td>T2K, C-R, High p_T</td>
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<td>2009</td>
<td>indium</td>
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<td>30</td>
<td>CP&amp;OoD</td>
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<td></td>
<td>protons</td>
<td>10, 30, 30, 40, 80, 158</td>
<td>30</td>
<td>CP&amp;OoD</td>
</tr>
<tr>
<td>2010</td>
<td>silicon</td>
<td>10, 20, 30, 40, 80, 158</td>
<td>30</td>
<td>CP&amp;OoD</td>
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<tr>
<td></td>
<td>protons</td>
<td>158</td>
<td>30</td>
<td>High p_T</td>
</tr>
<tr>
<td>2011</td>
<td>carbon</td>
<td>10, 20, 30, 40, 80, 158</td>
<td>30</td>
<td>CP&amp;OoD</td>
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<td></td>
<td>protons</td>
<td>10, 20, 30, 40, 80, 158</td>
<td>30</td>
<td>CP&amp;OoD</td>
</tr>
</tbody>
</table>

(event rate 100 Hz)
Status of NA61:

- NA61 is accepted as a new CERN experiment
- the 2007 proton run is approved
- an approval process of the following runs is in progress

LoI: CERN-SPSC-2006-001, SPSC-I-235 (January 6, 2006)
The NA61 Collaboration:
106 physicists from 25 institutes and 15 countries:

University of Athens, Athens, Greece
University of Bari and INFN, Bari, Italy
University of Bergen, Bergen, Norway
University of Bern, Bern, Switzerland
KFKI IPNP, Budapest, Hungary
Cape Town University, Cape Town, South Africa
Jagellonian University, Cracow, Poland
Joint Institute for Nuclear Research, Dubna, Russia
Fachhochschule Frankfurt, Frankfurt, Germany
University of Frankfurt, Frankfurt, Germany
University of Geneva, Geneva, Switzerland
Forschungszentrum Karlsruhe, Karlsruhe, Germany
Swietokrzyska Academy, Kielce, Poland
Institute for Nuclear Research, Moscow, Russia
LPNHE, Universites de Paris VI et VII, Paris, France
Pusan National University, Pusan, Republic of Korea
Faculty of Physics, University of Sofia, Sofia, Bulgaria
St. Petersburg State University, St. Petersburg, Russia
State University of New York, Stony Brook, USA
KEK, Tsukuba, Japan
Soltan Institute for Nuclear Studies, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
University of Warsaw, Warsaw, Poland
Rudjer Boskovic Institute, Zagreb, Croatia
ETH Zurich, Zurich, Switzerland

IFJ Krakow is still missing
RHIC Low Energy Scan

Based on:
H. G. Ritter, PoS(CPOD2007) 015,
P. Sorensen, APS DNP 2004 Long Range Plan
T. Satogata, BNL internal report
Experiments
Project schedule:

- Low energy (5 GeV/u) test run with Au, June 2007

- First physics run in 2010: Au+Au collisions at the NA49/61 energies (c.m. Energy per N+N pair = 4.86, 6.27, 7.62, 8.77 12.3 and 17.3) and 50 GeV

Physics goals:

- search for the critical point

- turn off the signals of deconfinement
The 2007 test will establish the event rate at lower energies (1 Hz?)
Nuclotron-based Ion Collider fAcility and MultiPurpose Detector (NICA/MPD)

Based on:
NICA/MPD Booklet
Experiment

(TPC, SVS, TOF, ZDC)
Commissioning of NICA and MPD planned for 2013

\[ \sqrt{s_{\text{NN}}} \leq 9 \text{ GeV}, \ A \leq U, \ \text{luminosity} = 10^{27} \text{ cm}^{-2} \text{ s}^{-1} \]

**Physics goal:**

- search for the mixed phase of strongly interacting matter
Facility for Antiproton and Ion Research and the CBM experiment (FAIR/CBM)
The CBM experiment
Commissioning of SIS-300 and CBM planned for 2015

\( \sqrt{s_{\text{NN}}} \leq 8.5 \text{ GeV}, \quad A \leq \text{Au}, \quad \text{event rate} \leq 10 \text{ MHz} \)

**Physics goal:**

- first order phase transition,
- hadrons in dense matter, rare probes (open and hidden charm)
- critical point
Summary (II)

the onset of deconfinement

LHC  SPS  NICA  SIS  RHIC

T (MeV)

hadrons

quark gluon plasma

\( \mu_B \) (MeV)

hadrons

chemical freeze-out

\( \Delta \) SIS, AGS
\( \square \) SPS (NA49)
\( \star \) RHIC

color superconductor
### Summary (III)

<table>
<thead>
<tr>
<th>Facility:</th>
<th>SPS</th>
<th>RHIC</th>
<th>NICA</th>
<th>SIS-300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.:</td>
<td>NA61</td>
<td>STAR</td>
<td>MPD</td>
<td>CBM</td>
</tr>
<tr>
<td>Pb Energy:</td>
<td>4.9-17.3</td>
<td>4.9-50</td>
<td>≤9</td>
<td>≤8.5</td>
</tr>
<tr>
<td>(GeV/(N+N))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Event rate:</td>
<td>100 Hz</td>
<td>1 Hz(?)</td>
<td>≤10 kHz</td>
<td>≤10 MHz</td>
</tr>
<tr>
<td>(at 8 GeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physics:</td>
<td>CP&amp;OD</td>
<td>CP&amp;OD</td>
<td>OD&amp;HDM</td>
<td>OD&amp;HDM</td>
</tr>
</tbody>
</table>

*CP* – critical point  
*OD* – onset of deconfinement, mixed phase, 1\(^{\text{st}}\) order PT  
*HDM* – hadrons in dense matter
Additional slides