Observation of the onset of deconfinement and
Search for the critical point

Past and future of the ion physics at the CERN SPS

M. Gazdzicki
Frankfurt, Kielce

- The problems
- Observation of the onset of deconfinement
- Search for the critical point
The problems

What are the phases of strongly interacting matter?

How do the transitions between them look like?
Phase diagram of water

the end point of a 1st order line = a critical point of the 2nd order
(at the critical point the phases start to be indistinguishable)
In our daily life ...

droplets of water

10^{-12}

droplets of strongly interacting matter
Two basic states of strongly interacting matter are expected:

**Hadron gas at low densities**

**Quark-gluon plasma at high densities**
Hypothetical phase diagram of strongly interacting matter

How does the nature look like?
COLLISIONS OF TWO NUCLEI
-the only tool to study properties of strongly interacting matter in laboratory

matter at high energy density
Heavy Ion Accelerators

FAIR SIS-100/300 (2.0-8.5)
GSI SIS-18 (2-2.5)
(CERN LHC (5400))
CERN SPS (5-20)

BNL RHIC (20-200)
BNL AGS (2.5-5)

JINR NT (2-4)

LAB ACC (center of mass energy per nucleon-nucleon pair in GeV)
Heavy Ion Experiments

BNL AGS → CERN SPS → BNL RHIC

E895 | NA49 | STAR

A large acceptance, a high momentum resolution, a good particle identification
PAST

- Observation of the onset of deconfinement

- The basic idea – the heating curve of water
- The heating curves of strongly interacting matter
The basic idea – the heating curve of water

- Heating of water
- Heat used to vaporize water to water vapor
- Heating of water vapor

Heat added (each division = 4 kJ)

Temperature (°C)

Collision energy
Heating curves of strongly interacting matter

1994-1998: Basic idea and predictions
Statistical Model of the Early Stage → Kink, Horn

M.G., Gorenstein 1994-1999

1998-2002: Pb+Pb collisions at low SPS energies
(energy scan program at the CERN SPS)
Observation of the predicted anomalies in energy dependence
of hadron production

NA49 at the CERN SPS

2002-now: Search for other effects, experimental test
Step ..., more NA49 data, future measurements
Heating curves of strongly interacting matter

hadrons  mixed  QGP

AGS  SPS  RHIC

hadronic observables

collision energy

collision energy

Kink  Horn  Step
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

\[ \left< K^+ / \pi^+ \right> \]
The kink in pion multiplicity

\[ F \approx \sqrt{\sqrt{S_{NN}}} \]

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

\[ \langle N_W \rangle - \text{number of interacting nucleons} \]
The step in $m_{\perp}$ 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\textsuperscript{st} order phase transition reproduce the data

$E_S = \langle \Lambda \rangle + \langle K + \bar{K} \rangle / \langle \pi \rangle$

... but consistent model description is still missing
Searches for further signals of the onset of deconfinement:

+ two-pion correlations
  Akkelin, Sinyukov
  see Sinyukov's talk

+ longitudinal expansion
  Bleicher

+ fluctuations
  Mishustin
  M.G., Gorenstein
  see Mishustin's and MG's talks
Summary of

Several anomalies in hadron production are observed at low SPS energies.

The onset of observed anomalies is located at about 30A GeV.

The anomalies cannot be reproduced by the models without phase transition.

Measured rapid changes are consistent with models assuming 1\textsuperscript{st} order PT.

FUTURE

collision energy

hadronic observables

AGS SPS RHIC

A+A: [NA49 AGS RHIC]
FUTURE

- Search for the critical point
- The critical point and its location
- Search for the critical point of strongly interacting matter
The critical point and its location

1st order phase transition

Casalbuoni et al. 1989

Fodor, Katz, Ejiri et al. 2005

Critical point and its location (lattice QCD)

Cross-over

Quark gluon plasma

Hadrons

Color superconductor

1st order phase transition

Cross-over
or the critical line?

a quark-gluon bag model

Gorenstein, M.G., Greiner

1\textsuperscript{st} order phase transition

see Gorenstein's talk
Search for the critical point of strongly interacting matter
Chemical freeze-out points for central Pb+Pb collisions from the hadron gas fits

Becattini et al. 1999-2005

see Becattini's talk
The position of chemical (and kinetic) freeze-out points depends on collision energy and system size.

\[(\text{collision energy}) - (\text{system size}) \text{ scan} = T - \mu_B \text{ scan}\]

\[p+p, \ C+C, \ Si+Si \text{ and } Pb+Pb \text{ collisions at } 158A \text{ GeV}\]

Becattini et al. 2005
Phase diagram domain possibly covered by chemical freeze-out points in the future SPS study

Search for the critical point

(collision energy) - (system size) scan at energies higher than the onset of deconfinement, i.e. 30A GeV

Stephanov, Shuryak, Rajagopal 1999
In the “critical” region matter shows anomalous properties

(In the case of water large fluctuations in the size of liquid/vapor domains lead to the critical opalescence)

Large characteristic multiplicity and transverse momentum fluctuations are expected when strongly interacting matter freezes-out close to the critical point

Stephanov, Shuryak, Rajagopal
Antoniou, Kapoyannis
Physics of strongly interacting matter vs accelerators
Search for the critical point

LHC RHIC SPS SIS NT

quark gluon plasma

hadrons

chemical freeze-out
- SIS, AGS
- SPS (NA49)
- RHIC

color superconductor

$T$ (MeV)

$\mu_B$ (MeV)
November 2003: Expression of Interest (study the properties of deconfinement) submitted to the SPS committee by the proto-collaboration (now 10 institutes from Croatia, Germany, Greece, Hungary, Korea, Norway, Poland, Russia, South Africa and United States)
September 2004:
A special SPSC meeting in Villars (Switzerland)
"Fixed-Target Physics at CERN Beyond 2005"

February 2005
The SPSC conclusions:
"... Recent developments confirm that heavy ion beams at CERN SPS energies and luminosity remain ideal tools to observe the features of the phase transition between the confined and the deconfined states of hadronic matter known as Quark Gluon Plasma (QGP). ... A major step forward in understanding the phase diagram of hadronic matter would be the discovery of a critical point. ... Once the LHC has been commissioned with ions, an SPS programme aimed at the identification of the critical point, as well as at the study of its properties, is likely to be of substantial significance. ..."

October 2005:
submission of a letter of intent
Summary of **past and future** of the ion physics at the CERN SPS

**PAST**

- Observation of the onset of deconfinement at low CERN SPS energies

**FUTURE**

- Search for the critical point at the CERN SPS
hadronic observables

\[ \langle \sigma/N_c \rangle \]

\[ \langle K_+^2/\pi^2 \rangle \]

\[ T(K_+) \text{ (MeV)} \]

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

hadrons

\[ \mu_B \text{ (MeV)} \]

quark gluon plasma

\[ \text{chemical freeze-out} \]

\[ \text{color superconductor} \]

collision energy

AGS SPS RHIC

A+A: NA49, AGS, RHIC

SIS, AGS

SPS (NA49)

RHIC
Examples of the "raw" data: transverse mass spectra
(central Pb+Pb collisions)

20A GeV

\[ T_f = 120 \pm 2 \text{ MeV} \]
\[ \beta_\perp = 0.47 \pm 0.01 \]
\[ \chi^2/\text{NDF} = 116/46 \]

30A GeV

\[ T_f = 130 \pm 3 \text{ MeV} \]
\[ \beta_\perp = 0.46 \pm 0.01 \]
\[ \chi^2/\text{NDF} = 153/55 \]
Examples of the "raw" data: rapidity spectra
(central Pb+Pb collisions)
...and energy dependence of various strange hadrons
... and in $\langle m_\perp \rangle$ of various hadrons
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 5 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.

A neutron has a radius\(^1\) of about 0.5–1 fm, and so has a density of about \(8 \times 10^{14} \text{ g cm}^{-3}\), whereas the central density of a neutron star\(^2\) can be as much as \(10^{16}–10^{17} \text{ g cm}^{-3}\). 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.

We first give arguments leading to this idea. It is commonly believed that hadrons consist of quarks\(^5–7\) despite the apparent nonexistence of free quarks.\(^8\) There are two main reasons for this belief. First, a quark model explains\(^5\) many properties of the hadron spectrum, and of strong-interaction decays. Secondly we have Bjorken scaling\(^7\) 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,\(^8\) it is assumed that they are permanently bound in hadrons\(^5\) by a mechanism as yet unknown, but much speculated on.
Brief history of the CERN SPS ion programs

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
(energy scan program at the CERN SPS)
Anomalies in energy dependence of hadron production
⇒ Observation of the onset of deconfinement?
Examples of the "raw" data: mean multiplicities
(central Pb+Pb collisions)
“... The discovery of the critical point would in a stroke transform the map of the QCD phase diagram which we sketch below from one base only on reasonable inference from universality, lattice gauge theory models into one within a solid experimental basis. ...”

K.Rajagopal, M. Stephanov, E. Shuryak and F. Wilczek (Nobel 2004) supporting the NA49 program
... and its location: experiment vs theory

the early stage of central Pb+Pb collisions at 30A GeV hits the transition line (the position of the measured anomalies in the energy dependence)

the chemical freeze-out point of central Pb+Pb collisions at 30A GeV (hadron gas analysis of the measured multiplicities: $T = 140$ MeV, $\mu_B = 430$ MeV)

the most recent lattice QCD results (T = 160 MeV, $\mu_B = 360$ MeV)

Becattini et al.

Fodor, Katz, Ejiri et al.
The best experimental and theoretical estimates are consistent:
the critical point, if exists, can be observed at energies higher/equal 30A GeV
\( (T > 140 \text{ MeV}, \mu_B < 430 \text{ MeV}) \)
**Search for the critical point of strongly interacting matter**

Search for a maximum of fluctuations in the two-dimensional space, temperature – baryo-chemical potential, of the freeze-out points.

A maximum in fluctuations: the freeze-out point hits the critical point.
NA49 at the CERN SPS

- A large acceptance: ≈50%
- A high momentum resolution:
  \[ \sigma(p)/p^2 \approx 10^{-4} \quad ((GeV/c)^{-1}) \]
- A good particle identification:
  \[ \sigma(TOF) \approx 60 \text{ ps}, \]
  \[ \sigma(dE/dx)/\langle dE/dx \rangle \approx 0.04, \]
  \[ \sigma(m_{inv}) \approx 5 \text{ MeV} \]