首届ALICE实验与重离子物理讲习班

The 1st ALICE Experiment and Heavy-Ion Physics School

夸克-胶子等离子体五十年：过去、现在和未来

(第二讲)

Federico Antinori

(INFN, Padova, Italy)

上海，复旦大学，2025年11月

第一讲回顾...

Hagedorn temperature: a limiting value?

e.g. following K Redlich, H Satz in “Melting Hadrons, Boiling Quarks”, J Rafelski ed (Springer, 2016)

- partition function for a system of non-interacting pions:

$$\ln \mathcal{Z}(T,V) = \frac{VTm_0^2}{2\pi^2} K_2(\frac{m_0}{T})$$

- interactions as resonance formation:
  - interacting system of pions ←→ non-interacting gas of all possible resonances

$$\ln \mathcal{Z}(T,V) = \sum_i \frac{VTm_i^2}{2\pi^2} \rho(m_i) K_2(\frac{m_i}{T}) \approx \frac{VT}{2\pi^2} \int dm\, m^2 \rho(m) K_2(\frac{m}{T})$$

- inserting Hagedorn’s spectrum:

$$\ln \mathcal{Z}(T,V) \approx V \left[\frac{T}{2\pi}\right]^{3/2} \int \frac{dm}{m^{3/2}} e^{-\left[\frac{m}{T} - \frac{m}{T_H}\right]}$$ ← diverges for T → T_H

  - energy pumped into such a system, goes to creating heavier and heavier resonances
  - asymptotically reaching T_H

→ T_H would then be the maximum possible temperature!

1975, Cabibbo and Parisi: “quark liberation” at high T

Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

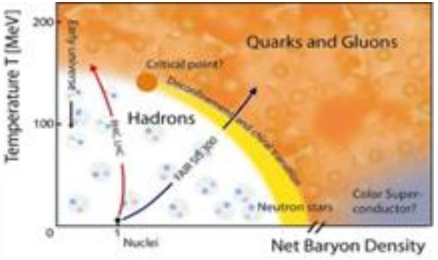
EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the “observed” exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confine



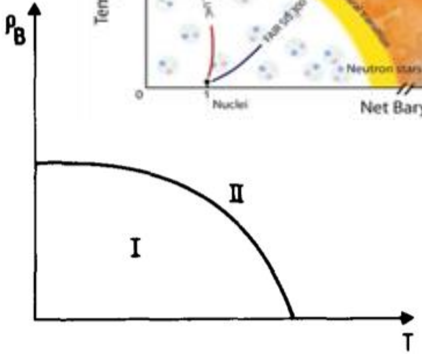


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

- T_H not maximum attainable, simply: for $T > T_H$ quarks not confined any more

The MIT Bag Model

- the essential phenomenology of confinement is described as follows:
  - assume quarks are confined within bubbles (bags) of perturbative (=empty) vacuum
  - on which the QCD vacuum ("liquid") exerts a confining pressure *B (*= bag constant*)*
  - B ~ Λ_{QCD}^4 → hadron size ~ 1/ $\boldsymbol{\Lambda_{QCD}}$

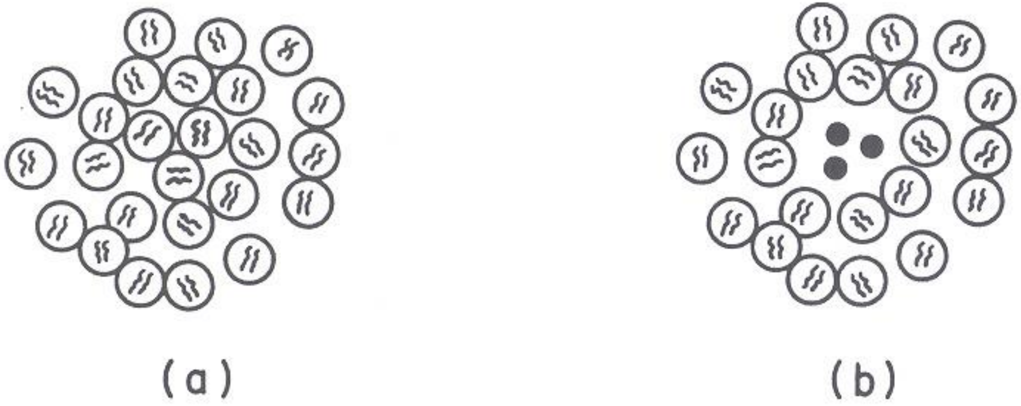
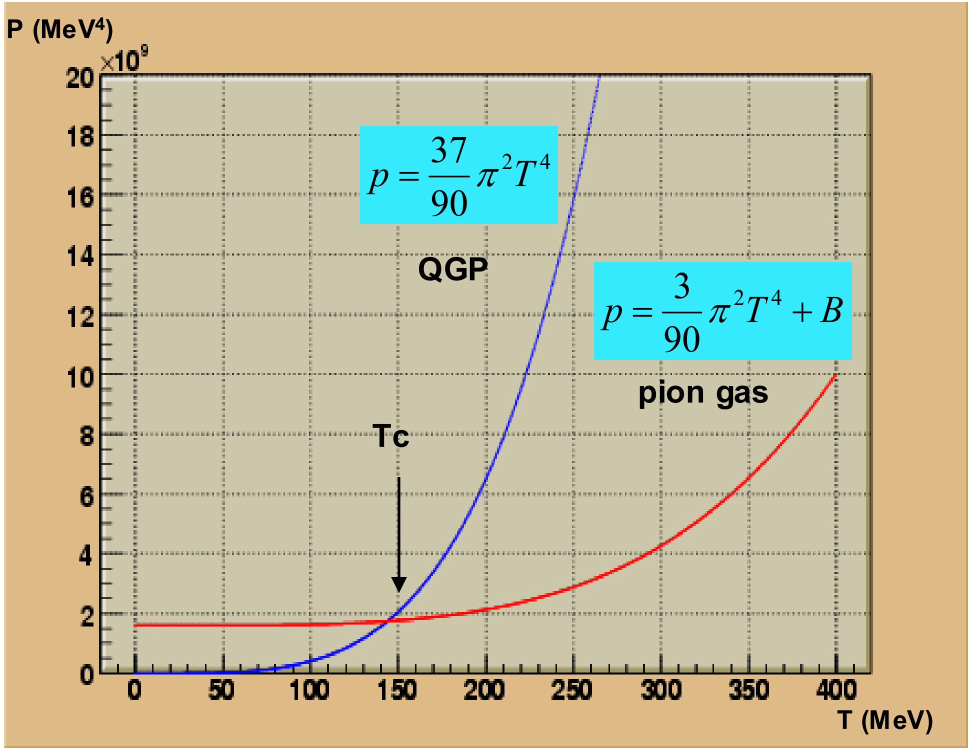


FIG. 9. The QCD vacuum state is depicted in (a). It is a random distribution of cells that contain a gluon pair in a color and spin singlet state. Quarks (in a color singlet configuration) displace these cells, creating a region (or "bag") of "empty" vacuum, as shown in (b).

(from: K Gottfried and V Weisskopf, "Concepts of Particle Physics", Vol. II, Oxford University Press, 1986)

- at low temperature the hadron gas is the stable phase
- but there is a temperature (T_C) above which the QGP “wins”
  - thanks to the larger number of degrees of freedom



one can easily derive:

$$T_C = \left[\frac{90}{34\pi^2}\right]^{1/4} B^{1/4}$$

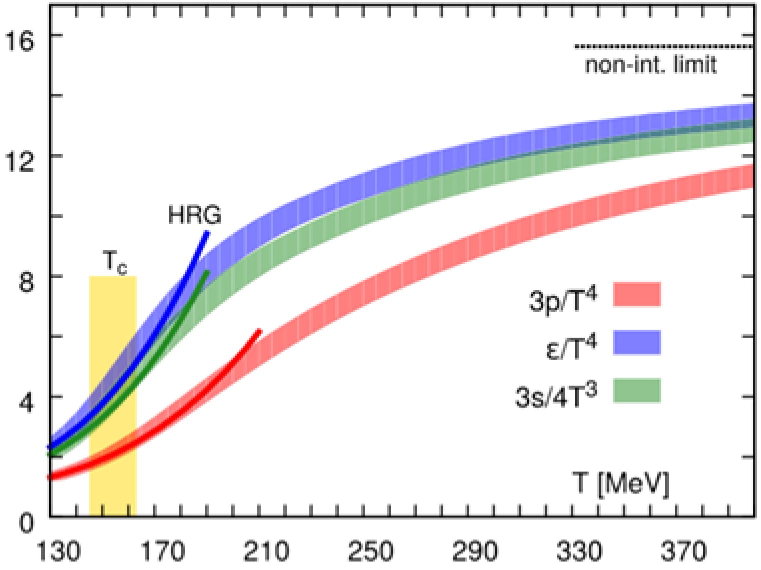
and plugging in $B^{1/4} \sim 200$ MeV one gets:

$$T_C \sim 150 \text{ MeV}$$

not too bad...
(latest lattice estimate: 156.5 ± 1.5 MeV)
[A Bazavov et al. Phys.Lett.B 795 (2019) 15]

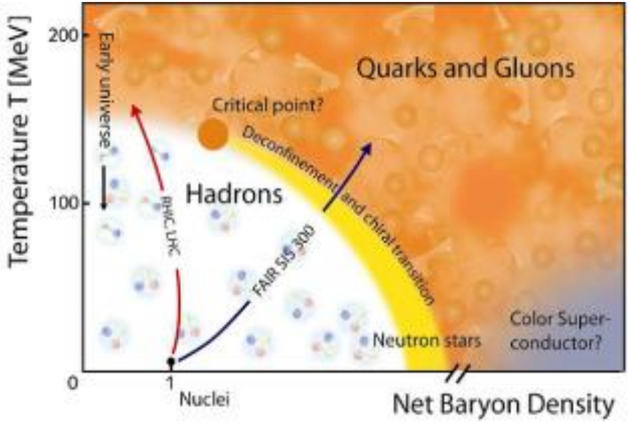
Lattice QCD

- the rigorous way of performing calculations in the non-perturbative regime of QCD
- discretisation on a space-time lattice
  - → ultraviolet (i.e. large-momentum scale) divergencies can be avoided



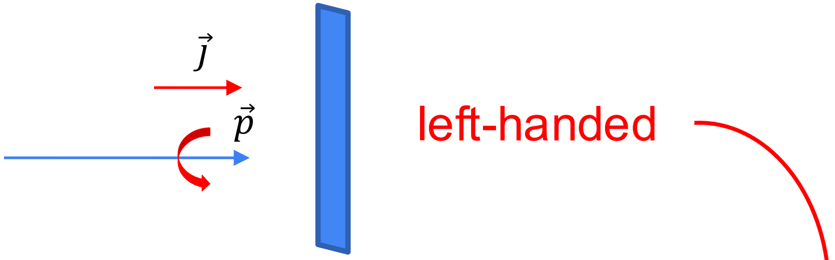
[A Bazavov et al. PRD 90 094503 (2014)]

- around critical temperature (T_C): rapid change of
  - energy density ε
  - entropy density s
  - pressure p
- due to activation of partonic degrees of freedom
- at zero baryon density → smooth crossover
- T_C = (156.5 ± 1.5) MeV [A Bazavov et al. Phys.Lett.B 795 (2019) 15]
- $\varepsilon \sim O(\mathrm{GeV/fm^3})$



Confinement, chiral symmetry and mass (an intuitive example)

- “chiral symmetry”: fermions and antifermions have opposite helicity
- exact only for massless fermions
  - travel at light speed → cannot be overtaken (overtaking would flip helicity...)
- now, take e.g. a left-handed, confined fermion
  - propagation is limited → at some point it will “hit a wall”...



  - ... and bounce back... reflection flips $\vec{p}$, but not $\vec{j}$!

→ even (quasi-)massless fermions acquire an additional mass term when confined!

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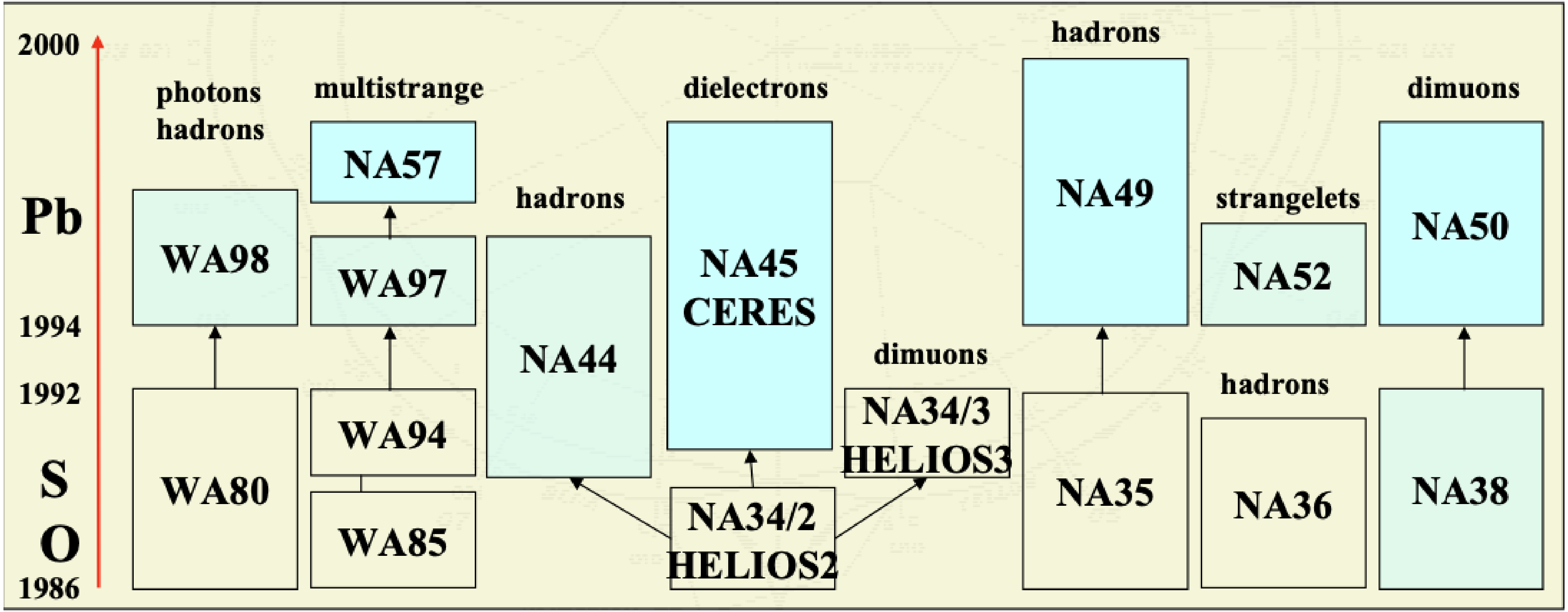
1980's: the hunt is on ...

- how to access this physics experimentally? high-energy nuclear collisions!
  - since the 70's nuclear physicists were already colliding heavy ions
    - Coulomb barrier, shock waves...
    - UNILAC (GSI), Super-Hilac and Bevalac (Berkeley), Synchrophasotron (Dubna)
  - it was realised that nuclear collisions could provide the conditions for QGP formation
  - but to reach T_c higher-energy accelerators were needed → ultrarelativistic AA collisions
- starting from the mid-80's: high-energy beams of nuclei on fixed target
  - at the Alternating Gradient Synchrotron (AGS)
    - at Brookhaven National Laboratory (New York)
    - $\sqrt{s_{NN}}$ ~ 5 GeV
    - O (1986), Si (1987), Au (1993)
  - at the Super-Proton Synchrotron (SPS)
    - at CERN (Geneva)
    - $\sqrt{s_{NN}}$ ~ 17 GeV
    - O (1987), S (1987), Pb (1994)

Nuclear beam experiments at the SPS (1986 – 2000)

- a wide spectrum of observables (and technologies!)



(from F Fleuret)

Pb-beam experiments at the SPS (1994 – 2000)

a very wide spectrum of techniques and observables!

- WA97: silicon pixel telescope spectrometer
  - production of strange and multi-strange particles
- WA98: photon and hadron spectrometer
  - production of photons and hadrons
- NA44: single-arm spectrometer
  - particle spectra, interferometry, particle correlations
- NA45: electron and hadron spectrometer
  - low mass lepton pairs, hadron production
- NA49: large acceptance TPCs
  - particle spectra, strangeness production, interferometry, event-by-event , …
- NA50: muon spectrometer
  - high-mass lepton pairs, J/ψ production
- NA52: focussing spectrometer
  - strangelet search, particle production
- NA57: silicon pixel telescope spectrometer
  - production of strange and multi-strange particles

Tutorial:
kinematic variables

or:

Everything You Always Wanted to Know About the Pseudorapidity*

(*But Were Afraid to Ask)

Rapidity

- four momentum (c = 1, z coordinate along beam axis)

$$p^{\mu} = (p^0, p^1, p^2, p^3) = (E, \vec{p}) = (E, \vec{p_T}, p_z = p_{//})$$

- addition of velocities along z:

$$v = v_1 + v_2$$ (Galileo)

$$\beta = \frac{\beta_1 + \beta_2}{1 + \beta_1 \beta_2}$$ (relativistic)

$$\tanh(y_1 + y_2) = \frac{\tanh y_1 + \tanh y_2}{1 + \tanh y_1 \tanh y_2}$$

$$y = \tanh^{-1} \beta = \frac{1}{2} \log\left(\frac{1+\beta}{1-\beta}\right)$$ "rapidity"

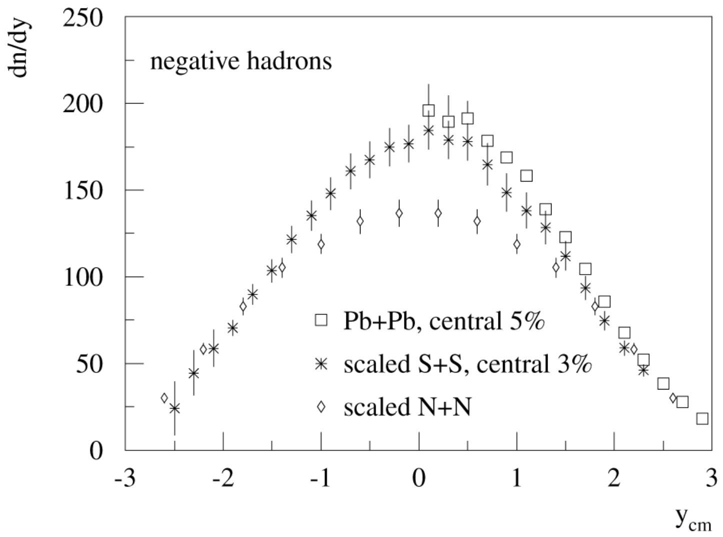
→ under a Lorentz transformation with velocity β along z :

$y \rightarrow y' = y - y_\beta$ (rapidities "add up") compare: $p'_z = \gamma(p_z - \beta E)$

$$\frac{dN}{dy'}(y') = \frac{dN}{dy}(y = y' - y_\beta)$$

e.g. at SPS :

$y_{cm} = y_{lab} - y_\beta$ with $y_\beta \approx 3$



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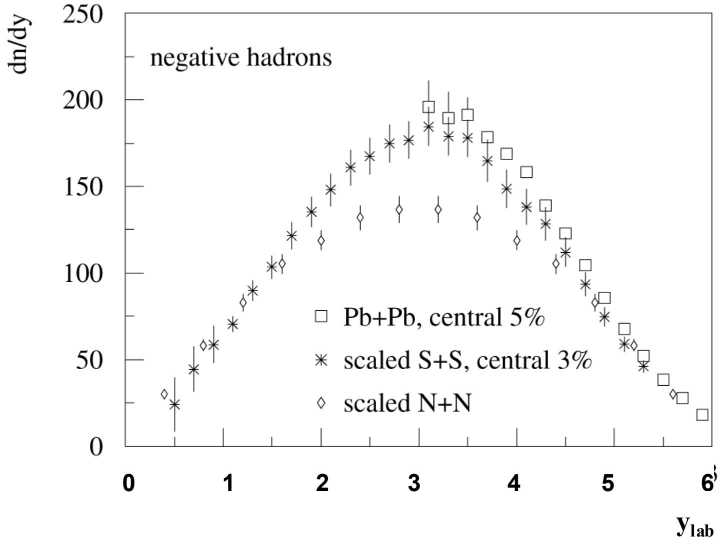

$$y = \tanh^{-1} \beta = \frac{1}{2} \log\left(\frac{1+\beta}{1-\beta}\right)$$

- in the non-relativistic limit:

$$y = \beta$$

- it can be shown that:

$$y = \frac{1}{2} \log\left(\frac{E+p_z}{E-p_z}\right)$$

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$$y = \beta$$

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$$y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$

← exercise: prove this

Transverse variables

- transverse momentum

$$\vec{p}_T = (p_x, p_y) \qquad p_T = \sqrt{p_x^2 + p_y^2}$$

- transverse mass

$$m_T = \sqrt{m^2 + p_T^2} \qquad E = \sqrt{m^2 + p^2} = \sqrt{m_T^2 + p_z^2}$$

$$p_z = m_T \sinh(y) \qquad E = m_T \cosh(y)$$

exercise: prove these

Pseudorapidity

$$y = \frac{1}{2}\log\left(\frac{E + p_z}{E - p_z}\right)$$

$$\eta = \frac{1}{2}\log\left(\frac{p + p_z}{p - p_z}\right)$$

- in the ultrarelativistic limit: $p \sim E \rightarrow \eta \sim y$

Pseudorapidity

$$y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$

$$\eta = \frac{1}{2}\log\left(\frac{p+p_z}{p-p_z}\right)$$

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$$\eta = -\log\tan(\theta/2)$$

← exercise: prove this

Pseudorapidity

$$y = \frac{1}{2}\log\left(\frac{E + p_z}{E - p_z}\right)$$

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← exercise: prove this

$$p_z = m_T \sinh(y)$$
$$E = m_T \cosh(y)$$

$$p_z = p_T \sinh(\eta)$$
$$p = p_T \cosh(\eta)$$

End of Tutorial

Two historic predictions...

- QGP phase, if existed, would obviously be very short-lived, how to observe it?
  - is there a memory of the passage through the QGP phase?
  - are there “signatures” of the QGP that we can look for in the final state?

two major proposals made in the 80’s:

- strangeness enhancement (Johann Rafelski and Berndt Müller)
  - enhanced production of strange quarks in the QGP
  - → enhancement of strange particles in the final state

- J/ψ suppression (Tetsuo Matsui and Helmut Satz)
  - colour field screened at short distances in QGP
  - → suppression of production of tightly-bound quarkonium states

Strangeness enhancement

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller

Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany

(Received 11 January 1982)

Rates are calculated for the processes $gg \to s\bar{s}$ and $u\bar{u}, d\bar{d} \to s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \gtrsim 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. The chemical equilibration time for gluons and light quarks is found to be less than 10^{-24} sec.

PACS numbers: 12.35.Ht, 21.65.+f

Given the present knowledge about the interactions between constituents (quarks and gluons), it appears almost unavoidable that, at sufficiently high energy density caused by compression and/or excitation, the individual hadrons dissolve in a new phase consisting of almost-free quarks and gluons.[1] This quark-gluon plasma is a highly excited state of hadronic matter that occupies a volume large as compared with all characteristic length scales. Within this volume individual color charges exist and propagate in the same manner as they do inside elementary particles as described, e.g., within the Massachusetts Institute of Technology (MIT) bag model.[2]

It is generally agreed that the best way to create a quark-gluon plasma in the laboratory is with collisions of heavy nuclei at sufficiently high energy. We investigate the abundance of strangeness as function of the lifetime and excitation of the plasma state. This investigation was motivated by the observation that significant changes in relative and absolute abundance of strange particles, such as $\bar{\Lambda}$,[3] could serve as a probe for quark-gluon plasma formation. Another interesting signature may be the possible creation of exotic multistrange hadrons.[4] After identifying the strangeness-producing mechanisms we compute the relevant rates as functions of the energy density ("temperature") of the plasma state and compare them with those for light u and d quarks.

In lowest order in perturbative QCD $s\bar{s}$-quark pairs can be created by annihilation of light quark-antiquark pairs [Fig. 1(a)] and in collisions of two gluons [Fig. 1(b)]. The averaged total cross sections for these processes were calculated by

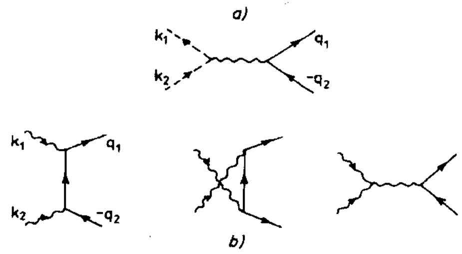


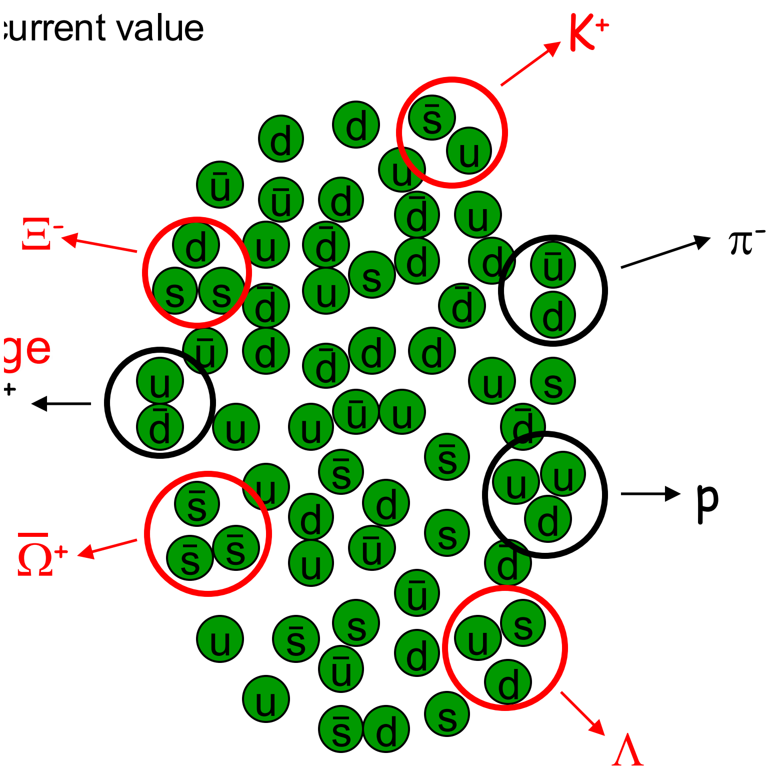
FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q} \to s\bar{s}$, (b) $gg \to s\bar{s}$.

on of s

current value

ge

+



Strangeness enhancement

- restoration of χ symmetry -> increased production of s
  - mass of strange quark in QGP expected to go back to current value
    - m_S ~ 150 MeV ~ Tc

  → copious production of $s\bar{s}$ pairs, mostly by gg fusion

  [J Rafelski: Phys. Rep. 88 (1982) 331]

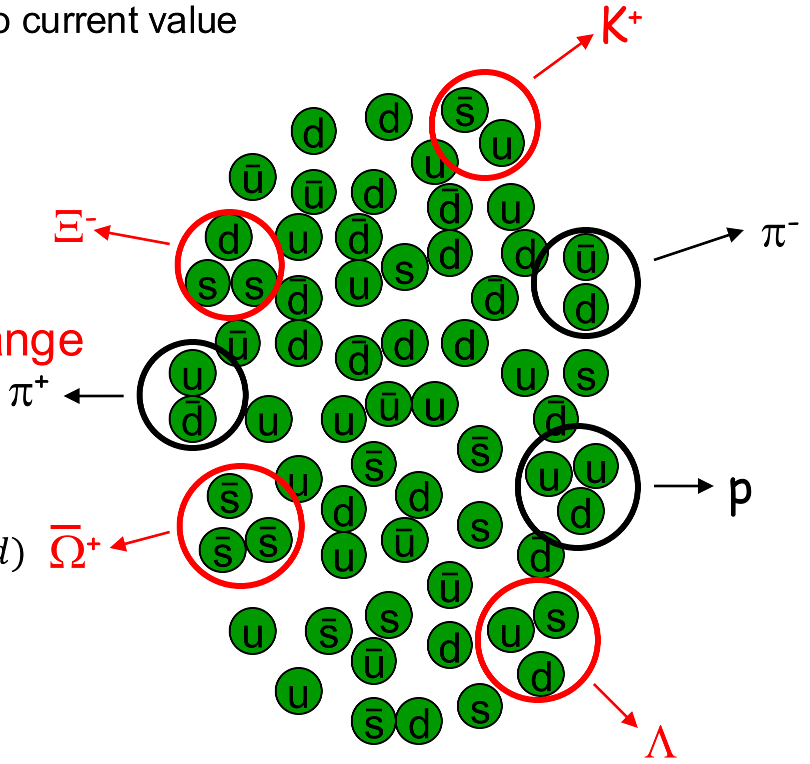
  [J Rafelski and B Müller: Phys. Rev. Lett. 48 (1982) 1066]

- deconfinement → stronger effect for multi-strange
  - can be built recombining s quarks

  → strangeness enhancement increasing with strangeness content

  → expect larger for $\Omega(sss)$ than for $\Xi(ssd)$ than for $\Lambda(sud)$

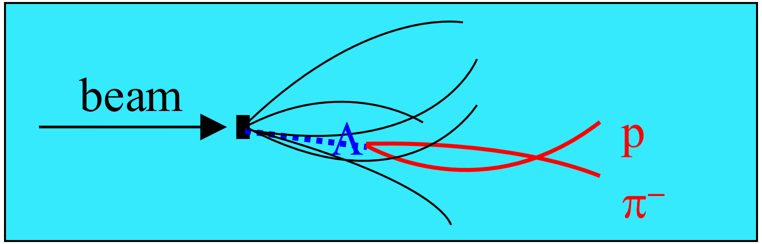
  [P Koch, B Müller and J Rafelski: Phys. Rep. 142 (1986) 167]



Strange baryons (hyperons)

- there are 35 strange baryons listed in the PDG summary tables
- only 6 decay weakly
(cτ ~ cm's → separate decay vertex from event interaction vertex):

$\Lambda, \Sigma^+, \Sigma^-$ (sqq)
Ξ^0, Ξ^- (ssq)
Ω^- (sss)



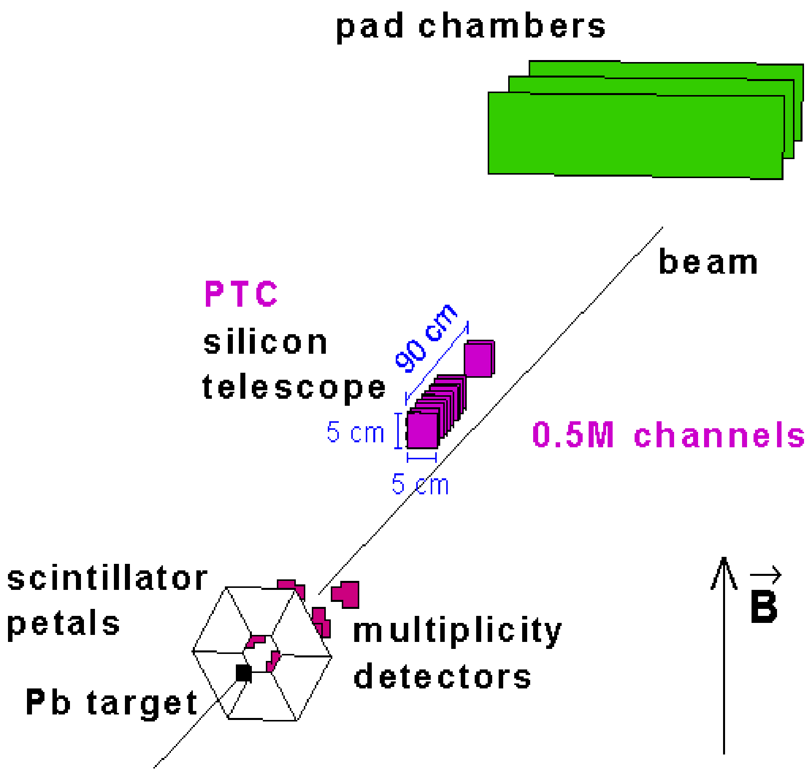
- only 3 of them can decay into final state with only charged particles

$$\Lambda \to p\pi^- (\text{B.R.} \approx 64\%)$$

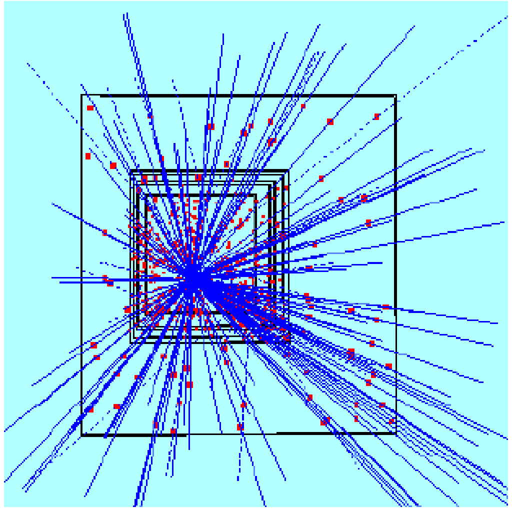
$$\Xi^- \to \Lambda\pi^- (\text{B.R.} \approx 100\%)$$

$$\Omega^- \to \Lambda K^- (\text{B.R.} \approx 68\%)$$

WA97/NA57 experiment



- silicon pixel telescope spectrometer
  - first pixel detector in particle physics (collaboration WA97/NA57 – RD19)



  - strange and multi-strange particles

Yield, enhancement

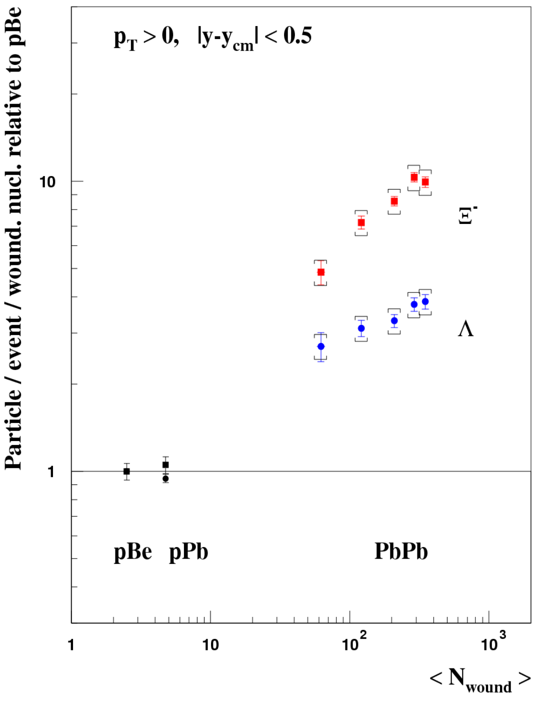
- yield: multiplicity per event
  e.g.: $Y_{\Omega^-} =$ # of Ω^- / event in $y_1 < y < y_2$

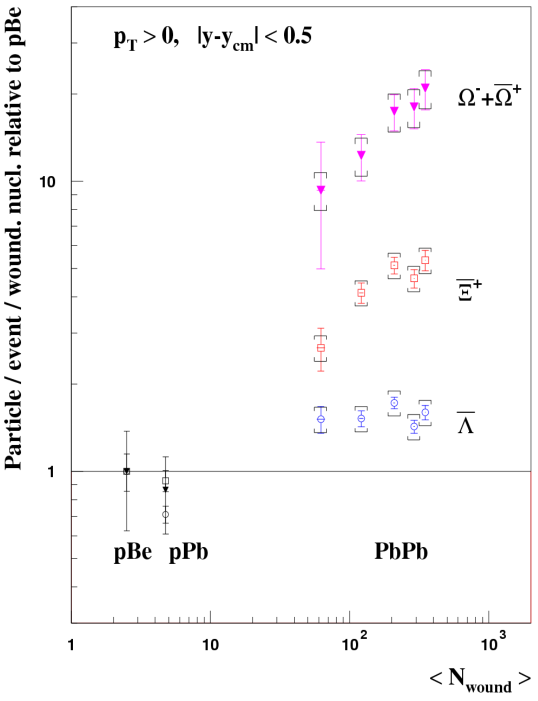
- enhancement: yield per participant relative to yield per participant in pp (p-Be)
  e.g.: Ω^- enhancement:

$$\mathcal{E}_\Omega = \frac{\left[Y_\Omega / N_{part}\right]_{Pb-Pb}}{\left[Y_\Omega / N_{part}\right]_{p-Be}}$$

Strangeness enhancement at the SPS

- WA97/NA57





- enhancement relative to p-Be, p-Pb
- increasing with |S|
- up to ~ x 20 for the Ω

Quarkonium suppression

- QGP signature proposed by Matsui and Satz, 1986

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

creened

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

ind → suppressed

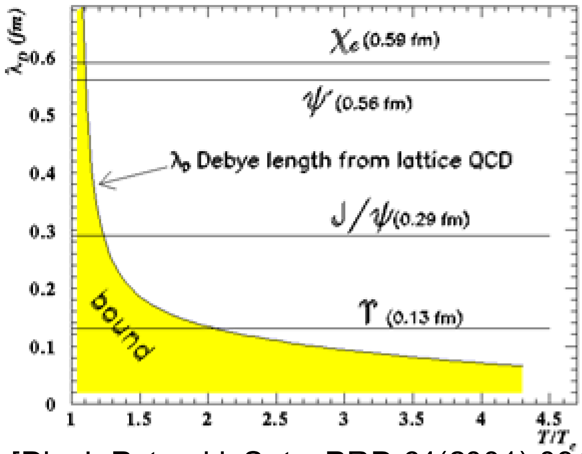
Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Quarkonium suppression

- QGP signature proposed by Matsui and Satz, 1986
- quarkonium: $c\bar{c}$ states (charmonium), $b\bar{b}$ states (bottomonium)
- in the plasma phase the interaction potential is expected to be screened
  - analogous to Debye screening in electromagnetic plasma
  - beyond the Debye screening length λ_D

λ_D depends on T



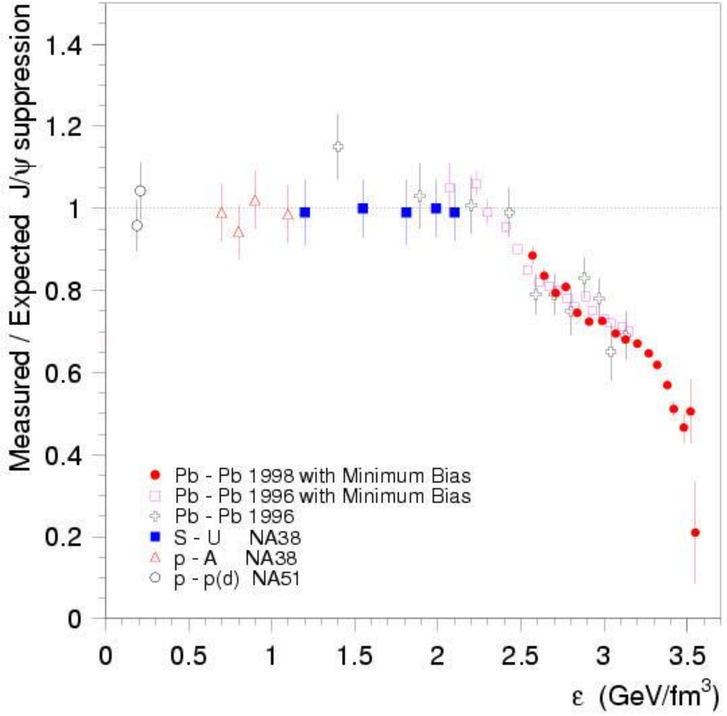
[Digal, Petrecki, Satz PRD 64(2001) 0940150]

→ states with radius > λ_D will not bind → suppressed

- J/ψ, ψ', χ_c → $c\bar{c}$ states
- Υ → $b\bar{b}$ states

J/ψ suppression at the SPS

- NA50: "anomalous" suppression



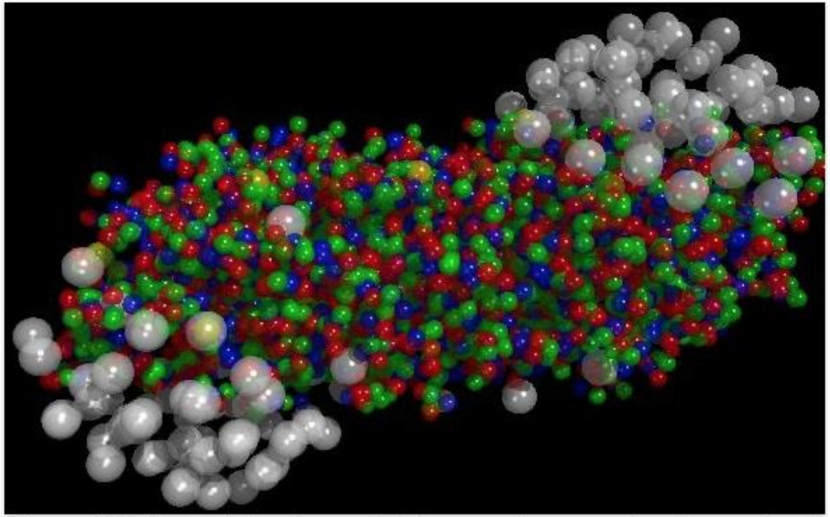
- measured/expected
- sets in at $\varepsilon \sim 2.3$ GeV/fm^3 ($b \sim 8$ fm)
- (on top of nuclear suppression)
  - due to nuclear absorption effects
  - measured in pA, light ion collisions
  - scaled to Pb-Pb (= 1 in the plot)

Two pillars of year 2000 announcement

- strangeness enhancement, J/ψ suppression

New State of Matter created at CERN

10 FEBRUARY, 2000



Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

C

SPECIAL SEMINAR

TITLE	:	A New State of Matter: Results from the CERN Lead-Beam Programme
TIME	:	Thursday 10 February at 09.30 hrs
PLACE	:	Council Chamber, bldg 503

ABSTRACT

This special seminar aims at an assessment of the results from the heavy ion programme with lead ion beams at CERN which was started in 1994. A series of talks will cover the essential experimental findings and their interpretation in terms of the creation of a new state of matter at about 20 times the energy density inside atomic nuclei. The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the characteristic features of the theoretically predicted Quark-Gluon Plasma.

Ulrich Heinz (CERN)
Making Quark-Gluon Matter in Relativistic Nuclear Collisions

Louis Kluberg (IN^2P^3)
The J/ψ suppression pattern observed in Pb-Pb collisions ions: a signature for the production of a new state of matter.

Johanna Stachel (University of Heidelberg)
Virtual and real photons radiated by the cooling and hadronizing fireball.

Reinhard Stock (University of Frankfurt)
Hadron Signals of the Little Bang.

Emanuele Quercigh (CERN)
Strange signals of a new state of matter from nuclear collisions at SPS.

Luciano Maiani (Director General, CERN)
Summary.

... meanwhile, in the US...

- 1978: start of construction of ISABELLE pp collider at Brookhaven (400 GeV)
- *1978: approval of transformation of SPS into $p\bar{p}$ collider at CERN (630 GeV)*
- 1981-82: problems in production of ISABELLE magnets
- *1983: discovery of $W^{\pm}$ (January) and Z^0 (May) bosons at SPS collider*

... meanwhile, in the US...

- 1978: st... GeV)
- *1978: ap... GeV)*
- 1981-82
- *1983: di...*

6 JUNE 1983.

The New York Times

Founded in 1851

Europe 3, U.S. Not Even Z-Zero

A team of 126 scientists at the CERN accelerator in Geneva reports proof of an important new subatomic particle, the Z-zero. The discovery carries two messages. The good news is that it confirms a major theory about the fundamental forces of nature. The bad news is that Europeans have taken the lead in the race to discover the ultimate building blocks of matter.

Spurred by an esthetic faith that nature's laws are at root elegantly simple, physicists have long

American physicists blame lack of Federal support. But some observers, like the President's science adviser, George Keyworth, blame the physicists for routinely spreading funds among the three major American research centers. "Our world leadership in high energy physics has been dissipated," he has said. "In the years American physicists squandered on a pork barrel squabble, the Europeans moved boldly ahead."

... meanwhile, in the US...

- 1978: start of construction of ISABELLE pp collider at Brookhaven (400 GeV)
- *1978: approval of transformation of SPS into $p\bar{p}$ collider at CERN (630 GeV)*
- 1981-82: problems in production of ISABELLE magnets
- *1983: discovery of $W^{\pm}$ (January) and Z^0 (May) bosons at SPS collider*

- July 1983: construction of ISABELLE stopped, project cancelled
- July 1983: NSAC town meeting in Aurora: ISABELLE infrastructure to build a RHIC
  - Relativistic Heavy-Ion Collider
  - (that was quick, but already in 1981, at an ISABELLE workshop in Brookhaven...)

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- 1978 ... /)
- *1978* ...)
- 1981
- *1983*

- July
- July ... a RHIC
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SECTION I - Lectures

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- *1986: start of heavy-ion collisions at CERN/SPS and Brookhaven/AGS*
- 1987: start of RHIC R&D
- 1991: start of construction
- 2000: first collisions

The RHIC experiments