Exploring strange realm

Andrzej K. Wróblewski- Warsaw University
Comforting world picture of yesteryears
✓ Periodic table – 92 elements
✓ Atoms – electrons and nuclei
✓ Nuclei – protons and neutrons (1932)
✓ Quantum theory successful

“We have all that. I think in six months we’ll have [description of] the proton, and physics as we know it will be over.”

Max Born to Isidor Rabi, after the Dirac equation (1928)
"mesotron" in cosmic rays (1937)
[Anderson & Neddermeyer, Street & Stevenson]

Hideki Yukawa – "On the interaction of elementary particles",

mesotron = Yukawa’s particle?
[Oppenheimer & Serber (1937), Stueckelberg (1937)]
Zahlentafel 1. Elementarteilchen und Photonen.1

<table>
<thead>
<tr>
<th>Name des Teilchens, Entdecker und Jahr der Entdeckung</th>
<th>Zeichen</th>
<th>Ruhmasse in Gramm</th>
<th>Atomgewicht</th>
<th>Elektrische Ladung in e, st. E. (cm² g⁻¹ sec⁻¹)</th>
<th>Beobachter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elektron (β-Teilchen): J. W. Hittorf, 1869 J. Perrin, 1895 P. Lenard, 1899</td>
<td>β, e⁻</td>
<td>$m_e = (9,118 \pm 0,010) \times 10^{-28}$</td>
<td>$A_e = 0,000549$</td>
<td>−e</td>
<td>−e $(4,805 \pm 0,005) \times 10^{-10}$</td>
</tr>
<tr>
<td>Positron: P. A. M. Dirac, 1928 C. D. Anderson, 1932</td>
<td>e⁺</td>
<td>$m_e$</td>
<td>$A_e$</td>
<td>$+e$</td>
<td>Bainbridge und Jordan</td>
</tr>
<tr>
<td>Proton (H⁺-Teilchen): Marsden, 1914</td>
<td>1p, 1H</td>
<td>$m_p = (1,673 \pm 0,010) \times 10^{-24}$</td>
<td>$A_p = 1,00758 \pm 0,00002$</td>
<td>$+e$</td>
<td>Bainbridge und Jordan</td>
</tr>
<tr>
<td>Neutron: J. Chadwick, 1932</td>
<td>1n</td>
<td>$m_n = (1,676 \pm 0,010) \times 10^{-24}$</td>
<td>$A_n = 1,00897 \pm 0,00006$</td>
<td>0</td>
<td>Bainbridge und Jordan</td>
</tr>
<tr>
<td>Deuteron (Deuton): H. C. Urey, F. G. Brickwedde, G. M. Murphy, 1932</td>
<td>2d, 2H, 2D</td>
<td>$m_d = (3,345 \pm 0,020) \times 10^{-24}$</td>
<td>$A_d = 2,01418 \pm 0,00002$</td>
<td>$+e$</td>
<td>Bainbridge und Jordan</td>
</tr>
<tr>
<td>α-Teilchen (Heliumkern): H. Becquerel, 1896</td>
<td>4α, 4He</td>
<td>$m_α = (6,647 \pm 0,040) \times 10^{-24}$</td>
<td>$A_α = 4,00379 \pm 0,00007$</td>
<td>$+2e$</td>
<td>Bainbridge und Aston</td>
</tr>
<tr>
<td>Photon (Lichtquant, γ-Quant): M. Planck, 1900 A. Einstein, 1905</td>
<td>γ</td>
<td>Masse $m_γ = \frac{hv}{c^2} = 7,36 \times 10^{-48}$</td>
<td>$A_γ = \frac{16 m_γ}{m_0} = \frac{16 hv}{m_0 c^2} = 4,42 \times 10^{-24}$</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

mesotron ≠ Yukawa’s particle

M. Conversi, E. Pancini, O. Piccioni (1947)


"Who ordered it?" (Isidor Rabi)

Cecil Powell

First π → μ decay
“I remember at the Pocono meeting* that Robert Oppenheimer said ‘Now we have field theory in hand’ and I remember vividly that Rabi got up and said ‘What the hell shall I measure now?’ There was the sense that one was very close to the end. And then, of course, came the great disillusionments…”

Julian Schwinger (1980)

* 1948
Discovery of curious particles
A surprising discovery

Rochester and Butler in Manchester reported the first photographs of forked tracks (later called “V particles”) in Nature (20 December 1947)

Neutral V particle | Charged V particle

George Rochester
Clifford Butler
“After the early discoveries that promised so much, there followed several frustrating years, a period of strain for Butler and myself, when no further examples of the V particles were found.”

Rochester at Fermilab Symposium (1985)
Carl Anderson
to Patrick Blackett,
28 November 1949

“Rochester and Butler may be glad to hear that we have about 30 cases of forked tracks similar to those they described in their article in *Nature* about two years ago, and so far as we can see now their interpretation of these events as caused by new unstable particle seems to be borne out by our experiments.”

“V particles” - June 1950 (Blackett, Bohr, Anderson)
Present symbols - July 1953 (Bagnéres-de-Bigorre)
V particles at once showed unusual properties

- They were copiously produced in high energy collisions (with cross section of a few percent of that for pion production)
- Thus, if the same mechanism was responsible for their production and decay, their lifetime should be of the order of $10^{-21}$ s.
- The observed lifetime was $\geq 10^{-10}$ s.
The first hypernucleus was discovered in September 1952 by Marian Danysz and Jerzy Pniewski at Warsaw University. It happened during the time of confusion concerning the newly detected heavy unstable particles. The study of hypernuclei was of considerable help in understanding the properties of strange particles.
“An excited hydrogen atom, to use the simplest example, consists of a proton and an electron in a state of higher energy than in the normal atom. The analogy might then suggest that the excited nucleon consists of a proton and an associated $\pi^-$ — that the $\Lambda^0$ is a composite particle. Such a view could not have been finally excluded while our knowledge was confined to the decay of the free $\Lambda^0$ particle... These considerations suggest that the $\Lambda^0$ particle is an excited nucleon in a different sense from that suggested by familiar analogies. We are entering a new field where basically new concepts remain to be established.”

“...my title... was: Isotopic Spin and Curious Particles. Physical Review rejected “Curious Particles”. I tried “Strange Particles” and they rejected that too. They insisted on: “New Unstable Particles”. That was the only phrase sufficiently pompous for the editors of the Physical Review...”

M. Gell-Mann (1982)
“The interpretation of the new particles as displaced charge multiplets” – Gell-Mann’s paper at the 1955 Pisa Conference presented his scheme in a final form. New quantum number ‘strangeness’ officially introduced (but used in talks since September 1953)

In Japan Nishijima proceeded along similar lines as Gell-Mann and also presented his results in the years 1953-1955; but his papers published in Japanese Progress in Theoretical Physics had less impact than Gell-Mann’s
“Strange particles...were not considered respectable, especially among the theorists. I am told... that when he wrote his excellent paper on the decay of the tau particle into three pions Dalitz was warned that it might adversely affect his career, because he would be known as the sort of person who worked on that kind of things.”

“Pion physics was indeed the central topic for theoretical physics in the mid 1950s, and that was what the young theoretician was expected to work on. The strange particles were considered generally to be an obscure and uncertain area of phenomena, as some kind of dirt effect which could not have much role to play in the nuclear forces, whose comprehension was considered to be the purpose of our research.”
Quarks postulated, doubted, and accepted
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the $F$-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_+ - n_-$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles $d^-$, $s^-$, $u^0$ and $b^0$ exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon $b$ if we assign to the triplet $t$ the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) $q$ and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q q q)$, $(q q q q q)$, etc., while mesons are made out of $(q \bar{q})$, $(q q \bar{q} q)$, etc. It is assuming that the lowest baryon configuration $(q q q)$ gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration $(q \bar{q})$ similarly gives just 1 and 8.
“The paper proposing the existence of quarks was accepted by *Physics Letters* only because it had Gell-Mann’s name on it. The editor said, ‘The paper looks crazy but if I accept it and it is nonsense, everyone will blame Gell-Mann and not *Physics Letters*. If I reject it and it turns out to be right, I will be ridiculed’”

Harry Lipkin (1997)
“The establishment prejudice against quarks even created serious difficulties for obtaining appointments and promotions for young people in our group. Deans and committees were influenced by pejorative comments in letters from well-known physicists about people who rush into print with such garbage.”

Harry Lipkin (1997)
Additive quark model

Just valence quarks, no gluons, no sea, no bag;
Hadron-hadron amplitude = sum of quark-quark amplitudes

$$\sigma(\pi p)/\sigma(pp) \approx \frac{6}{9} = \frac{2}{3}$$

Levin & Frankfurt (1965)
Lipkin & Scheck (1966)
Satz (1967)

....

Anisovich & Shekhter (1974)
Wrong turn of theory

Around 1960 some theorists expressed disbelief in Quantum Field Theory. Geoffrey Chew proposed the idea of ‘nuclear democracy’, which included a ‘bootstrap’ mechanism (all hadrons should be self-generated from the mathematical structure of the theory).

“I do not wish to assert (as does Landau) that conventional field theory is necessarily wrong, but only that it is sterile with respect to the strong interactions and that, like an old soldier, it is destined not to die but just to fade away.”

Geoffrey Chew,
*S-matrix Theory of Strong Interactions* (1962)

(This approach has been gradually discarded in the 1970s)
"The theoretical interpretation remained obscure. Reactions were supposed to go via particle exchange: pions, kaons, baryons. It was found that the more quantum numbers were transported by the exchanged particle, the faster will decrease the cross section when the energy increased. This looked interesting but was also more or less a dead end. Then, the theory became more obscure. Experimentalists were invited into a mysterious country called analytical plane (made of two sheets to make the game more interesting). In this country moved strange objects called Regge poles. They were moving on trajectories and you were not exchanging particles any more, but trajectories (whatever that meant). Even a simple phenomenon like shadow scattering, which a beginner in wave mechanics is supposed to understand, was explained by the exchange of a super mysterious pole called Pomeron. At least the other poles sometimes were supposed to be true particles (resonances). The Pomeron never..."
On quarks in 1970

“The [quark] model came after the use of SU(3) and SU(6) groups. For the applicability of these groups it is of course not necessary at all that quarks or the quark model should exist. Nor can one with absolute certainty say that quarks cannot exist. From the way they make up the hadrons it is seen that it would be highly unusual, if the quarks actually did exist.”

A. Barut, Rapporteur’s talk at the XVth International Conference on High Energy Physics, Kiev, 1970,
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLEAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

HIGH-ENERGY PHYSICS 25 YEARS AFTER THE DISCOVERY OF THE \( \eta \) MESON

L. Van Hove

G E N E V A
1972
Survey of high energy physics in 1972 (Van Hove)
The fact that all baryons can be represented by SU(3) tensors $B_{\alpha\beta\gamma}$ and all mesons by tensors $M^\beta_\alpha$ would become immediately understandable if there would exist SU(3) triplets $Q_\alpha$ which would be the building blocks of hadrons. The $Q_\alpha$ would be the celebrated quarks, baryons being composed of three quarks, and mesons of a quark and an antiquark:

$$B_{\alpha\beta\gamma} = Q_\alpha Q_\beta Q_\gamma, \quad M^\beta_\alpha = Q_\alpha Q^\beta,$$

with simple couplings for the quark spins which should have the value $\frac{1}{2}$. The $Q_\alpha$ should have baryon number $\frac{1}{3}$ and electric charges $\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3}$ (for $\alpha = 1, 2, 3$, respectively). Since no quarks have been found despite extensive searches, the nature of the SU(3) classification of hadrons remains puzzling.

Van Hove – High energy physics 25 years after the discovery of the $\pi$ meson (1972)
“Somehow one is left with the impression that nature is trying to show us something simple which nobody is seeing”

Wolfgang Panofsky (1967)

[Concluding words of his talk at the Heidelberg Conference]
Discovery of the structure within the proton

Jerome Friedman  Henry Kendall  Richard Taylor

Bjorken's scaling

Parton model

QCD - Gross & Wilczek, Politzer, Gell-Mann etc.
The ‘November revolution’ of 1974

J/psi discovery at BNL and SLAC
published in *Phys. Rev. Letters*,
December 2, 1974

Sam Ting
Burton Richter
The search for Quark-Gluon Plasma
Our basic picture then is that matter at densities higher than nuclear consists of a quark soup. The quarks become free at sufficiently high density. A specific realization is an asymptotically free field theory. For such a theory... high-density matter is the second situation where one expects to be able to make reliable calculations - the first is Bjorken scaling.
Statistical Thermodynamics
of Strong Interactions at High Energies.

R. Hagedorn

CERN - Geneva

(riccenvuto il 12 Marzo 1965)


1. — Introduction.

Recently, the statistical model of Fermi (1) has been applied to large-angle elastic (2) and exchange (3) scattering with a rather unexpected success. Roughly, the result can be stated as follows: if one calculates with the (non-invariant) statistical model the probabilities $P_j$ for all channels $j$ of the reaction $p + p \rightarrow s$ channel $j$, then one finds for c.m. energies from 2 to 8 GeV the numerical formula

$$\left( \frac{P_j}{\sum P_j} \right)_{E=2} = \exp[-3.30(E-2)] \quad \text{[E in GeV]}$$

(1)

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Università 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 confined.

"...we expect a phase diagram of the kind indicated in Fig. 1. The true phase diagram may actually be substantially more complex..."
Understanding the freeze-out

Howel Pugh (1981)

Jean Cleymans & Krzysztof Redlich compilation (1999)

Cleymans (Skopelos, May 2004)
КВАРК-ГЛЮОННАЯ ПЛАЗМА И РОЖДЕНИЕ ЛЕПТОНОВ, ФОТОНОВ И ПСИНОВ В АДРОННЫХ СОУДАРЕНИЯХ

Э. В. ШУРАК

Институт ядерной физики СО АН СССР

(Поступила в редакцию 14 марта 1978 г.)

Предлагается теория явлений, связанных с массами $M$ и поперечными импульсами $p_\perp$, такими, что $1 \leq \theta \leq M, p_\perp < \sqrt{s}$. Для их описания применяется модель локально-равновесной кварк-глюонной плазмы, разглашающейся по определенному закону. Применение квантовой хромодинамики для вычисления скоростей ряда реакций в такой плазме позволяет вычислить спектры масс дилептонов, распределение по $p_\perp$ лептонов, фотонов, пионов и адронных струй, сечения рождения пар очарованных кварков и различных состояний чармона (псионов): $J/\psi$, $\chi$, $\psi'$-мезонов. Результаты согласуются с экспериментальными данными.

1. Введение

Существенный прогресс в понимании реакций, происходящих на малых расстояниях, который достигнут в последние годы в рамках партонной модели, сейчас углублен и развит на основе асимметрически-свободной теории сильных взаимодействий — квантовой хромодинамики (КХД) [1]. Применение же этой теории к обычным адронным реакциям, происходящим на больших расстояниях, не дало пока ощутимых результатов, поскольку в этом случае эффективная константа связи $\alpha_s$ не мала и разложение по ней невозможно.
Highly relativistic nucleus-nucleus collisions: The central rapidity region

J. D. Bjorken

Fermi National Accelerator Laboratory, * P.O. Box 500, Batavia, Illinois 60510
(Received 13 August 1982)

The space-time evolution of the hadronic matter produced in the central rapidity region in extreme relativistic nucleus-nucleus collisions is described. We find, in agreement with previous studies, that quark-gluon plasma is produced at a temperature $\geq 200-300$ MeV, and that it should survive over a time scale $\geq 5$ fm/c. Our description relies on the existence of a flat central plateau and on the applicability of hydrodynamics.
Early example of relativistic heavy ion collisions

[Peter Fowler, 1969]
Nuclei

just peculiar,
unusual,
NOT with
strangeness
Bevalac
Synchrophasotron
SPS
AGS
RHIC
Why strangeness?

* the strange quark mass is close to the critical temperature $T_c$
* strange quarks are light enough to be abundantly present at temperatures above $T_c$

"When the quark matter dissociates into hadrons, some of the numerous $\bar{s}$ may, instead of being bound in a $q\bar{s}$ kaon, enter into a $(q\bar{q}\bar{s})$ antibaryon and, in particular, a $\bar{\Lambda}$ or $\bar{\Sigma}^0$... We thus would like to argue that a study of $\bar{\Lambda}$, $\bar{\Sigma}^0$ in nuclear collisions ... could shed light on the early stages of the nuclear collisions in which quark matter may be formed."

Rafelski & Hagedorn, Bielefeld Proceedings (1980)
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 $gg \rightarrow s\bar{s}$ and $u\bar{u}, d\bar{d} \rightarrow s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \simeq 160$ 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 $10^{-25}$ 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. 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.

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 $\Lambda^0$, could serve as a probe for quark-gluon plasma formation. Another interesting signature may be the possible creation of exotic multistrange hadrons. 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

![Diagram](https://example.com/diagram.png)

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

„Production of strange quarks is assumed to be suppressed relative to non-strange quarks roughly by a factor of three” (Anisovich & Shekhter, 1973)

„We suppose that strange s-sbar pairs are half as likely as unstrange u-uubar pairs...It is not unreasonable that s-sbar pairs are formed less often than u-uubar and d-dbar, for s quarks may have a larger mass than u or d.” (Field & Feynman, 1978)
Strange quark suppression

\[ u\bar{u} : d\bar{d} : s\bar{s} = 1 : 1 : \lambda_s \]

\[ \lambda_s = \frac{2\langle N_{s\bar{s}} \rangle}{\langle N_{u\bar{u}} \rangle + \langle N_{d\bar{d}} \rangle} \]

\( \lambda_s \) determined directly from data by quark counting method (1982-1985)

Helena Białkowska, Marek Gaździcki, Waldemar Retyk and Ewa Skrzypczak adapted the method for heavy ion collisions (1992)
Strange quark suppression

Białkowska et al. (1992)  Becattini et al. (2001)
Japanese American Cooperation Emulsion Experiment

$n_s = 1010 \pm 30$

Intermittency (Bia\l{}as & Peschanski)
"Is this a first experimental indication for the chromoplasma?"

Helmut Satz – Quark Matter 1984: A Summary
[Proceedings, p. 295]
**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*

Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents cc 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.

First NA38 data for O-U (1989)
Possible Manifestation of Quark-Gluon Plasma in Multiplicity Distributions from High-Energy Reactions

G. N. Fowler, (a) E. M. Friedlander, (b) and R. M. Weiner
Physics Department, University of Marburg, Marburg, Federal Republic of Germany

and

G. Wilk (c)
Physics Department, University of Illinois, Chicago, Illinois 60637
(Received 6 May 1986)

We show that in order to explain the observed dependence of multiplicity distributions on energy and shifts of the centers of rapidity bins it is sufficient to assume the existence of two sources. One source is concentrated at small rapidities and has properties of a thermally equilibrated system as could be expected from a quark-gluon plasma. The other one, contributing to the whole rapidity region, displays characteristics of bremsstrahlung emission.

PACS numbers: 13.85.Hd, 12.38.Mh, 12.40.Ee

The search for the quark-gluon plasma (QGP) is in the center of interest of strong-interaction physics at high energies. While heavy-ion reactions may provide a way to obtain this new state of matter in the laboratory, this approach is by far not the only one possible. Indeed, already before the establishment of a heavy-ion "industry," it had been advocated that hadronic reactions, too, provide interesting information about QGP. In this Letter, we present new evidence, based upon multiplicity distributions, which supports this point of view. We show that a consistent picture of

The first dependence is what one would expect from a thermally equilibrated source with an equation of state in which pressure is equal to one third of the energy density; a QGP is expected to satisfy such an equation of state (see Carruthers4). The second dependence is again what one would expect, this time from a coherent emission mechanism. Furthermore, a rather generally accepted picture of hadronic collisions in terms of quarks and gluons4-6 asserts that in each event there are leading particles due to the throughgoing quarks and a central blob formed by the interacting
Intermittency parameters
as a possible signal for quark–gluon plasma formation

A. Bialas ¹
CERN, CH-1211 Geneva 23, Switzerland

and

R.C. Hwa
Institute of Theoretical Science, University of Oregon, Eugene, OR 97403, USA

Received 9 October 1990

It is suggested that measurements of anomalous dimensions in the spectra of particles produced in high-energy heavy-ion reactions obtained from studies of intermittency, can serve as a possible signal of the formation of quark–gluon plasma and its subsequent phase transition into hadrons. Existing data suggest a quark–gluon plasma signal for 200 GeV/nucleon S–Ag, Br central collisions.

Recently, several experiments [1–6] confirmed the power law behaviour of normalized factorial moments predicted by the hypothesis of intermittency [7]. The relation

plain (1) in particle production processes:

(1) Second-order phase transition [12–14]. At the critical point the correlation length diverges and the system becomes scale invariant. If there are no long-range interactions we then expect that all anomalous
At a special seminar on 10 February, spokespersons from the experiments on CERN'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.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.
New Forms of QCD Matter Discovered at RHIC.

Miklos Gyulassy\textsuperscript{a} and Larry McLerran\textsuperscript{b}

\textsuperscript{a}Physics Department, Columbia University, New York, NY USA
\textsuperscript{b}Physics Department POB 5000 Brookhaven National Laboratory, Upton, NY 11973 USA

May 5, 2004

Abstract

We discuss two special limiting forms of QCD matter which may be produced at RHIC. We conclude from the available empirical evidence that an equilibrated, but strongly coupled Quark Gluon Plasma has been made in such collisions. We also discuss the growing body of evidence that its source is a Color Glass Condensate.
“It would be desirable to have some signal which would immediately make it possible to tell the hadronic phase from the quark-gluon phase in A-A collisions. It may be impossible to find one.”

Keijo Kajantie (1982)

Do we have to stay with circumstantial evidence?

The jury is still out
Quark matter meetings
Concluding remarks
“It isn’t that they can’t see the solution. It is that they can’t see the problem.”

G. K. Chesterton -
(in The Scandal of Father Brown)
„When you are awaiting a friend, do not take your heartbeat for the hoofbeats of his horse”

(Chinese proverb)
"This could be the discovery of the century. Depending, of course, on how far down it goes."

Drawing by O'Brian  © 1958 The New Yorker Magazine, Inc.

The cartoon shown by Weisskopf at the conclusion of the 1962 ICHEP in Geneva is still timely.
"Physics will change even more. If it is radical and unfamiliar and a lesson that we are not likely to forget, we think that the future will be only more radical and not less, only more strange and not more familiar, and that it will have its own new insights for the inquiring human spirit."

J. R. Oppenheimer