The Physics of Relativistic Heavy Ion Collisions

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**NEW YORK TIMES**

**NATIONAL DESK | January 13, 2004, Tuesday**

**Newly Found State of Matter Could Yield Insights Into Basic Laws of Nature**

By JAMES GLANZ (NYT) 866 words  
Late Edition - Final, Section A, Page 19, Column 2

**ABSTRACT** - Scientists from Brookhaven National Laboratory say fleeting, ultradense state of matter, comparable in some respects to bizarre kind of subatomic pudding, has been discovered deep within core of ordinary gold atoms; some scientists describe finding as breakthrough in understanding powerful, immensely complex forces that hold together building blocks of atomic nuclei: protons and neutrons (M)

**NATIONAL DESK | January 14, 2004, Wednesday**

**Tests Suggest Scientists Have Found Big Bang Goo**

By JAMES GLANZ (NYT) 832 words  
Late Edition - Final, Section A, Page 12, Column 3

**DISPLAYING FIRST 50 OF 832 WORDS** - At least three advanced diagnostic tests suggest that an experiment at the Brookhaven National Laboratory has cracked open protons and neutrons like subatomic eggs to create a primordial form of matter that last existed when the universe was roughly one-millionth of a second old, scientists said here on Tuesday ...  

**SCIENCE DESK | January 20, 2004, Tuesday**

**Like Particles, 2 Houses of Physics Collide**

By JAMES GLANZ (NYT) 1356 words  
Late Edition - Final, Section F, Page 1, Column 1

**DISPLAYING FIRST 50 OF 1356 WORDS** - ... What, has this thing appear'd again ... I have seen ... -- "Hamlet," Act 1, Scene ... A bland and bulky conference center in this city's fogbound downtown was transformed in recent days into the Elsinore of particle physics. The ghost that continually appeared, disappeared and appeared again during...
Curiosity
Going Back to School…

Many times as a field advances and matures, people forget the basic principles and only focus on the latest detailed measurements and theoretical developments.

In these lectures, I hope to talk in detail about the basics and then connect these to the latest and greatest results (from select topics).

Very broad subject area, and thus focus on a few topics and unfortunately leave out many other important ones.
QCD
and the
Quark Gluon Plasma
1973 = Birth of QCD
Gross, Politzer, Wilczek

The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

David J. Gross  H. David Politzer  Frank Wilczek
Quantum Electrodynamics (QED)

Field theory for electromagnetic interactions
Exchange particles (photons) do not have electric charge
Flux is not confined - $U(r) \propto 1/r$ and $F(r) \propto 1/r^2$

The Nobel Prize in Physics 1965

"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"

Sin'itiro Tomonaga  Julian Schwinger  Richard P. Feynman
Quantum ChromoDynamics (QCD)

Field theory for strong (nuclear) interactions
Exchange particles (gluons) do have “color” charge
Flux is confined - $U(r) \propto r$ and $F(r) = \text{constant}$
QCD Looks Simple, but Is Not

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} \left( i\gamma_\mu D^\mu - m \right) \psi \]

\[ F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu \]
Running Coupling Constant

Infrared Slavery

Asymptotic Freedom

\[ \alpha_s(Q) \]

\[ Q \text{ [GeV]} \]

\[ 0.2 \text{ fm} \quad 0.02 \text{ fm} \quad 0.002 \text{ fm} \]
Free Quarks?

No one has ever seen a free quark. QCD is a “confining” gauge theory, with an effective potential:

\[ V = -\frac{4}{3} \frac{\alpha_s}{r} + kr \]
“Seeing” the Gluon

A two jet event

A three jet event
Quarks, Gluons and the Strong Interaction

Proton is a composite object made of quarks and gluons.

“Three quarks on a lark.” James Joyce
Perturbative QCD

For processes where coupling is small, one can do a perturbative expansion (to a given order) and expect increasingly accurate results.

Note that there are still many tricky issues in pQCD calculations.
Perturbative QCD Successes

High Energy Jet Observations

Deep Inelastic Scattering DGLAP

Inclusive Jet cross section

CDF Preliminary

NLO QCD prediction (EKS)
cteq4m $\mu=E_t/2$ $R_{sep}=1.3$

Statistical Errors Only
Non-Perturbative Lattice QCD Results

Using lattice QCD we can calculate the various hadron masses.

Agreement at 10% level, excluding $\pi^0$. 
Lattice Limitations

Computations are costly in terms of computer equipment and time.

Also, lattice results determine equilibrium properties and do not address well dynamical quantities.
Heating Up Nuclear Matter
Limiting Temperature

The very rapid increase of hadron levels with mass yields an exponential level density

and would thus imply a “limiting temperature”

\[ T_H \sim 170 \text{ MeV} \]

No Limiting Temperature

Lattice QCD results indicate that as one increases the energy input (bunsen burner heat), it is very hard to move the temperature above \( \sim 170 \text{ MeV} \).

However, eventually the temperature does exceed the "limiting temperature"!
Where is the Energy Going?

Input energy is not increasing the kinetic energy per particle, but instead going into the rearrangement of the constituents of the matter (i.e. a phase transition).

Phase Transition: \[ T = 150-200 \text{ MeV} \sim 10^{12} \text{ 0F} \]
\[ \varepsilon \sim 0.6-1.8 \text{ GeV/fm}^3 \]

If there is a period where all energy goes into rearrangement with no temperature increase, it is a first order phase transition with latent heat (and a mixed phase).
Melting the Hadrons

Can we melt the hadrons and liberate these quark and gluon degrees of freedom?

\[ \varepsilon = g \frac{\pi^2}{30} T^4 \]

Energy density for “g” massless d.o.f.

\[ \varepsilon = 3 \cdot \frac{\pi^2}{30} T^4 \]

Hadronic Matter: quarks and gluons confined
For \( T \approx 200 \) MeV, 3 pions with spin=0

\[ \varepsilon = \left\{ 2 \cdot 8_g + \frac{7}{8} \cdot 2_s \cdot 2_a \cdot 2_f \cdot 3_c \right\} \frac{\pi^2}{30} T^4 \]

Quark Gluon Matter:
8 gluons;
2 quark flavors, antiquarks,
2 spins, 3 colors

\[ \varepsilon = 37 \cdot \frac{\pi^2}{30} T^4 \]

37!
Lattice Equation of State (EoS)

Speed of sound drops near transition ("soft point in EoS") and actually goes to zero in first order transition. Sound wave transmits energy. In true mixed phase, all energy is absorbed into rearranging constituents.
Transition Order?

\[
\begin{align*}
N_f &= 2 \quad (m_s = \infty, \ m_{u,d} = 0) \quad \text{2nd order} \quad (O(4) \text{ universality}) \\
N_f &= 3 \quad (m_s = 0, \ m_{u,d} = 0) \quad \text{1st order} \quad (\text{fluctuation/instanton}) \\
N_f &= 2+1 \quad (m_s >> m_{u,d} \neq 0) \quad \text{1st order or crossover}
\end{align*}
\]

Most recent lattice QCD results for a realistic strange quark mass favor a smooth cross over transition for zero net baryon density, but this may not be the final word.
Lattice Thermodynamics

Lattice QCD (for heavy quarks as a test) show a screening of the long range confining potential gradually as one passes the transition temperature.

F. Karsch, hep-ph/0103314
Approximate Chiral Symmetry

Up and Down quarks have very small neutral current masses (< 15 MeV). These masses are of interest to electroweak symmetry breaking (i.e. Higgs). However, there is spontaneous breaking of chiral symmetry in the QCD vacuum we live in. A condensate of qqbar pairs results in the observed hadronic masses. At high temperature this condensate goes away and thus hadronic masses should change near the transition.

![Graph showing the transition of chiral symmetry with temperature]
Color Flux Tubes
Phase Transition

T (MeV) vs. μ (MeV)

Early Universe

QGP, quasi-free quarks, gluons

RHIC

200

SPS

AGS

nuclei

packed hadrons

Color superconductor

Net Baryon density

Normal Melting and Boiling Points

Liquid Water

Ice

Water vapor

0°C

100°C

Temperature

760 mm
Shuryak publishes first “review” of thermal QCD and coins a phrase:  

“Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the QCD (or quark-gluon) plasma.”
Physics goals of RHIC

- Achieve highest energy densities in extended matter for relatively long times
- Learn the dynamics of high density matter: energy deposition, stopping, formation of excitations, onset of equilibration, hadronization, freezeout
- Search for collective effects beyond individual pp scattering, or pA scattering
- Study role of new degrees of freedom
- Produce and study quark-gluon plasma with large A at E above a few GeV/fm$^3$
- Extract nuclear equation of state, application to astrophysics

What are the properties of matter at extremely high energy, or baryon density? From nuclear matter scales ($\rho_0=0.16/fm^3$, $E_0=0.15$GeV/fm$^3$) to orders of magnitude beyond?

- What are its effective degrees of freedom? From nucleonic to hadronic to quark-gluon.
- What are the states of matter? Recognizable quark-gluon plasma? Strangelets? ...?
- What is the structure of QCD on large distance scales? Phase transitions? Monopoles?
- Surprises!

Terra incognita
QCD
and
Cosmology
First attempt at QGP formation was successful!

The Early Universe, Kolb and Turner

\[ g_*(T) \equiv \frac{1}{\pi^2 T^4 / 30} \sum_{\text{species}} \int_0^\infty \frac{E_i(p)}{e^{(E_i-\mu_i)/T_i} \pm 1} \frac{d^3 p}{(2\pi)^3} \]
Brief History of Time

- Too hot for quarks to bind!!!
  Standard Model (N/P) Physics

- Too hot for nuclei to bind
  Nuclear/Particle (N/P) Physics

- Nucleosynthesis builds nuclei up to He
  Nuclear Force…Nuclear Physics

- Universe too hot for electrons to bind
  E-M…Atomic (Plasma) Physics

- Today’s Cold Universe
  Gravity…Newtonian/General Relativity

- Quark
- Gluon
- Plasma
- Hadron
- Gas
- E/M
- Plasma
- Solid
- Liquid
- Gas
Cosmology Connection

“A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario.”

“Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets.”

Ed Witten
Over 1000 citations
Strange Quark Matter

• Matter of roughly equal numbers of up, down and strange quarks.

• Strange Quark Matter could be more stable than Fe$^{55}$ and thus be the ground state of nuclear matter.

• If stable, it could be a source of baryonic dark matter.
Strange Stars

Matter of roughly equal u, d, s stays electrically neutral and thus SQM objects can have very large baryon number.

Stars with quark matter cores have a different density profile.

Also, at the point of a phase transition, they can exhibit interesting behaviour (e.g. spin up).

There are some candidates, but nothing definitive yet.
Creating Strangelets

- Twenty years later, SQM still theoretically allowed.

- Experiments searches in terrestrial matter and nuclear reactions for small $A< 100$ SQM have yielded null results.
Supercooling and Bubbles

If the plasma-to-hadrons transition were strongly first order, bubble formation could lead to an inhomogeneous early universe, thus impacting big bang nucleosynthesis (BBN).

Are the bubbles too small and close together such that diffusion before nucleosynthesis erases the inhomogeneities? (200 MeV to 2 MeV)

This line of investigation was quite active when the dark matter issue raised questions about the implied baryon content in the universe from BBN.
No BBN Problem

Physics Today, July 2001: Cosmic Microwave Background Observations

“The value deduced from the second harmonic in the acoustic oscillations for $\Omega_B=0.042 \pm 0.008$ (cosmic baryon mass density) is in very good agreement with the value one gets by applying the theoretical details of primordial big bang nucleosynthesis to the observations of cosmic abundances of deuterium.”

However, this confirmation of BBN does not rule out a first order phase transition in QCD because of the diffusion issue.
Flat Universe

WMAP Results
Age of the Universe = 13.8 billion years
Isotropic (1:100,000)
Total Energy = 0 (Universe is flat!)