Ultrarelativistic heavy ion collisions: the first billion seconds

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Why ultrarelativistic heavy ion collisions?

The first serious planning for an ultrarelativistic heavy ion collider, RHIC, began in the summer of 1983, a mere $1.0163 \times 10^9$ sec ago.

*What did we have in mind when we planned and built RHIC and incorporated heavy ion collisions at LHC?*

*The scientific motivations?*

*Connections envisioned with the rest of physics: Astrophysics, cosmology, condensed matter, ...?*

*How have we shed light on the scientific issues?*
Why ultrarelativistic heavy ion collisions?

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Pre-history of ultrarelativistic heavy ion collisions

Workshop at Bear Mountain, NY, Fall 1974 (t = - 0.25 x 10^9 sec.)

“The workshop addressed itself to the intriguing question of the possible existence of a nuclear world quite different from the one we have learned to accept as familiar and stable.”

Bear Mountain was the turning point: workshop brought heavy ion physics to forefront as research tool!
"I name this place Terra Incognita."
Stability and variability of the vacuum

Is the vacuum a medium whose properties we can change?
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Nuclei as heavy as bulls
Through collision
Generate new states of matter

Li Keran 1989 (T.D. Lee)
What are the properties of matter under extreme conditions? High temperature, high densities!

Bear Mountain 1974:

- Lee-Wick abnormal nucleon matter
- Hagedorn hadronic resonance gas
- Walecka mean field model

Quark matter as the ultimate state:

- Itoh 1970: in neutron stars
- Carruthers 1973: “quarkium, a bizarre Fermi liquid”
- Gross, Wilczek & Politzer: Asymptotic freedom of QCD, 1973
- Cabbibo & Parisi, 1975: Deconfinement transition
- Collins & Perry, 1975: Ultrahigh density and temperature ⇔ asymptotic freedom. Weakly interacting “quark soup”
- Quark matter in neutron stars: “Can a neutron star be a giant MIT bag?” -- GB and Chin, 1976
Could seeds of unusual states set off a global catastrophe?

New ground state, stable or metastable?

“Lee-Wick theory indicates that $10^8$ or $10^9$ [abnormal superdense nuclei] have already been produced on the moon, and that the moon is still there, albeit with large holes.” Leon Lederman

At RHIC startup
... and even now!

Are we all going to die next Wednesday?

Two nightmare scenarios: two ends of the world. In the first, there is little warning. For maybe a month there would be no sign that the end was about to come to an abrupt and nasty end for all living things on Earth. Then, earthquakes would start unexpectedly, startling geologists that something terrible, unimaginable, was afoot. After a few days, these seismic disturbances would reach catastrophic proportions. Cities would be levelled, the oceans would rise and wash in a series of mega-tsunamis that would attack the world’s coasts, killing millions.

The end of the world, tonight? Doomsday clouds fear the consequences of scientists replicating the Big Bang.
Significant early meetings

*First workshop on ultra-relativistic nuclear collisions*, Berkeley, May 1979 (w. GSI) (L. Schroeder) = QM 0


*Statistical mechanics of quarks and hadrons*, Bielefeld (H. Satz), Aug. 1980 = QM IA (theory)

*Workshop on future relativistic heavy ion experiments*, GSI, Oct. 1980 (R. Bock & R. Stock) = QM IB (expt.)

*Quark matter formation and heavy ion collisions*, Bielefeld, May 1982 (M. Jacob & H. Satz) = QM II \[ = (n+1)A.B. \]

*Quark Matter '83*, Brookhaven, Sept. 1983 (T. Ludlam and H. Wegner) = QM 3
International Symposium

Statistical Mechanics of Quarks and Hadrons

Bielefeld, August 24-31, 1980
Getting going

Fixed target heavy ion machines
  Bevalac at Berkeley -- 1974
  Numatron (INS Tokyo) ~1979-82, up to $U \leq 1.3 \text{ GeV/A}$ -- not built

Interest in U.S., Europe, and Japan in colliding heavy ions -- 1983.
  VENUS at LBL

Open meeting of U.S. Nuclear Science Advisory Committee (NSAC) Aurora, N.Y., July 1983:

During the meeting Isabelle (or Colliding Beam Accelerator) 200 X 200 GeV protons at Brookhaven was cancelled, in favor of building the Superconducting Super Collider (SSC, or Desertron) 20 X 20 TeV -- itself cancelled in 1993

Forlorn beam tunnel of the CBA (Isabelle), 1983
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AGS fixed target heavy ion program proposed 1983. Ran 1986 - ~2002, Au from 1992 at $\sqrt{s_{NN}} \leq 4.3$ GeV
First glimmer of RHIC

Subgroup on nuclear matter under extreme conditions:

Arthur Kerman, Arthur Schwarzschild, GB, Miklos Gyulassy, Tom Ludlam, Larry McLerran, Lee Schroeder, Steve Vigdor, & Steve Koonin
Promised connections of heavy ions to outside

**Neutron stars**

\[ \rho > \rho_{\text{nm}}, \ T < 10^{-10} \text{ MeV}, \ R \sim 10^{-12} \text{ km}, \ M \sim 1.2-2 \ M_{\text{sun}} \]

--birth, evolution and cooling (x-ray satellite observations)
--upper mass limits, black hole identification

**Supernova and gravitational collapse**

-- bounce above \( \rho_{\text{nm}} \), energy release
-- hot n-rich nuclei

**Cosmology**

-- confinement phase transition?
-- mini-black holes \( M \sim M_{\text{jupiter}} \sim 10^{-2} \ M_{\text{sun}} \)

**Cosmic rays**

**Condensed Matter Physics**

-- many body effects (quasiparticles, ...)
-- broken symmetry states (pairing, chiral phase transitions)

**High energy physics**

-- QCD on large distance scales
Expected Phase Diagram

Many Opportunities

Deconfinement
Quarks - Gluons
No massless \( \pi \)

Hadrons (massless) Pions

Gas-Liquid 2 Phase Region

\( T \) vs \( \rho \)

\( p \) vs \( \rho \)

Plus:
- \( Z/A \) Dependence
- High Angular Momentum Dependence
- Pairing (\( 1S_0, 3P_0 \)) Transitions (\( T_c \sim 500 \))
Possibility of deconfinement phase transition

Phase transitions

Confinement - Deconfinement
Hadrons dissolve into plasma of quarks + gluons.

Chiral symmetry restoration

$T=0 \quad m_{\pi} \approx 0, \quad m_{n} \approx 1 \text{GeV}$

but chiral symmetry $\Rightarrow$

$m_{\pi} \neq 0, \quad m_{n} \approx 0$.

Best estimates* from the lattice

* Lattice is small
Light mass fermions somewhat mutilated
but much easier than hadron spectroscopy, or
"fine structure" such as nuclei.

Confinement
1st order transition
(or non-existent?)

$T_{c_{\text{conf}}} \approx 140 - 210 \text{ MeV}$

$E_{c_{\text{conf}}} \approx 0.5 - 2 \text{GeV/fm}^{3}$

Ideal gas at high $T$

L. McLerran
Shutting down of CBA in favor of the SSC set the stage for building colliding beam heavy ion accelerator in the CBA tunnel!

Construction at 100 GeV/A driven by possibility of producing jets that propagate through collision volume -- a wise decision.
Shutting down of CBA in favor of the SSC set the stage for building colliding beam heavy ion accelerator in the CBA tunnel!

Construction at 100 GeV/A driven by possibility of producing jets that propagate through collision volume -- a wise decision.
Scientific questions in the 1983 NSAC Long Range Plan:

“What is the nature of nuclear matter at energy densities comparable to those of the early universe?”

“What are the new phenomena and physics associated with the simultaneous collision of hundreds of nucleons at relativistic energies?”

The most outstanding opportunity opened by an ultrarelativistic heavy ion collider is “the creation of extended regions of nuclear matter at energy densities beyond those ever created in the laboratory over volumes far exceeding those excited in elementary particle experiments and surpassed only in the early universe.”
Physics goals of RHIC

Main issue for RHIC was to discover the properties of nuclear matter under extreme conditions -- high temperatures, high densities:
-- entropy and equation of state
-- the nature of its excitations: quasiparticles, collective modes
-- transport of conserved quantities: energy-momentum, baryons, etc.
-- dynamics
-- stopping of hadronic and quark projectiles; energy dissipation
-- particle emission

Possible discovery of new states of matter
-- quark-gluon plasma: A GOAL, NOT THE GOAL!
-- insights into $\pi$ condensation, liquid-gas phase transition at low density and temperature.
Physics goals of RHIC, II

Study behavior of QCD at large distance scales:
-- long range forces between q, gluons at 5-10 fm?
-- deconfinement transition, order? sharp? Measure $\Lambda_{\text{QCD}}$
-- chiral symmetry restoration
-- plasma modes

System would be strongly interacting!

Unusual objects:
-- multiquark states
  -- hadrons with heavy quarks
-- extended droplets of large strangeness
-- multi-baryon states of unusual chiral topology
-- $\pi$-$\mu$ and other exotic atoms
-- production of free quarks
PROBLEM SET # 2
DUE: JULY 17, 1984


2. Better understanding of signals for plasma.


4. Nuclear stopping power; width of fireball region.

5. How to probe QCD plasma after it is discovered.
1995-97 Creation of RIKEN BNL Research Center
T.D. Lee, first director
In 2000, a mere 17 years later, the first beams at RHIC.
Heavy Ions at CERN

Intersecting Storage Rings (ISR), 1971–1984:
- discussions about injecting heavy ions.
  G. Cocconi at Bear Mountain: transfer ions up to $^{16}\text{O}$ (and even U) from PS to ISR and eventually to SPS.

Super Proton Synchrotron (SPS), 1986–
- heavy ion experiments: NA34 (Helios), NA44, NA49, ...
- first results ($^{16}\text{O}$ at SPS & AGS) reported at QM VI – Nordkirchen 1987

1984 ECFA-CERN workshop laid down foundations of LHC
Towards the LHC Experimental Programme
5-8 March 1992
Evian-les-Bains, France

GENERAL MEETING on LHC
Physics Objectives
Expressions of Interest
Detector R&D
Machine

LARGE HADRON COLLIDER
IN THE LEP TUNNEL
Vol. I

PROCEEDINGS OF THE ECFA–CERN WORKSHOP
held at Lausanne and Geneva,
21-27 March 1984
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1984 ECFA-CERN workshop laid down foundations of LHC

1992 Evian-les-Bains meeting on LHC experimental program. Call for proposals. Suggestion of heavy ion collisions.

1993-5 ALICE Letter of Intent, and Proposal

2010 (26 years later) first exptl. runs at LHC: Pb-Pb at 2.76 TeV/A
The QCD phase diagram

Phase diagram of sake
Further features in phase diagram

Asakawa-Yazaki critical point (1989)

Search in RHIC & SPS energy scans.

States of color superconductivity – diquark BCS pairing

2SC / Color flavor locked (Alford, Rajagopal, Wilczek, ...)

The Phases of QCD

- Early Universe
- Future LHC Experiments
- Current RHIC Experiments
- 1st order phase transition
- Critical Point
- Quark-Gluon Plasma
- Hadron Gas
- Nuclear Matter
- Neutron Stars
- Color Superconductor
- Baryon Chemical Potential
- 900 MeV
- 0 MeV
- Vacuum

Temperature

RhIC Energy Scans

Crossover

Future FAIR Experiments
Possible new low temperature critical point

Chiral condensate \( (\Phi) \) – diquark \( (d) \) coupling, induced by 6 quark Kobayashi-Miskawa-‘t Hooft interaction via \( U(1)_A \) axial anomaly (T. Hatsuda et al. 2007)

\[
\Phi \sim \Phi^3 \\
\Phi \sim d_L^+ d_R \Phi
\]

Too cold to be accessible experimentally at RHIC. Possibly at FAIR.

Consistent with quark-hadron continuity (Schäfer-Wilczek 1999) – cf. quarks in neutron stars

Spatially ordered chiral transition = quarkyonic phases

( Kojo, Hidaka, Fukushima, McLerran, & Pisarski 2012)

Structure deduced in limit of large number of colors, $N_c$
Quark-Gluon Plasma

Hadron Phase

Quarkyonic Matter

Color Super

K. Fukushima (I-Pad)
Connections with ultracold atomic physics: a 2-way street

* Bose-Einstein condensation of overpopulated gluons in collisions at early times: \((\text{Blaizot, McLerran, \ldots})\)

* Viscosity/entropy in ultracold \(^6\text{Li}\) gas at unitarity \(\gtrsim 0.2\ \hbar\) \((\text{Schäfer, Thomas, \ldots})\)

* Analog systems: boson-fermion mixtures of ultracold atoms. \(\text{K. Maeda, \ldots}\)

Bosons \(^{87}\text{Rb}\) \(\leftrightarrow\) diquarks, Fermions \(^{40}\text{K}\) \(\leftrightarrow\) unpaired quarks

Formation of b-f molecules \(\leftrightarrow\) transition to nucleons

\(\text{arXiv: 1503.07260}\)

\(\text{Science 58, 311 (2011)}\)
Connections with ultracold atomic physics:

*BEC-BCS crossover in fermions $\Leftrightarrow$ quark hadron continuity
Continuously transform from molecules to Cooper pairs:

Unitary regime (Feshbach resonance) in gas of ultracold fermions.
No phase transition through crossover

In cold dense matter gradual transition from quark pairs (diquarks) to BCS paired quark matter.

BEC: $\mu < 0$, $\Delta \ll |\mu|$  
BCS: $\mu > 0$, $\Delta < \mu$
From polarization of the cosmic microwave background to photon polarization in ultrarelativistic collisions

Planck polarization map of entire sky

Thomson scattering at last scattering preserves polarization (⊥ to momentum); polarization reflects momentum anisotropy of photons

Similar effects in gluon to photon Compton scattering and quark-anti quark annihilation into gluon and photon. Direct photon (and dilepton) polarization measures initial gluon anisotropy. *Hatsuda, GB, Strickland, Ipp*
Neutron stars: cold quark matter

Masses \( \sim 1.3-2 \, M_\odot \)
Baryon no. \( \sim 10^{57} \sim (Gm_p^2/\hbar c)^{-3/2} \)
Radii \( \sim 10-12 \) km
Temperatures \( \sim 10^6-10^9 \) K

*Recent observations of 2 massive neutron stars requires very stiff equation of state:
PSR J1614-2230: \( M_{\text{neutron star}} = 1.97 \pm 0.04 M_\odot \)
PSR J0348+0432: \( M_{\text{neutron star}} = 2.01 \pm 0.04 M_\odot \)

*Recent inferences of mass & radius for \( \sim 12 \) neutron stars

\( R \sim 10-11 \) km

What can we learn about cold QCD matter from these observations?
Neutron stars: cold quark matter

Fundamental limitations of equation of state based on nucleon-nucleon interactions alone

Accurate for \( n \sim n_0 \). But for \( n \gg n_0 \): 

- can forces be described with static few-body potentials?

- Force range \( \sim 1/2m_\pi \) \( \Rightarrow \) relative importance of 3 (and higher) body forces \( \sim n/(2m_\pi)^3 \sim 0.4n_{fm^{-3}} \).

- No well defined expansion in terms of 2,3,4,...body forces.

- Can one even describe system in terms of well-defined ˜ asymptotic" laboratory particles? Early percolation of nucleonic volumes!

How can quark matter give stiff eq. of state, to explain large mass?

Construct neutron star from equation of state (pressure vs. baryon chemical potential). We do not know much about the transition region from hadronic to quark degrees of freedom – between about 2 to 8 times nuclear matter saturation density \( n_0 \).
Quarks in Nambu-Jona-Lasinio (NJL) model with universal repulsive short-range qq coupling (Kunihiro)

\[ \mathcal{L}_V^{(4)} = -g_V (\bar{q} \gamma^\mu q)^2 \]

APR = Akmal, Pandharipande, Ravenhall nucleonic equation of state with nucleonic potentials (2 and 3 body) fit to NN scattering and light nuclei
Have good idea of equation of state at nuclear densities and at high densities. Look at pressure vs. baryon chemical potential

Quarks in Nambu-Jona-Lasinio (NJL) model with universal repulsive short-range qq coupling (Kunihiro)

\[ \mathcal{L}^{(4)}_V = -g_V (\bar{q} \gamma^\mu q)^2 \]

APR = Akmal, Pandharipande, Ravenhall nucleonic equation of state with nucleonic potentials (2 and 3 body) fit to NN scattering and light nuclei

\( g_V = 0 \Rightarrow \) too soft to give 2M⊙ neutron stars
Increasing $g_V$ stiffens equation of state.

Shift of pressure in quark phase towards higher $\mu$ introduces unphysical thermodynamic instability.
Increasing $g_V$ stiffens equation of state

Shift of pressure in quark phase towards higher $\mu$ introduces \textit{unphysical} thermodynamic instability.
In this house, we obey the laws of thermodynamics!
Increasing $g_V$ stiffens equation of state

Shift of pressure in quark phase towards higher $\mu$ introduces unphysical thermodynamic instability
Stability restored with increased BCS (diquark) pairing strength, $H$

\[ \mathcal{L}_d^{(4)} = H \sum_{A,A'=2,5,7} [(\bar{q}i\gamma_5 \tau_A \lambda_{A'} C\bar{q}^T)(q^T C i\gamma_5 \tau_A \lambda_{A'} q)] \]

Increased diquark pairing (onset of stronger 2-body correlations) as quark matter approaches confinement

NJL, $H=1.5 \text{ G}$, $g_v=\tilde{G}$
NJL, $H=0$, $g_v=\tilde{G}$

shifts to lower $\mu$
Sample “unified” equation of state

T. Kojo et al.

quarks (NJL H=1.5 G, g_v=G)

Interpolated region

n_B = 2n_0

nucleons

M-R relation similar to results of nucleonic (APR) equation of state but with correct high density degrees of freedom

<= Reasonable agreement with eq. of state inferred from M vs. R measurements.

Quark eqs. of state can be stiffer than previously thought: allow for n.s. masses > 2 M_☉, and with substantial quark cores in neutron stars!!!
Reaching original goals and beyond

Discovery of new state of matter, the quark gluon plasma:
High energy densities achieved.
Plasma very strongly interacting; behaves collectively.

**Dynamical evolution:** From initial (weakly interacting?) system to hydrodynamics?
Quasiparticle structure (*Blaizot-lancu*)
Corrections to relativistic hydro. Triangle anomalies (*Dam Son*)
Freezeout? Final state interactions?
Dynamics of heavy quarks – diffusion over large distances;
screening of J/Ψ, B’s to probe deconfinement?
Effects of system size? Prepackaged statistics mimicking collectivity?
Correlations and event-by-event fluctuations to set systematics.

**Transport properties:** Very small viscosity; consistent with AdS/CFT bound on $\eta/s$.
Jets, shocks, and stopping power.

**Phase diagram:** Undergoing continuous refinement.
Search for critical point(s).
Reaching original goals and beyond

Impact on cosmology: QGP in early universe highly correlated system. Transition to hadrons expected to be 2nd order.

Cold dense matter (neutron stars) - to extract equation of state from experiment need to extrapolate from high T to sub-MeV degenerate regime. Theoretical framework?? Onset of quark degrees of freedom with increasing $\rho$? Informed by parallel studies of neutron stars.

A few evolving connections to further areas of physics:

Experimental realization of non-Abelian artificial gauge fields in cold atomic systems. Future atomic simulations of lattice gauge theory!

Cold atomic plasmas (Rolston, Killian, ...) Study strongly coupled plasmas on tabletop: dynamical evolution, instabilities, ...

Role of topology in heavy-ions (e.g., chiral magnetic effect – Kharzeev) closely related to topologically interesting condensed matter systems. Transitions in energy scans? Cold atom analogs!

Be on the lookout for Nature to surprise us!!!
どうもありがとう
THANK YOU