Introduction to high-energy heavy-ion collisions

Gang Wang (UCLA)

A collision full of colors and flavors...
"Reductionism"

the practice of analyzing and describing a complex phenomenon in terms of phenomena that are held to represent a simpler or more fundamental level, especially when this is said to provide a sufficient explanation.

Is there a limit?
Indivisible building blocks
1) Gravity
• one “charge” (mass)
• separate constituents
• force decreases with distance

2) Electric (& Magnetic)
• two “charges” (+/−)
• separate constituents
• force increases with distance
Constituents of nuclei:

- **protons** (+ electric charge)
- **neutrons** (no electric charge)

Do not fly apart!?

→ “nuclear force”

- overcomes electrical repulsion
- determines nuclear reactions (stellar burning, bombs…)

- arises from fundamental **strong force**
  - acts on **color** charges of quarks
  - three “charges”
How to study it? Separation...

to study structure of an atom…

To understand the strong force and the phenomenon of confinement:
Create and study a system of **deconfined** colored quarks (and gluons)

**Confinement**: fundamental & crucial (but not understood!) feature of strong force
- colored objects (quarks) have $\infty$ energy in normal vacuum… QCD

\[ E=mc^2 \]

quark-antiquark pair
created from vacuum

“white” proton
(confined quarks)

“white” $\pi^0$
(confined quarks)

“Strange” proton field
Energy grows with separation !!!
Liberating quarks

Present understanding of Quantum Chromodynamics (QCD)

- heating
- compression

→ deconfined color matter!
Expectations from Lattice QCD

$\varepsilon/T^4 \sim \# \text{ degrees of freedom}$

deconfined:  
quarks,  
many d.o.f.

confined:  
nucleons,  
few d.o.f.

$T_c \approx 173 \text{ MeV} \approx 2 \times 10^{12} \text{ K} \approx 130,000 \cdot T[\text{Sun's core}]$
QCD phase diagram
We must create/compress/heat a bulk (geometrically large) system

- freeze/melt a single H₂O molecule?
- fundamental distinction from particle physics

Only achievable through collisions of the heaviest nuclei (Au, Pb) at the highest available energy— at Relativistic Heavy Ion Collider (RHIC) or Large Hadron Collider (LHC)

1000’s of particles produced in each collision
Relativistic Heavy Ion Collider

\[ v = 0.99995 \cdot c = 186,000 \text{ miles/sec} \]
Relativistic Heavy Ion Collider

- PHOBOS
- PHENIX
- STAR
- BRAHMS
- AGS
- TANDEMS
Relativistic Heavy Ion Collider

STAR ~550 Collaborators
Large Hadron Collider

Can NOT be accomplished by a couple of super-scientists alone!
How to observe a collision

**STAR: Solenoidal Tracker at RHIC**

multipurpose detector system for hadronic measurements

- large coverage (geometrical acceptance)
- tracking of charged particles in high multiplicity environment
- measure correlations of observables
- study of hard processes (jet physics)

emitted in each collision
Solenoidal Tracker At RHIC
Charged particle flies thru TPC gas...

Anode wires with +HV sitting ~5 mm above pads

..generating a cluster of liberated electrons

“Avalanche” as electrons approach anode wire...

..capacitively inducing a signal on nearby pads...

..which is amplified, digitized, and recorded for later analysis
One collision seen by STAR TPC

Momentum determined by track curvature in magnetic field...

...and by direction relative to beam
Particle identification

**Time Projection Chamber (TPC)** measures the mean energy loss per distance travelled of swift charged particles.

**Time-of-Flight (TOF)** measures the flight duration, hence velocity ($\beta = v/c$) of swift charged particles.
One collision seen by STAR TPC… and by direction relative to beam.
Jet quenching

- Suppression of high $p_T$ particles
  (~ leading jet fragments)

$$R_{AA}(p_T) = \frac{d^2 N^{AA}/dp_Td\eta}{T_{AA}d^2\sigma^{NN}/dp_Td\eta}$$

$R_{AA} = 1$ for (very) hard QCD processes
in absence of nuclear modifications

Phys.Rev.Lett.108.072302
My name is $\psi$, $J_{\text{ames}} / \psi$ (a Charming Bond...)
A few by-products

Observation of the antimatter helium-4 nucleus

This rendering shows antihelium-4 (anti-alpha) emerging from a collision in the Relativistic Heavy Ion Collider at Brookhaven National Laboratory.

Nature 473 (2011) 353
A few by-products

Observation of an Antimatter Hypernucleus

A nucleus containing at least one hyperon in addition to nucleons.

Hypernuclei of lowest $A$

\[ ^3\Lambda H(n + p + \Lambda) \]

\[ ^3\bar{\Lambda} H(\bar{n} + \bar{p} + \bar{\Lambda}) \]

No one has ever observed any anti-hypernucleus before us (STAR).

The first hypernucleus was discovered by Danysz and Pniewski in 1952, formed in a cosmic ray interaction in a balloon-flown emulsion plate.

M. Danysz and J. Pniewski, Phil. Mag. 44 (1953) 348
A few by-products

Observation of an Antimatter Hypernucleus

Science 328 (2010) 58
A few by-products

Nature 527 (2015) 345
A few by-products

Global Λ hyperon polarization and the most vortical fluid

(Supercell tornado cores have only $10^{-1}\text{s}^{-1}$.)
QCD phase diagram

Temperature (MeV) vs. Baryon Chemical Potential (MeV) diagram showing various energy points and phase transitions.
Backup slides
Evidence of quarks

Deep inelastic scattering at SLAC

Bjorken scaling: scattering from point-like constituents within the proton

Callan–Gross relation: elastic scattering from point-like spin-half constituents -- quarks
Evidence of gluons

3-jet events at PETRA
Evidence of fractional electric charges

Deep inelastic scattering

\[
\langle Q^2 \rangle = \frac{\int F_2^{\nu N} dx}{4G^2M} = 0.303 \pm 0.01
\]

\[
\Delta = \text{CG (ref. 4)}
\]

\[
\bullet = \text{This experiment}
\]

Neutral-current (photon) DIS:

\[
F_2 = x \sum e_q^2 (q + \bar{q}), \quad p: uud, \quad n: ddu
\]

\[
F_2^{\nu N} = x \frac{e_u^2 + e_d^2}{2} (u + \bar{u} + d + \bar{d})
\]

Charged-current DIS:

\[
F_2^{\nu P} = 2x (d + \bar{u}), \quad F_2^{\nu N} = 2x (u + \bar{d})
\]

\[
F_2^{\nu N} = x (u + \bar{u} + d + \bar{d})
\]

Ratio:

\[
\frac{F_2^{N}}{F_2^{\nu N}} = \frac{1}{2} (e_u^2 + e_d^2) = \frac{5}{18} \approx 0.28
\]
Evidence of color charges

\[ R = \frac{\sigma_{\text{hadrons}}}{\sigma_{\text{muons}}} = \frac{\sum \sigma_{q\bar{q}}}{\sigma_{\text{muons}}} = \sum \left( \frac{q_q}{e} \right)^2 \]