Melting nuclei

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Higgs

Structure of matter

nucleus ~10^{-12} cm

proton (neutron)

quark <10^{-16} cm

atom ~10^{-8} cm

Standard model

Quarks

Top, Bottom, Strange, Charm, Up, Down

Leptons

Electron, Muon, Tau, Neutrino

Mesons

Kaon, Pion, Phi

Higgs

Hadrons

Baryons

Proton, Neutron

Mesons

Sigma, Lambda

Quarks

u u u d d d

Leptons

Neutrino

Mesons

Kaon, Pion, Phi

Higgs
Phase diagram of nuclear matter

Quark Gluon Plasma – a liquid of quarks and gluons created at temperatures above \( \sim 170 \) MeV \((2 \cdot 10^{12} \text{K})\) – over a million times hotter than the core of the sun.
How to make a Quark Gluon Plasma

nucleus

Heat

Compress

nucleon boundary irrelevant

CGP
The phase transition in the laboratory

Phase Transition/Cross-Over
Chemical Freeze-Out (inel. collisions cease)
Thermal Freeze-Out (el. collisions cease)

QGP
Hadron Gas

Collision
pre-equilibrium

$T_c$
$T_{ch}$
$T_{fo}$

$\tau_0$

time
Relativistic Heavy Ion Collider

Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, U+U
\( \sqrt{s_{NN}} = 9 - 200 \text{ GeV} \)

Geneva, Switzerland
8.6km diameter
p+p, p+Pb, Pb+Pb
\( \sqrt{s_{NN}} = 2.76 \text{ GeV}, 5.5 \text{ TeV} \)

Large Hadron Collider

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Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18

Trigger detectors: When do we have a collision?
Tracking detectors: Where did the particle go?
Identification detectors: What kind of particle is it?
Calorimeters: How much energy does the particle have?
p+p collisions

3D image of each collision
Pb+Pb collisions
QGP Chemistry
Chemistry - equilibrium

- Ratios of particles expected from a model
- Even strange quarks are at equilibrium!

T \sim 170 \text{ MeV}

200 \text{ GeV} ^{197}\text{Au} + ^{197}\text{Au}

arXiv:1701.07065
Quark Gluon Plasma – a liquid of quarks and gluons created at temperatures above ~170 MeV ($2 \cdot 10^{12}$K) – over a million times hotter than the core of the sun.
QGP Thermometers
Measuring temperature

[Graph showing the relationship between intensity and wavelength for different temperatures, with peaks indicating maxima.]
Thermal photons

**PHENIX collaboration:** Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Inverse slope: $T = 221 \pm 19$ (stat) $\pm 19$ (syst) MeV

**ALICE collaboration:** Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

Inverse slope: $T = 304 \pm 51$ MeV

**QCD processes**

- Direct photons
- Direct photon NLO for $\mu = 0.5, 1.0, 2.0 p_T$ (scaled pp)
- Exponential fit: $A \times \exp(-p_T/T)$, $T = 304 \pm 51$ MeV

*Phys. Rev. Lett. 104:132301, 2010*
Building a quarkonium-thermometer

CMS-PAS HIN-11-011

CMS PbPb $\sqrt{s_{\text{NN}}} = 2.76$ TeV

- Red: Prompt $J/\psi$ (Preliminary)
- Green diamond: $\Upsilon(1S)$
- Blue circle: $\Upsilon(2S)$

Clear hierarchy in $R_{AA}$ of different quarkonium states

$T/T_c$ vs $1/\langle r \rangle$ [fm$^{-1}$]

- $\Upsilon(1S)$
- $J/\psi(1S)$
- $\chi_b''(2P)$
- $\chi_c'(1P)$
- $\Upsilon''(3S)$
- $\Psi'(2S)$

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Building a quarkonium-thermometer

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- Prompt $J/\psi$ (Preliminary)
- $\Upsilon(1S)$
- $\Upsilon(2S)$

Clear hierarchy in $R_{AA}$ of different quarkonium states

Note: $6.5 < p_T < 30$ GeV for $J/\psi$ and $\psi(2s)$

CMS Preliminary

$\sqrt{s_{NN}} = 2.76$ TeV

- Inclusive $\psi(2S)$ ($6.5 < p_T < 30$ GeV/c, $|y| < 1.6$)
- $\Upsilon(3S)$ ($|y| < 2.4$), 95% upper limit
- $\Upsilon(2S)$ ($|y| < 2.4$)
- Prompt $J/\psi$ ($6.5 < p_T < 30$ GeV/c, $|y| < 2.4$)
- $\Upsilon(1S)$ ($|y| < 2.4$)

Expected in terms of binding energy

CMS-PAS HIN-12-014, HIN-12-007

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QGP Energy Density
How can we estimate the energy density?

- Transverse energy ($E_T$)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- $\tau =$ formation time
- Energy density $\epsilon$

\[
\epsilon = \frac{1}{V} \frac{dE_T}{dy} = \frac{J}{A_T \tau c} \frac{dE_T}{d \eta}
\]

- QGP formation for $\epsilon > 0.5$ GeV/fm$^3$
Energy density

Standard estimate $\tau_0 \approx 1 \text{ fm/c}$

$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$

ALICE Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV

RHIC

QGP formation
Probing the Quark Gluon Plasma

Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe
Probes of the Quark Gluon Plasma

Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
Probes of the Quark Gluon Plasma

Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe
Jets

Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles.
Jets

Quenched jets

- One of the jets is absorbed by the medium
- The quark or gluon has equilibrated with the medium
Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-\(p_T\) probes (jets) are suppressed, this is evidence of jet quenching

\[
R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}d^2\sigma_{pp}/dp_Td\eta}
\]

Enhancement

Suppression
Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-$p_T$ probes (jets) are suppressed, this is evidence of jet quenching
• **Electromagnetic probes** – consistent with no modification – medium is transparent to them
• **Strong probes** – significant suppression – medium is opaque to them

**Nuclear modification factor** $R_{AA}^{\text{RHIC}}$ and $R_{AA}^{\text{LHC}}$
Like for charged particles, high-$p_T$ jet $R_{AA}$ flat at $\approx 0.5$
Take home messages

- If we get nuclear matter dense enough, we make a new phase of matter, which we produce in high energy heavy ion collisions.
- This medium is extremely hot and dense...
- ...and opaque to colored probes and translucent to electromagnetic probes.
About me

- BS, Colorado State University, 2003
- PhD, Yale University, 2009
- Postdoc, University of Tennessee, Knoxville, 2009-2012
- Assistant prof, University of Tennessee, Knoxville 2012 –

- Active on issues related to women in physics
- Working on being a more effective ally for people of color
- Parent
- Brew beer & wine, keep bees, avid cook, cyclist
- Talk to me about: strategies for dealing with harassment, careers outside of physics, choosing a mentor, having kids and a career