Perspectives on Nuclear Physics Input into High-Energy Cosmic Ray Interactions

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Disclaimer: My expertise in nuclear collisions is mostly at low energies; my expertise in high energies is mostly with neutrinos. So this is essentially an outsider’s perspective!
Why are laboratory nuclear experiments relevant to the cosmic-ray physics?
Recent results suggest presence of a significant nuclear component in the higher-energy cosmic-ray flux from the measurements of the depth of the shower maximum.

AUGER Collaboration, PRL 104, 091101 (2010)

However, see
HIRES Collaboration,
PRL 104, 161101 (2010)
Recent results suggest presence of a significant nuclear component in the higher-energy cosmic-ray flux from the measurements of the depth of the shower maximum.

**CAUTION:** Heitler's original formula:

\[ \langle X_{\text{max}} \rangle = \alpha (\ln E - \langle \ln A \rangle) + \beta \]

assumes that heavier nuclei are basically superposition of the nucleons

(see however Ulrich et al., arXiv:0906.0418)
Are nuclear collisions simply a superposition of nucleon collisions?

\[
R_{AA} = \frac{dN_{AA}/dp_T}{N_{\text{coll}} (dN_{pp}/dp_T)}
\]

\(N_{\text{coll}} = \text{number of binary collisions}\)

Absence of nuclear medium interactions (i.e. \(\gamma\)'s) \(\Rightarrow R_{AA} \approx 1\)

Energy loss in the medium \(\Rightarrow\) reduction of \(p_T\)
PHENIX Au+Au (central collisions):
- Direct $\gamma$
- $\pi^0$
- $\eta$
- GLV parton energy loss ($dN^0/dy = 1100$)
QCD jets are quenched by the nuclear medium. Nuclear collisions are NOT simply a superposition of pp collisions!
Glauber formula and its extensions represent multiple scatterings in the target, but do not take into account the emergent properties of the quark-gluon system for which there are strong experimental hints.

\[
\sigma_{AA} = \int d^2b \left( 1 - \exp \left[ -\sigma_{pA} \int \rho_A(b)dz \right] \right)
\]
Recent results suggest presence of a significant nuclear component in the higher-energy cosmic-ray flux from the measurements of the depth of the shower maximum.

If there are sources of ultra-high energy cosmic-ray nuclei, these sources should also produce neutrinos!

Murase & Beacom, PRD 81, 123001 (2010).
What have we recently learned from relativistic heavy-ion experiments?

1. An effective “temperature” in 200 GeV Au-Au collisions has been measured. Result is not exactly what we expected.

2. Negative Binomial Distributions continue to fit the data well.

3. There are strong experimental indications that the quark-gluon system formed in relativistic heavy-ion collisions is not a gas, but almost a perfect liquid.
Measuring the “temperature” at $\sqrt{s_{NN}} \sim 200$ GeV Au-Au collisions

First measure opposite-charge lepton pairs

PRL 104, 132301 (2010)
...then convert to real photons by going to zero invariant mass

\[ T_{	ext{eff}} = 221 \pm 19 \pm 19 \text{ MeV} \] (effective because \( \gamma \)'s are emitted as the temperature evolves)

\[ + \text{ theoretical input} \]

300 MeV < \( T_{\text{initial}} \) < 600 MeV as opposed to the QCD prediction of \(~ 170 \text{ MeV}!\)
Negative Binomial Distribution continues to fit multiplicity fluctuations well

PHENIX Collaboration, PRC 78, 044902 (2008)
Negative Binomial Distribution continues to fit multiplicity fluctuations well

The charged-particle density is higher than theoretical expectations!

ALICE Collaboration,
arXiv:1004.3514
Negative Binomial Distribution

Basic assumption: Probability of emitting $n$ particles by the $i$th source is $b_i^n$.

$$\Rightarrow F(\lambda) = \sum_{n=0}^{\infty} P_n \lambda^n = \prod_i \frac{1 - b_i}{1 - \lambda b_i}$$

All $b_i$'s are the same $\Rightarrow$ Negative Binomial Distribution:

$$\sum_{n=0}^{\infty} P_n \lambda^n = \left( \frac{1 - b}{1 - \lambda b} \right)^{k_{NBD}}$$

Note: In fits $k_{NBD}$ is not constrained to be an integer.

Note: $P_n$ is the complete symmetric function of degree $n$ in the arguments $b_i$. The ubiquity of negative binomial distribution is likely to be statistical.
What is a perfect fluid?

Low viscosity

*F* = \( \nu \frac{\partial v_x}{\partial y} \)

High viscosity

“good” fluid ⇒ low viscosity, \( \eta \)
Is there a lower bound on shear viscosity, $\eta$? - Heuristic argument

$$F_x = \eta A \frac{\partial v_x}{\partial y}$$

For a dilute (weakly-interacting) gas of quasi-particles:

$$\eta = \frac{1}{3} n \langle p \rangle L_{\text{mean}},$$

$n$: density, $\langle p \rangle$: ave. momentum, $L_{\text{mean}} = 1/n\sigma$: mean free path

Uncertainty principle:

$$\langle p \rangle L_{\text{mean}} \geq \hbar \Rightarrow \frac{\eta}{n} \geq \hbar$$

Danielewicz & Gyulassy, 1985
Relativistic fluids

For relativistic fluids it is more appropriate to normalize the viscosity to the entropy density.

Entropy: \( S \propto k_B N \); Entropy density: \( s = \frac{S}{V} \propto k_B n \)

Is there a lower limit to \( \frac{n}{s} k_B \)?

Kovtun, Son, Starinets, 2005
AdS/CFT duality

Large N conformal field theory in 4D \iff String theory on 5D Anti deSitter space \times S_5

Thermal CFT \iff AdS_5 Black Hole

CFT entropy \iff Hawking entropy of the black hole

Shear viscosity \iff \sigma_{\text{graviton absorption}}

Then one can calculate the viscosity in the strong coupling limit:

$$\frac{\eta}{s} = \frac{1}{4\pi} \frac{\tilde{h}}{k_B}$$

Policastro, Son, Starinets, 2001
Hydrodynamic behavior of the quark-gluon system

Hydrodynamic evolution:

\[
\frac{dN_i}{p_T dp_T dy d\phi_p}(b) = \frac{1}{2\pi} \frac{dN_i}{p_T dp_T dy}(b) \left( 1 + 2 \sum_i \nu_n^i \cos(n\phi_p) \right)
\]

\(\phi_p\): azimuthal emission angle relative to the reaction plane

\[
\text{midrapidity, } y=0 \Rightarrow \nu_{n=\text{odd}} = 0
\]

\[
\nu_2 > 0 \Rightarrow \text{elliptic flow}
\]

The larger the shear velocity, \(\eta\), is the more transverse expansion of the system slows down.
The quark-gluon system formed in relativistic heavy-ion collisions is almost a perfect fluid!
Concluding remarks

• At higher energies nuclei are not simply a “collection” of nucleons. Much interesting physics comes into play!

• Recent relativistic heavy-ion experiments found a broad spectrum of interesting phenomena, ranging from the observation of the quark-gluon system as a “perfect fluid” to measuring its temperature.

• Some of the recent cosmic ray experiments suggest an increase in the nuclear component of the cosmic-ray flux at higher energies. Insight gained from recent relativistic heavy-ion experiments could help to understand this nuclear component.