Understanding A+A collisions with h+A data at SPS energies

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Summary.
Strongly interacting matter around SPS energies

Results from lattice QCD calculations suggest a phase transition of strongly interacting matter.

Expectation: collision evolution samples both phases around $\sqrt{s_{NN}} \approx 20 \text{ GeV}/c$ nucleus-nucleus collisions.

Top SPS energies is an interesting region to study from the point of view of phase transition. Energy dependence of medium effects on particle spectra is a relatively explicit test.
Inclusive methods of measuring medium effects

Particle production in an $A + B$ nuclear collision is characterized by the invariant per event yield:

$$ Y_{AB} := \frac{1}{2\pi p_T} \frac{d^2 n}{dy dp_T} $$

This measures particle production inclusively as a function of momentum space.

Glauber eikonal calculations show that hard scattering yield in a given centrality $A+B$ nuclear collision is related to hard scattering yield in $N+N$ nuclear collisions:

$$ Y_{AB}(c_1, c_2) = \langle N_{AB} \rangle(c_1, c_2) Y_{NN} $$

where $\langle N_{AB} \rangle(c_1, c_2)$ are mean number of binary collisions in centrality interval $[c_1, c_2]$.

This takes into account only collision geometry effects, provided that the $A+B$ collision can be considered as incoherent sums of $N+N$. Nuclear modification factor

$$ R_{AB}(c_1, c_2) := \frac{1}{\langle N_{AB} \rangle(c_1, c_2)} \frac{Y_{AB}(c_1, c_2)}{Y_{NN}} $$

is motivated by this, and it measures the deviation from the Glauber picture.

Deviation from the Glauber picture is attributed to medium effects.
Experimental observations (as first seen at RHIC from $h^\pm$ spectra):

![Graph showing $R_{AB}$ vs. $p_T$ for different systems at RHIC.]

$R_{AB} := \frac{1}{\langle N_{AB} \rangle} \frac{Y_{AB}}{Y_{pp}}$


$\sqrt{s_{NN}} = 200$ GeV

Suppression of high $p_T$ hadrons in Au+Au(centr).

Enhancement in d+Au(minbias).

Qualitative explanation proposed: energy loss of energetic partons in the intensely interacting medium, so that less hadrons can be formed at larger $p_T$.

Energy dependence?
Measurements on energy dependence of medium effects

$R_{AA}$ in Pb+Pb at $\sqrt{s_{NN}} = 2760$ GeV
EPJC 72 1945, CMS
(for this energy $h^\pm \approx \pi^\pm$ at $y \approx 0$)

$R_{AA}$ in Au+Au at $\sqrt{s_{NN}} = 200$ GeV
PRL 91 072303, PRC 83 064903, PHENIX
(for this energy $h^\pm \approx \pi^\pm$ at $y \approx 0$)

$R_{AA}$ in Au+Au at $\sqrt{s_{NN}} = 130$ GeV
PLB 561 82, PHENIX
(for this energy $h^\pm \approx \pi^\pm$ at $y \approx 0$)
What about lower energies? For this, PID matters...

\[ \sqrt{s_{NN}} = 17.3 \text{ GeV (NA49)} \quad \sqrt{s_{NN}} = 200 \text{ GeV (PHENIX)} \]

\[ \sqrt{s_{NN}} = 200 \text{ GeV}: \text{PRC 69 (2004) 034910 and PRC 74 (2006) 024904.} \]

\[ \sqrt{s_{NN}} = 17.3 \text{ GeV}: \text{PRC 77 (2008) 034906, } \sqrt{s_{NN}} = 19.4 \text{ GeV}: \text{PRD 19 (1979) 764.} \]

Spectrum range up to relatively low \( p_T \), due to p+p statistics limitation.
The Glauber picture \( Y_{AB}(c_1, c_2) = \langle N_{AB} \rangle(c_1, c_2) \) \( Y_{NN} \) is not supposed to account for any initial state medium effects. These can, however, be very large.

Let us consider an A+A collision. One can call one of the incident nucleus as projectile. Assuming that for each projectile nucleon the initial state will be the same, the A+A spectrum (without final state effects) can be reconstructed from weighted sum of N+A with different centralities:

\[
Y_{AA}(\text{central}) = \int_0^{b_{\text{max}}} Y_{NA}(b) \langle M \rangle(b) \, db
\]

where \( \langle M \rangle(b) \) is the mean number of projectile participants in A+A at the impact parameter slice \( b \).

Can be re-expressed as sum over N+A centrality intervals:

\[
Y_{AA}(\text{central}) \approx \sum_{[c_1, c_2]} Y_{NA}(c_1, c_2) \langle M \rangle(c_1, c_2)
\]
The constructed "differential" reference spectrum can be compared to real A+A(central) if N+A measurement is centrality differentiated:

\[ r_{AA} := \frac{Y_{AA}(\text{central})}{Y_{AA}(\text{central, constructed})} \]

Here, initial state effects should be factorized. Energy dependence?

Centrality differentiation of N+A is critical here.

Construct based on data in: PRC 69 034909, PRC 74 024904.

Here, initial state effects should be factorized. Energy dependence?
NA61 (also called SHINE) is a fixed target experiment at CERN SPS. Large acceptance TPC system for mostly midrapidity and forward rapidity tracking + dE/dx. Primary/secondary beam: 10-350 GeV/c had., 10-160 GeV/c ion (\(\sqrt{s_{NN}}\) =4.5-17.3 GeV/c). New detector for centrality determination in p+A: the LMPD around target.
Upon a hadron-nucleus collision, part of the target nucleus gets destabilized.

Some target spectator nucleons get emitted, characteristic momentum $\sim$ Fermi motion. Multiplicity of such 'gray' nucleons correlate with event centrality (impact parameter). By counting gray protons in an event, a measure of event centrality may be introduced. LMPD detector (Low Momentum Particle Detector) optimized for that (50-250 MeV/c p).
The LMPD detector for p+A centrality measurement

LMPD is a TPC-based tracking device around target, picking up particles radially emitted from target.

- It has a vertical drift field, 5 detection volumes (field cages), separated by plastic absorbers.
- Simultaneous detection of energy loss (dE/dx) and range provides PID and momentum estimation capabilities.

Proton tracks with ‘gray’ momentum (50-250 MeV/c) leave a characteristic dE/dx response peak after traversing 3 layers.

LMPD detector installed for physical data taking around the target position.

LMPD and Pb target without He atmosphere. LMPD and Pb target with its He atmosphere.

Solid (Pb) plate target was used. Made thin, in order to decrease in-target absorption.

He atmosphere was used in order to decrease contribution of off-target collision background.

Drift field is vertical, MWPC amplification plane and readout electronics at the top.
Readout FEE range optimized for MIPs \(\Rightarrow\) optimized gas gain on different layers.

- Non-negligible fake cluster and missing cluster probability due to this setting.
- There are stopping tracks.
- There is off-vertex track contamination.

LMPD event display.

Track finding was optimized for the above requirements.

Hough transform method combined with maximum likelihood principle for track finding.
Pion, proton signal is seen along with heavier fragments.

Dynamical range optimized for proton response.

Gain calibration using radioactive Kr in order to improve resolution.

LMPD response.

Proton peak well visible, detector capable of measuring multiplicity of gray protons.
Data taking on p+A spectra at $\sqrt{s_{NN}} \approx 20$ GeV

- NA61/SHINE recorded 14 M p+Pb centrality differentiated events at $\sqrt{s_{NN}} = 17.3$ GeV.
- The 14 M p+Pb statistics is to be doubled in 2014 after long shutdown of SPS.
- A+A spectra have been measured by NA49 at $\sqrt{s_{NN}} = 17.3$ GeV for a sufficient extent.

- These data will be used to construct $r_{AA}$. 

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Summary

 Energy dependence of medium effects on particle production spectra in nucleus-nucleus collisions may be experimentally studied via nuclear modification factors in A+A with respect to weighted N+A. This quantity factorizes initial state effect to a large extent.

 Large statistics A+A we have from $\sqrt{s_{NN}} = 17.3$ GeV to LHC energies.

 Good quality N+A reference data are needed, which are mostly available for RHIC energies and above.

 N+A reference provides the most detailed baseline if centrality differentiated. Centrality differentiated data has been taken on p+Pb at $\sqrt{s_{NN}} = 17.3$ GeV (NA61/SHINE).

 Specially developed centrality measurement apparatus (LMPD) was used.

 The $\sqrt{s_{NN}} = 17.3$ GeV p+Pb sample is to be complemented in 2014 after LS.