Strange hadron correlations in Heavy-Ion collisions at RHIC energies and below

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Outline

Introduction
- QCD phase diagram
- HIC and femtoscopy method

Results
- Strong interactions between (anti)baryons
- Motivation to Y-N and Y-Y correlations
- Femtoscopy of strange baryons and their interactions
- Possible bound states
- Coalescence production of deuterons
- Nonidentical particle correlation

Summary and conclusions
Introduction
Phase diagram of strongly interacting matter
Phase diagram of strongly interacting matter
Measurement of interaction between antiprotons

The STAR Collaboration

Published: 04 November 2015

Abstract

One of the primary goals of nuclear physics is to understand the force between nucleons, which is a necessary step for understanding the structure of nuclei and how nuclei interact with each other. Rutherford discovered the atomic nucleus in 1911, and the large body of knowledge about the nuclear force that has since been acquired was derived from studies made on nucleons or nuclei. Although antinuclei up to antihelium-4 have been discovered\(^1\) and their masses measured, little is known directly about the nuclear force between antinucleons. Here, we study antiproton-pair correlations among data collected by the STAR experiment\(^2\) at the Relativistic Heavy Ion Collider (RHIC)\(^3\), where gold ions are collided with a centre-of-mass energy of 200 gigaelectronvolts per nucleon pair. Antiprotons are abundantly produced in such collisions, thus making it feasible to study details of the antiproton–antiproton interaction. By applying a technique similar to Hanbury Brown and Twiss intensity interferometry\(^4\), we show that the force between two antiprotons is attractive. In addition, we report two key parameters that characterize the corresponding strong interaction: the scattering length and the effective range of the interaction. Our measured parameters are consistent within errors with the corresponding values for proton–proton interactions. Our results provide direct information on the interaction between two antiprotons, one of the simplest systems of antinucleons, and so are fundamental to understanding the structure of more complex antinuclei and their properties.

Unveiling the strong interaction among hadrons at the LHC

ALICE Collaboration

Published: 09 December 2020

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Abstract

One of the key challenges for nuclear physics today is to understand from first principles the effective interaction between hadrons with different quark content. First successes have been achieved using techniques that solve the dynamics of quarks and gluons on discrete space-time lattices\(^1,2\). Experimentally, the dynamics of the strong interaction have been studied by scattering hadrons off each other. Such scattering experiments are difficult or impossible for unstable hadrons\(^3,4,5,6\) and so high-quality measurements exist only for hadrons containing up and down quarks\(^7\). Here we demonstrate that measuring correlations in the momentum space between hadron pairs\(^8,9,10,11,12\) produced in ultrarelativistic proton–proton collisions at the CERN Large Hadron Collider (LHC) provides a precise method with which to obtain the missing information on the interaction dynamics between any pair of unstable hadrons. Specifically, we discuss the case of the interaction of baryons containing strange quarks (hyperons). We demonstrate how, using precision measurements of proton–omega baryon correlations, the effect of the strong interaction for this hadron–hadron pair can be studied with precision similar to, and compared with, predictions from lattice calculations\(^13,14\). The large number of hyperons identified in proton–proton collisions at the LHC, together with accurate modelling\(^15\) of the small (approximately one femtometre) inter-particle distance and exact predictions for the correlation functions, enables a detailed determination of the short-range part of the nucleon-hyperon interaction.
Heavy-Ion collision and the femtoscopy method

- beam axis
- pair transverse $p$
- perpendicular to out and long
Correlation femtoscopy

Size: $\sim 10^{-15}$ m (fm)
Time: $\sim 10^{-23}$ s

Impossible to measure directly!
Correlation **femtoscopy**

Size: $\sim 10^{-15}$ m (**fm**)  
Time: $\sim 10^{-23}$ s

Impossible to measure directly!

**Femtoscopy (HIC)** inspired by Hanbury Brown and Twiss interferometry method (Astronomy)

**but!**
- different scales,
- different measured quantities
- different determined quantities
Femtoscopy (known as HBT): the method to probe geometric and dynamic properties of the source

Space-time properties \((10^{-15} \text{m}, 10^{-23} \text{s})\) can be determined due to two-particle momentum correlations that arise due to:

Quantum Statistics (Fermi-Dirac, Bose-Einstein);
Final State Interactions (Coulomb, strong)

\[
C(k^*, r^*) = \int S(r^*) |\Psi(k^*, r^*)|^2 d^3r^* = \frac{Sgln(k^*)}{Bckg(k^*)}
\]

- **\(C(k^*, r^*)\)** determined
- \(S(r^*)\) assumed
- **\(\Psi(k^*, r^*)\)** measured
- two-particle wave function (includes e.g. FSI interactions)
- \(Sgln(k^*)\) correlation function
- \(Bckg(k^*)\) emission function
Traditional and non-traditional femtoscopy

If we assume we know the **emission function**, measured correlation function can be used to determine **parameters of Final State Interactions**

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- **assumed**
- **determined**
- **measured**

$S(r^*)$ - emission function

$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

$\frac{Sgnl(k^*)}{Bckg(k^*)}$ - correlation function
Traditional and non-traditional femtoscopy

Object of study of traditional femtoscopy

\[ C(k^*, r^*) = \int S(r^*) |\Psi(k^*, r^*)|^2 d^3r^* = \frac{S_{gnl}(k^*)}{Bc_{kg}(k^*)} \]

Emission source \( S(r^*) \)
Traditional and non-traditional femtoscopy

\[ C(k^*, r^*) = \int S(r^*) |\Psi(k^*, r^*)|^2 \, d^3r^* = \frac{Sgnl(k^*)}{Bckg(k^*)} \]
Traditional and non-traditional femtoscopy

\[ C(k^*, r^*) = \int S(r^*) |\Psi(k^*, r^*)|^2 d^3r^* = \frac{Sgnl(k^*)}{Bckg(k^*)} \]

Object of study of Traditional femtoscopy

Object of study of non-traditional femtoscopy

Pairs from the same collision

Pairs from the different collisions

Nature 588, 2020, (233-238)
Results
So far, the knowledge on nuclear force was derived from studies made on nucleon or / and nuclei.

**Nuclear force** between anti-nucleons is studied for the first time.

The knowledge of interaction between two anti-protons is fundamental to understand the properties of more sophisticated anti-nuclei.
a) Strong interactions between anti-nucleons

Fit results:

**p-p CF,**

$R = 2.75 \pm 0.01 \text{fm}; \quad \chi^2/\text{NDF} = 1.66;$

**antiproton-antiproton CF,**

$R = 2.80 \pm 0.02 \text{fm}, \quad f_0 = 7.41 \pm 0.19 \text{fm}, \quad d_0 = 2.14 \pm 0.27 \text{fm}; \quad \chi^2/\text{NDF} = 1.61$

$x^2/\text{NDF}(f_0, d_0)$ map of the results between measured function and fitted one to find the best values of $f_0, d_0$ parameters

*Nature 527, 345–348 (2015)*
a) Strong interactions between anti-nucleons

The scattering length $f_0$: determines low-energy scattering.

The elastic cross section, $\sigma_e$, (at low energies) determined solely by the scattering length, $\lim_{k \to 0} \sigma_e = 4\pi f_0^2$

$d_0$ - the effective range of strong interaction between two particles.
It corresponds to the range of the potential in an extremely simplified scenario - the square well potential.

$f_0$ and $d_0$ - two important parameters of strong interaction between two particles.

Theoretical correlation function depends on: source size, $k^*$, $f_0$ and $d_0$.

• $f_0$ and $d_0$ for the antiproton-antiproton interaction consistent with parameters for the proton-proton interaction.

• Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined.

• A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei.

**b) Y-N and Y-Y interactions**

**Experiment:** Studies Y–N and Y–Y interactions in progress

**Theory:** Major steps forward have been made (Lattice QCD).

Numerous theoretical predictions exist, but no clear evidence for any such bound states, despite many experimental searches.

The existence of hypernuclei is confirmed by attractive strong Y–N interaction -> indicates the possibility to bind Y to a nucleus.

The measurement of the Y–N and Y–Y interactions leads to important implications for the possible formation of Y–N or Y–Y bound states.

A precise knowledge of these interactions will have impact to the physics of neutron stars.

The structure of the neutron stars cores is still unknown, hyperons can appear there depending on the Y–N and Y–Y interactions.
The data are compatible with hypernuclei results and lattice computations. The binding energy of the possible Lambda–Lambda bound state is estimated within an effective-range expansion approach.

<table>
<thead>
<tr>
<th>N</th>
<th>lambda</th>
<th>r0</th>
<th>1/f0</th>
<th>d0</th>
<th>ares</th>
<th>rres</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>2.0 fm</td>
<td>1.0 fm</td>
<td>3.0 fm</td>
<td>-0.04</td>
<td>0.05 fm</td>
</tr>
</tbody>
</table>

**ALICE’s study**


F0 became positive!!

<table>
<thead>
<tr>
<th>1/f0</th>
<th>0.480 fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>d0</td>
<td>10.455 fm</td>
</tr>
</tbody>
</table>
The femtoscopy technique to study interactions between particles can be applied to many colliding systems at very different energies, which can help to improve the understanding of hyperon-nucleon interactions.
c) Strange Baryon Correlations (including $p-\Omega$)

A comparison of the measured correlation functions from Au+Au collisions with theoretical predictions.
Scattering length is positive and favor $p-\Omega$ bound state hypothesis.

<table>
<thead>
<tr>
<th>$V_1$</th>
<th>$V_2$</th>
<th>$V_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{bin}$ [MeV]</td>
<td>-</td>
<td>6.3</td>
</tr>
<tr>
<td>$a_0$ [MeV]</td>
<td>-1.12</td>
<td>5.79</td>
</tr>
<tr>
<td>$r_{eff}$ [MeV]</td>
<td>-1.16</td>
<td>0.96</td>
</tr>
</tbody>
</table>
c) Strange Baryon Correlations (including p-Ξ)

**First measurement** of p-Ξ correlation in Au+Au collisions at RHIC

Feed-down correction not included yet.

p-Ξ correlation shows enhancement above Coulomb interaction

Large uncertainties due to limited proton-Ξ pairs at low energy

Modeled by hadronic transport model UrQMD + an afterburner, model results

Au+Au collisions @ 3 GeV; 0 - 60% centrality
c) Strange Baryon Correlations (Including $\Xi$ Hyperons)

**First measurement** of $\Xi-\Xi$ correlation in Au+Au collisions.

**Lattice QCD/chiral EFT calculations** indicate an attractive interaction, but not strong enough to form a bound state.

The result shows anti-correlation at $Q < 0.25$ GeV/c.

Combination of quantum statistics, strong interaction, and Coulomb interaction.

Feed-down and Coulomb effects need to be evaluated for further discussion.

<table>
<thead>
<tr>
<th>N</th>
<th>lambda</th>
<th>$r_0$</th>
<th>1/f0</th>
<th>d0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>1.5fm</td>
<td>1.0 fm</td>
<td>5.0 fm</td>
</tr>
</tbody>
</table>

F0 became positive!!

<table>
<thead>
<tr>
<th>1/f0</th>
<th>0.345 fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>d0</td>
<td>2.586 fm</td>
</tr>
</tbody>
</table>
d) Neutral kaons

<table>
<thead>
<tr>
<th>Kaon correlation functions are sensitive to:</th>
<th>$K^0 K^0$</th>
<th>$K^0 K^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^\pm K^\pm$</td>
<td>Quantum Statistical effects (QS)</td>
<td>Final State Interaction (FSI)</td>
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<td></td>
</tr>
<tr>
<td>Final State Interaction (FSI)</td>
<td>Final State Interaction (FSI)</td>
<td></td>
</tr>
<tr>
<td>- Coulomb interaction (COUL)</td>
<td>- strong interaction (SI)</td>
<td></td>
</tr>
</tbody>
</table>

See D. Pawłowska talk
Kaon correlation functions are sensitive to:

- $K^\pm K^\pm$
- $K^0_s K^0_s$
- $K^0_s K^\pm$

Theoretical prediction

$q_{inv} = 2k^*$
d) Neutral kaons

Kaons can provide complementary information to pions: contain strange quarks (larger production of strange particles is one of the signatures of QGP)
- less affected by the feed-down from resonance decays
- smaller cross section on reaction with the hadronic matter

Very interesting:
- compare femtososcopic results for all possible kaon combination $(K^\pm - K^\pm, K_S^0 - K_S^0, K_S^0 - K^\pm)$;
- $K_S^0$ could be a 4-quark state
d) Neutral kaons

The strong final-state interaction has a significant effect on the neutral kaons correlation due to the near-threshold $f_0(980)$ and $a_0(980)$ resonances
The $a_0(980)$ FSI parametrization gives very good representation of the shape of the signal region in CF. The parametrization with the larger $a_0(980)$ mass and decay coupling gives larger size of the source. Antonelli parametrization favors $a_0(980)$ resonance as a tetraquark.
d) Neutral kaons

The $a_0(980)$ FSI parametrization gives very good representation of the shape of the signal region in CF

The parametrization with the larger $a_0(980)$ mass and decay coupling gives larger size of the source

Antonelli parametrization favors $a_0(980)$ resonance as a tetraquark
e) Light nuclei formation at $\sqrt{s_{NN}} = 3$ GeV

- First measurement of proton-deuteron and deuteron-deuteron correlation functions from STAR

- Proton-deuteron and deuteron-deuteron CF qualitatively described by L&L model -> deuteron-deuteron has larger emission source size than proton-deuteron

- Deuteron-deuteron CF described better by the model including coalescence. Light nuclei are likely to be formed via coalescence.
f) Nonidentical particle correlations

Same charges 0-10% @ Au+Au 39 GeV

Opposite charges 0-10% @ Au+Au 39 GeV

Determined by **Coulomb** Interactions

\[ C_0(k^*) \]

\[ k^*[\text{GeV/c}] \]

\[ C_0^0(K^- p) \text{ different shape due to strong interaction} \]

Determined by full **FSI: Coulomb and Strong** interactions (kaon-proton)

See P. Szymański poster
e) Nonidentical particles - emission asymmetry

**Same charges**

- $C^0_0(k^*)$
- $C^1_1(k^*)$
- $C^1_0(k^*)$

- Lighter particle emitted closer to the system’s center and / or later
- Heavier particle emitted closer to the system’s center and / or later

**Opposite charges**

- $C^0_0(k^*)$
- $C^1_1(k^*)$
- $C^1_0(k^*)$

- Lighter particle emitted closer to the system’s center and / or later
- Heavier particle emitted closer to the system’s center and / or later

See P. Szymański poster
e) Nonidentical particle correlations

**Like-sign 0-10% @ Au+Au 39 GeV**

Statistical uncertainties only

STAR preliminary

Determined by Coulomb Interactions

**Unlike-sign 0-10% @ Au+Au 39 GeV**

Statistical uncertainties only

STAR preliminary

Determined by full FSI: Coulomb and Strong interactions (kaon-proton)

Heavier particles freeze-out earlier


\[
\beta_f - \text{the same for both particles} \\
\beta_i \sim 1/m_T - \text{smaller for heavier particles}
\]
Conclusions & Summary
Summary

• Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined.
• A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei.
• Scattering length is positive and favor $\Lambda - \Lambda$ bound state hypothesis
• Scattering length is positive and favor $p - \Omega$ bound state hypothesis
• Searched for $\Xi - \Xi$ bounds states have started
• Antonelli parametrization of $K_S^0 - K^\pm$ strong interactions favors $a_0(980)$ resonance as a tetraquark
• d-d CF described better by the model including coalescence
• Light nuclei are likely to be formed via coalescence
• Heavier directed towards edge of the source and/or ...
• Heavier particles freeze-out earlier
Summary

• Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined.

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• Heavier directed towards edge of the source and/or ...

• Heavier particles freeze-out earlier.

Thank you for Your attention.
Back-up slides
e) Program **Beam Energy Scan**

**RHIC Top Energy**
- $p+p$, $p+Al$, $p+Au$, $d+Au$,
- $^3He+Au$, $Cu+Cu$, $Cu+Au$,
- $Ru+Ru$, $Zr+Zr$, $Au+Au$, $U+U$

QCD at high energy density/temperature

Properties of QGP, EoS

**Beam Energy Scan**

- Au+Au 7.7-62 GeV
- QCD phase transition
- Search for critical point
- Turn-off of QGP signatures

**Fixed-Target Program**
- Au+Au =3.0-7.7 GeV
- High baryon density regime
  - with 420-720 MeV
How to measure a phase transition?

Clear evolution in the freeze-out shape indicated

Lower energies: system more oblate ($R_{side} > R_{long}$)
Higher energies: system more prolate ($R_{side} < R_{long}$)

$\sqrt{s_{NN}} = 4.5$ GeV: round system ($R_{side} \approx R_{long}$)

Transition region between dynamics dominated by stopping and boost-invariant dynamics.
How to measure a phase transition?

Visible peak in $\frac{R_{out}}{R_{side}}(\sqrt{s_{NN}})$ near the $\sqrt{s_{NN}} \approx 20$ GeV

QCD calculations predict a peak near to the QGP transition threshold - signature of first-order phase transition?

Theoretical attention from hydro and transport models needed.

$R_{out}^2 - R_{side}^2 = \beta^2 t \Delta \tau^2$
How to measure a phase transition?

Pre-thermal phase → Hydrodynamical phase → Hydronic cascades

UrQMD → vHLEE → UrQMD

vHLEE + UrQMD model verify sensitivity of HBT measurements to the first-order phase transition

vHLEE (3+1)-D viscous hydrodynamics
Iu. Karpenko, P. Huovinen, H. Petersen, M. Bleicher

HadronGas + Bag Model → 1\textsuperscript{st} order PT

Chiral EoS → crossover PT (XPT)
b) Strange Baryon Correlations (Including $\Lambda$ Hyperons)

\[
C_{XY \to p\Lambda}(k_{p\Lambda}^*) = \frac{\int C_{XY}(k_{XY}^*)W(k_{XY}^*, k_{p\Lambda}^*)dk_{XY}^*}{\int W(k_{XY}^*, k_{p\Lambda}^*)dk_{XY}^*}
\]

\[
C(k_{p\Lambda}^*) = 1 + \lambda_{p\Lambda} \left( C_{p\Lambda}^*(k_{p\Lambda}^*) - 1 \right)
+ \sum_{XY} \lambda_{XY} \left( C_{XY}(k_{p\Lambda}^*) - 1 \right)
\]

HZ, A. Kisiel, M. Szymański

$r_0 = 3.0 \text{ fm}$
$\text{Re}(f_0) = 0.2 \text{ fm}$
$\text{Im}(f_0) = 0.88 \text{ fm}$