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The proton-Ω correlation function in Au + Au collisions at sNN=200GeV

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We present the first measurement of the proton-Ω correlation function in heavy-ion collisions for central (0-40%) and peripheral (40-80%) Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV by the STAR experiment at the Relativistic Heavy-Ion Collider (RHIC). Predictions for the ratio of peripheral collisions to central collisions for the proton-Ω correlation function are sensitive to the presence of a nucleon-Ω bound state. These predictions are based on the proton-Ω interaction extracted from (2+1)-flavor lattice QCD calculations at the physical point. The measured ratio of proton-Ω correlation function from peripheral (small system) to central (large system) collisions is less than unity for relative momentum smaller than 40 MeV/c. Comparison of our measured correlation ratio with the theoretical calculation slightly favors a proton-Ω bound system with a binding energy of \(\sim 27\) MeV.
**INTRODUCTION**

The study of nucleon-nucleon (NN), hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions are of fundamental importance in understanding relativistic heavy-ion collisions [1, 2]. modeling of neutron stars [3, 4] and examining the existence of various exotic hadrons [7, 9]. A significant amount of NN scattering data acquired over the years allows us to construct precise NN potential models [10, 11]. The availability of nominal YN scattering data and no scattering data for the multi-strange YY systems makes the task of constructing YY potentials very challenging. With the development of sophisticated computational techniques, it has become possible to carry out first principle calculations based on lattice Quantum Chromodynamics (QCD) to provide constraints on some of the NN, YY and YN interactions [11, 15]. Very often the experimental information on the bound states of strange baryons and nucleons (hypernuclei) is used to provide information on YY interactions [16, 18]. However, this method becomes difficult to use because these measurements are contaminated by many-body effects, which makes it very difficult to extract NΞ, NΩ, ΥΞ and ΥΩ interactions.

High-energy heavy-ion collisions produce a sizable number of hyperons in each collision [19], which provides an excellent opportunity to study the NN, YY and YN interactions. Measurement of two-particle correlations at low relative momentum, also known as femtoscopy, have been used to study the space-time dynamics of the source created in heavy-ion collisions. In addition to this, the measurement of two-particle correlations at low relative momentum can also be used to measure final state interactions (FSI) between NN, YY and YN. This approach has been used by the STAR experiment at RHIC to extract the FSI for ΛΛ [20] and antiproton-antiproton [21].

Recent study of (2+1)-flavor lattice QCD simulations for heavy quark masses shows that the nucleon-Ω interaction (NΩ) is attractive at all distances [15]. Using this NΩ interaction, it is shown that the shape of the two particle correlation function at low relative momentum changes substantially with the strength of the NO attraction [22]. However, the presence of the Coulomb interaction in the proton-Ω channel makes it difficult to access the strong interaction directly from the measured two-particle correlation function. Therefore, a new measure, namely the ratio of the correlation functions between the peripheral (small) and central (large) collision systems is proposed in Ref [22]. This ratio provides direct access to strong interaction between proton and Ω, independent of the model used for the emission source.

The attractive nature of an NΩ interaction leads to the possible existence of the NΩ dibaryon with strangeness = -3, spin = 2, and isospin = 1/2, which was first proposed in [23]. Such an NΩ dibaryon is the most interesting candidate after the H-dibaryon [7]. The Pauli exclusion principle does not apply among quarks in the NΩ dibaryon and it is stable against strong decay [28, 29]. Several attempts have been made to estimate the binding energy of the NΩ state in different QCD motivated models [15, 30]. The NΩ dibaryon can be produced in high-energy heavy-ion collisions through the coalescence mechanism [31]. For an S-wave bound state of nucleon and Ω, the strong decays to octet-decuplet systems are prohibited by kinematics and those into octet-octet systems (e.g. ΛΛ) are suppressed dynamically due to the D-wave nature [15]. This makes direct searches via the invariant mass method very challenging in heavy-ion collisions. The measurement of the proton-Ω correlation function for peripheral and central Au+Au collisions at √sNN = 200 GeV, presented in this Letter, will provide insight into the existence of an NΩ dibaryon.

**DATA ANALYSIS**

STAR is a large acceptance detector at RHIC [32]. The measurements presented in this Letter are from the data taken for Au+Au collisions at √sNN = 200 GeV in 2011 and 2014. 5.30 × 10^8 minimum bias events from 2011 and 8.76 × 10^8 minimum bias events from 2014 were analyzed. The tracking and particle identification for the measurements were provided by the Time Projection Chamber (TPC) [33] and Time-of-Flight (TOF) [34] detectors. These detectors are located in a 0.5 T magnetic field, which allows determination of the momentum and charge of the particles traversing the TPC. Minimum bias triggered events were selected by requiring coincident signals at forward and backward rapidities in the Vertex Position Detectors (VPD) [35] and requiring a signal at mid-rapidity in the TOF. Centrality was determined by the charged particle multiplicity at mid-rapidity (|η| < 0.5) in the TPC. To suppress events from collisions with the beam pipe, the reconstructed primary vertex was required to lie within ±40 and ±6 cm of the center of the detector for the data from years 2011 and 2014, respectively.

**Ω IDENTIFICATION**

The TPC was used for tracking, decay topology and identification of particles for Ω (Λ) reconstruction in the pseudorapidity range |η| < 1. To reconstruct the Ω (Λ), the decay channel Ω(Λ) → ΛK−(ΛK+) with a branching ratio of 67.8%, with subsequent decay Λ(Λ) → pπ−(pπ+) (branching ratio of 63.9%) was used [36]. The Λ (Λ) candidates were formed from pairs of p (p) and π− (π+) tracks whose trajectories pointed to a common secondary decay vertex, which was well separated from the Ω (Λ) vertex. These Λ (Λ) candidates were then combined with bachelor K− (K+) tracks, which points to a
common decay vertex well separated from the primary vertex. The decay length (DL) of an Ω (Ω) candidate was required to be larger than 4 cm from the primary vertex. As listed in Table II additional selection criteria on the distance of closest approach (DCA) between the two Λ (Λ) daughter tracks, between the Λ (Λ) and bachelor track, the Λ (Λ) and the primary vertex position were applied to select Ω (Ω). Furthermore, the pointing angle of Ω (Ω) track with respect to the primary vertex (∥rΩ − rPV∥/∥rΩ − rPV∥∥pΩ∥), where r is the position of Ω and primary vertex, respectively and pΩ is the momentum of Ω) were applied to select Ω (Ω). To reduce the combinatorial background, Λ (Λ) candidates were selected in the invariant mass range between 1.112 and 1.120 GeV/c². In addition, the candidates due to misidentification of π⁻ (π⁺) tracks as the bachelor K⁻ (K⁺) tracks were removed by checking a Ξ hypothesis. The invariant mass distributions of combined Ω and Ω candidates for 0-40% and 40-80% Au+Au collisions at √sNN=200 GeV for the transverse momentum (p_T) ranges 1.5<p_T<2.0 GeV/c (a) and 3.0<p_T<3.5 GeV/c (b). The invariant mass distributions of combined Ω and Ω sample for 40-80% Au+Au collisions at √sNN=200 GeV for the transverse momentum (p_T) range 1.5<p_T<2.0 GeV/c (c) and 3.0<p_T<3.5 GeV/c (d). The solid lines at 1.665 and 1.679 GeV/c² show the mass region of the reconstructed Ω and Ω candidates used for the measurement of the proton-Ω correlation function.

PROTON IDENTIFICATION

The TOF and TPC detectors were used for proton (antiproton) identification in the pseudorapidity range |η| < 1. The proton tracks were selected if their DCA was less than 0.5 cm to the primary vertex, greater than 20 points were measured out of a maximum of 45, and the number of points used in track reconstruction divided by the number of possible points was greater than 0.52 in order to prevent split tracks. The time of flight of the particles reaching the TOF detector along with the tracking information from the TPC detector was used to calculate the square of the particle mass (m²) to identify protons. Figure 2 shows m² from the TOF detector versus momentum from the TPC. All candidates with invariant mass between 1.665 and 1.679 GeV/c² were used in the analysis.

TWO-PARTICLE CORRELATION FUNCTION

The two-particle correlation function is defined as:

\[ C_2(M) = \frac{\sum_{i,j} n_i n_j}{\sum_{i} n_i} \]

where \( n_i \) and \( n_j \) are the number of events in the mass bins \( i \) and \( j \), respectively.
TABLE I. Selection criteria for Ω and Ω̄ reconstruction.

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>0-40%</th>
<th>40-80%</th>
<th>All ( p_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Omega ) DCA</td>
<td>&lt; 0.6 cm</td>
<td>&lt; 0.7 cm</td>
<td>&lt; 0.8 cm</td>
</tr>
<tr>
<td>( \Lambda ) DCA</td>
<td>&gt; 0.4 cm</td>
<td>&gt; 0.3 cm</td>
<td>&gt; 0.3 cm</td>
</tr>
<tr>
<td>DL(( \Omega ))</td>
<td>&gt; 4.0 cm</td>
<td>&gt; 4.0 cm</td>
<td>&gt; 4.0 cm</td>
</tr>
<tr>
<td>DL(( \Lambda ))</td>
<td>&gt; 6.0 cm</td>
<td>&gt; 6.0 cm</td>
<td>&gt; 5.0 cm</td>
</tr>
<tr>
<td>(</td>
<td>(\vec{r}<em>\Omega - \vec{r}</em>{PV}) \times \vec{p}_0</td>
<td>/</td>
<td>\vec{r}<em>\Omega - \vec{r}</em>{PV}</td>
</tr>
<tr>
<td>( DL(\Omega) &lt; DL(\Lambda) )</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>proton DCA</td>
<td>&gt; 0.8 cm</td>
<td>&gt; 0.8 cm</td>
<td>&gt; 0.6 cm</td>
</tr>
<tr>
<td>pion DCA</td>
<td>&gt; 2.0 cm</td>
<td>&gt; 2.0 cm</td>
<td>&gt; 1.8 cm</td>
</tr>
<tr>
<td>bachelor DCA</td>
<td>&gt; 1.2 cm</td>
<td>&gt; 1.2 cm</td>
<td>&gt; 1.0 cm</td>
</tr>
<tr>
<td>proton to pion DCA</td>
<td>&lt; 0.8 cm</td>
<td>&lt; 0.8 cm</td>
<td>&lt; 1.0 cm</td>
</tr>
<tr>
<td>( \Lambda ) DCA to bachelor</td>
<td>&lt; 0.8 cm</td>
<td>&lt; 0.8 cm</td>
<td>&lt; 1.0 cm</td>
</tr>
<tr>
<td>(</td>
<td>M_\Lambda - 1.1156</td>
<td>) GeV/( c^2 )</td>
<td>&lt; 0.007 GeV/( c^2 )</td>
</tr>
<tr>
<td>(</td>
<td>M_\Omega - 1.672</td>
<td>) GeV/( c^2 )</td>
<td>&lt; 0.007 GeV/( c^2 )</td>
</tr>
</tbody>
</table>

For the particles in the pair rest frame, for a proton and antiproton. The selected sample of proton candidates also included secondary protons from \( \Lambda \), \( \Sigma \) and \( \Xi \) decays. The purity of the proton sample is obtained as a product of identification probability and fraction of primary protons. The selected sample of proton candidates also included secondary protons from \( \Lambda \), \( \Sigma \) and \( \Xi \) decays. The estimated fraction of primary protons (antiprotons) from thermal model [37] studies is 52% (48%) [38]. The purity of the proton sample is obtained as a product of identification probability and fraction of primary protons. The pair purity is 0.2 (0.36) for 0-40% (40-80)% centrality and is constant over the analyzed range of invariant relative momentum.

The effect of momentum resolution on the correlation functions has also been investigated using simulated tracks from \( \Omega \) decay and tracks for protons, with known momenta, embedded into real events. Correlation functions have been corrected for momentum resolution using the expression:

\[
C'(k^*) = \frac{C_{\text{measured}}(k^*) - 1}{P(k^*)} + 1,
\]

where the pair purity, \( P(k^*) \), was calculated as a product of \( S/(S + B) \) for the \( \Omega \) (\( \bar{\Omega} \)) and purity of the proton (antiproton). Correlations to the raw correlation functions were applied according to the expression:

\[
C(k^*) = \frac{C_{\text{measured}}(k^*)}{C_{\text{res}}(k^*)},
\]

where \( C(k^*) \) represents the corrected correlation function, and \( C_{\text{in}}(k^*)/C_{\text{res}}(k^*) \) is the correction factor. \( C_{\text{in}}(k^*) \) was calculated without taking into account the effect of momentum resolution and \( C_{\text{res}}(k^*) \) included the effect of momentum resolution applied to each \( \Omega \) and proton candidates. More details related to these corrections.
FIG. 3. Measured correlation function (C(k')) for proton-Ω and antiproton- ¯Ω (PΩ + ¯PΩ) for (0-40)% (a) and (40-80)% (b) Au+Au collisions at √s_{NN} = 200 GeV. The triangles represent raw correlations, open circles represent pair-purity corrected (PP) correlations, and solid circles represent pair-purity and smearing corrected (PP+SC) correlations. The error bars correspond to statistical errors and caps correspond to the systematic errors. The predictions from [22] for proton-Ω interaction potentials V_I, V_{II} and V_{III} for source sizes R_p = R_Ω = 5 fm and R_p = R_Ω = 2.5 fm are shown in (a) and (b) respectively.

can be found in Ref. [39]. The impact of momentum resolution on correlation functions is negligible compared with statistical errors.

To study the shape of correlation function for the background, the candidates from the side-bands of invariant mass of Ω are chosen in the range M < 1.665 GeV/c^2 and M > 1.679 GeV/c^2. These selected candidates are then combined with the proton tracks from the same event to construct the relative momentum for the same event. The relative momentum for the mixed event is generated by combining the selected candidates from the side-band of invariant mass of Ω with protons from different events with approximately the same vertex position along the z-direction.

RESULTS AND DISCUSSION

After applying the selection criteria for proton and Ω identification, as mentioned in the data analysis section, a total of 38065±195 (8816±94) and 3037 ±55 (679±26) pairs of proton-Ω and antiproton- ¯Ω for k' <0.2 (0.1) GeV/c are observed for (0-40)% and (40-80)% Au+Au collisions, respectively. The measured proton-Ω and antiproton-Ω correlation functions, PΩ + ¯PΩ, the correlation functions after corrections for pair purity, PΩ + ¯PΩ (PP), and the correlation function after corrections for pair purity and momentum smearing, PΩ + ¯PΩ (PP+SC), for 0-40% and 40-80% Au+Au collisions at √s_{NN} = 200 GeV are shown in Figures 3(a) and 3(b). The systematic errors for the measured proton-Ω correlation function were estimated by varying the following requirements for the selection of Ω candidates: the decay length, DCA of Ω to the primary vertex, pointing angle cuts and mass range, which affect the purity of the Ω sample. The DCA and m^2 requirements were varied to estimate systematic from the proton purity. In addition, systematic errors from normalization and feed-down contributions were also estimated. The systematic errors from different sources were then added in quadrature. The combined systematic errors are shown in Figure 3 as caps for each bin of the correlation function.

Predictions for the proton-Ω correlation function from [22] for proton-Ω interaction potentials V_I, V_{II} and V_{III} for a static source with sizes R_p = R_Ω = 5 fm and R_p = R_Ω = 2.5 fm are also shown in Figure 3(a) and Figure 3(b). The selected source sizes are not fit to the experimental data. The choice of the potentials in Ref. [22] is based on an attractive NΩ interaction in the ^5S_2 channel from the lattice QCD simulations with heavy u-, d-, s- quarks from Ref. [15]. The potential V_{II} is obtained by fitting the lattice QCD data with a function V(r) = b_1 e^{-b_2 r^2} + b_3 (1 - e^{-b_4 r^2})/(e^{-b_5 r}/r)^2, where b_1 and b_3 are negative and b_2, b_4 and b_5 are positive, which represents a case with shallow NΩ bound state. Two more potentials V_I and V_{III} represent cases without a NΩ bound state and a deep NΩ bound state, respectively. Binding energy (E_b), scattering length (a_0) and effective range (r_{eff}) for the NΩ interaction potentials V_I, V_{II} and V_{III} are listed in Table II [22]. The measured correlation functions for PΩ + PΩ are in agreement with the predicted trend for the PΩ correlation functions with inter-
action potentials $V_I$, $V_H$ and $V_{III}$ for the 0-40% Au+Au collisions as shown in Figure 3(a). However, due to limited statistics at lower $k^*$, strong enhancement due to Coulomb interaction is not visible in the 40-80% Au+Au collisions in Figure 3(b).

![Image](image.png)

<table>
<thead>
<tr>
<th>Spin-2 p\Omega potentials</th>
<th>$V_I$</th>
<th>$V_H$</th>
<th>$V_{III}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_b$ (MeV)</td>
<td>-</td>
<td>6.3</td>
<td>26.9</td>
</tr>
<tr>
<td>$a_0$ (fm)</td>
<td>-1.12</td>
<td>5.79</td>
<td>1.29</td>
</tr>
<tr>
<td>$r_{eff}$ (fm)</td>
<td>1.16</td>
<td>0.96</td>
<td>0.65</td>
</tr>
</tbody>
</table>

TABLE II. Binding energy ($E_b$), scattering length ($a_0$) and effective range ($r_{eff}$) for the Spin-2 proton-\Omega potentials [22].

The Coulomb interaction between the positively charged proton and negatively charged \Omega introduces a strong enhancement in the correlation function at small $k^*$, as seen in Figure 3. The same ratio, $R$, for the background is unity as shown as open crosses in Figure 4. Previous measurements of source size for $\pi-\pi$, $K^0_{S}-K^0_{S}$, proton-proton and proton-\Lambda correlations show that the source size decreases as the transverse mass increases [21, 38, 41]. Using this transverse mass dependence [41], the expected source size for proton-\Omega is 2-3 fm for peripheral collisions and 3-5 fm for central collisions. The predictions for the ratio of small system to large system from Refs. [22, 12] for proton-\Omega interaction potentials $V_I$, $V_H$ and $V_{III}$ for static source with different source sizes (S,L) = (2.3), (2,4), (2.5, 5) and (3,5) fm, where S and L correspond to small and large collision system, are shown in Figure 3(a-d). A small variation in the source size does not change the characteristic of the ratio for the choice of three potentials.

Predictions for the ratio of small to large system with the effects of collective expansion are also shown in the Figure 4(e) [22]. The transverse source sizes are taken as $R_{tr}^p = R_{tr}^{\Omega}$ = 2.5 fm for small system and $R_{tr}^p = R_{tr}^{\Omega}$ = 5 fm for large system. The temperature at the thermal freeze-out is $T_p$ = 164 MeV for peripheral collisions and $T_p$ = 120 MeV for the central collisions [13,14] and the proper-time at the thermal freeze-out is $\tau_p(t_{\Omega}) = 3(2)$ fm/c for the peripheral collisions and $\tau_p(t_{\Omega}) = 20(10)$ fm/c for the central collisions [15].

The predictions with expanding source for the proton-\Omega interaction potentials $V_I$ and $V_H$ are 3\sigma larger than the data at $k^* = 20$ MeV/c. The prediction for the proton-\Omega interaction potential $V_{III}$ with expanding source and static source are within 1\sigma of the data at $k^* = 20$ MeV/c. As shown in Figure 4, the measured ratios at $k^* = 20$ and 60 MeV/c are $R = 0.28 \pm 0.03_{stat} \pm 0.03_{sys}$ (background $= 0.96 \pm 0.13_{stat}$) and $R = 0.81 \pm 0.22_{stat} \pm 0.08_{sys}$ (background $= 0.97 \pm 0.05_{stat}$), respectively. Comparing these values with the model calculations shown in Figure 5(b) of the Ref. [22], where a bound state with $E_b \sim 27$ MeV for the proton-\Omega system is assumed in calculation, we conclude that our data favor a positive scattering length for the proton-\Omega interactions. The positive scattering length and the measured ratio of proton-\Omega correlation function from peripheral to central collisions less than unity for $k^* < 40$ MeV/c favors the proton-\Omega interaction potential $V_{III}$ with $E_b \sim 27$ MeV for proton and \Omega.

CONCLUSIONS

The first measurement of the proton-\Omega correlation function in heavy-ion collisions for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is presented in this Letter. The measured ratio of proton-\Omega correlation function from peripheral to central collisions is compared with the predictions based on proton-\Omega interaction extracted from (2+1)-flavor lattice QCD simulations. At present, due to limited statistics, it is not possible to extract the interaction parameters. However the measured ratio of proton-\Omega correlation function from peripheral to central collisions less than unity for $k^* < 40$ MeV/c within 1\sigma indicates that the scattering length is positive for the proton-\Omega interaction and favors the proton-\Omega bound state hypothesis.

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FIG. 4. The solid circle represents the ratio \( R \) of small system (40-80% collisions) to large system (0-40% collisions) for proton-\( \Omega \) and antiproton-\( \bar{\Omega} \) \( (P\Omega + \bar{P}\bar{\Omega}) \). The error bars correspond to the statistical errors and caps correspond to systematic errors. The open crosses represent the ratio for background candidates from the side-band of \( \Omega \) invariant mass. Predictions for the ratio of small system to large system \([22, 42]\) for proton-\( \Omega \) interaction potentials \( V_{I}, V_{II} \) and \( V_{III} \) for static source with different source sizes \((S,L) = (2,3), (2,4), (2.5, 5) \) and \((3,5) \) fm, where \( S \) and \( L \) corresponding to small and large systems, are shown in (a), (b), (c) and (d) respectively. In addition, the prediction for the expanding source is shown in (e).

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