Coherent $\rho^0$ Production in Ultraperipheral Heavy-Ion Collisions

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In ultraperipheral heavy-ion collisions, the two nuclei geometrically “miss” each other and no hadronic nucleon-nucleon collisions occur. At impact parameters $b$ significantly larger than twice the nuclear radius $R_A$, the nuclei interact by photon exchange and photon-photon or photon-Pomeron collisions [1]. Examples are nuclear Coulomb excitation, electron-positron pair and meson production, and vector meson production. The exchange bosons can couple coherently to the nuclei, yielding large cross sections. Coherence restricts the final states to low transverse momenta, consistent with coherent coupling to both nuclei. The cross sections at $\sqrt{s_{NN}} = 130$ GeV agree with theoretical predictions treating $\rho^0$ production and Coulomb excitation as independent processes.

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FIG. 1. Diagram for (a) exclusive $\rho^0$ production in ultraperipheral heavy-ion collisions, and (b) $\rho^0$ production with nuclear excitation. The dashed lines indicate factorization.
the emission of charged particles, nearly all nuclear decays following photon absorption include neutron emission [9].

The photon and Pomeron can couple coherently to the gold nuclei. The wavelength $\lambda_{\gamma p} > 2R_A$ leads to coherence conditions: a low transverse momentum of $p_T < \pi \hbar / R_A$ ($\sim 90$ MeV/c for gold with $R_A \sim 7$ fm), and a maximum longitudinal momentum of $p_{\parallel} < \sqrt{\gamma A} / R_A$ ($\sim 6$ GeV/c at $\gamma = 70$), where $\gamma$ is the Lorentz boost of the nucleus. The photon flux is proportional to the square of the nuclear charge $Z$ [3], and the forward cross section for elastic $\rho^0A$ scattering $d\sigma / dz/A^2$ scales as $A^{2/3}$ for surface coupling and $A^2$ in the bulk limit. At a center-of-mass energy of $\sqrt{s_{NN}} = 130$ GeV per nucleon-nucleon pair, a total $\rho^0$ cross section, regardless of nuclear excitation, $\sigma(AuAu \rightarrow Au^{(*)}Au^{(*)}\rho^0) = 350$ mb is predicted from a Glauber extrapolation of $\gamma p \rightarrow \rho^0p$ data [5]. Calculations for coherent $\rho^0$ production with nuclear excitation assume that both processes are independent, sharing only a common impact parameter [5,7].

In the year 2000, the RHIC at Brookhaven National Laboratory collided gold nuclei at $\sqrt{s_{NN}} = 130$ GeV. In the Solenoidal Tracker at RHIC (STAR) [10], charged particles are reconstructed with a cylindrical time projection chamber (TPC) [11] operated in a 0.25 T solenoidal magnetic field. A central trigger barrel (CTB) of 240 scintillator slats surrounds the TPC. Two zero degree hadron calorimeters (ZDCs) at $\pm 18$ m from the interaction point are sensitive to the neutral remnants of nuclear breakup, with 98 ± 2% acceptance for neutrons from nuclear breakup through Coulomb excitation [8,12].

Exclusive $\rho^0$ production has a distinctive signature: the $\pi^+\pi^-$ from the $\rho^0$ decay in an otherwise “empty” detector. The tracks are approximately back to back in the transverse plane due to the small $p_T$ of the pair. The gold nuclei remain undetected within the beam.

Two data sets are used in this analysis. For AuAu $\rightarrow$ AuAu$\rho^0$, about 30 000 events were collected using a low-multiplicity “topology” trigger. The CTB was divided in four azimuthal quadrants. Single hits were required in the opposite side quadrants; the top and bottom quadrants acted as vetoes to suppress cosmic rays. A fast on-line reconstruction [13] removed events without reconstructable tracks from the data stream. To study AuAu $\rightarrow$ AuAu$\rho^0$, a data set of about 800 000 “minimum bias” events, which required coincident detection of neutrons in both ZDCs as a trigger, is used.

Events are selected with exactly two oppositely charged tracks forming a common vertex within the interaction region. The $\rho^0$ candidates are accepted within a rapidity range $|y| < 1$. A systematic uncertainty of 5% is assigned to the number of $\rho^0$ candidates by varying the event selection criteria. The specific energy loss $dE/dx$ in the TPC shows that the event sample is dominated by pion pairs. Without the ZDC requirement in the topology trigger, cosmic rays are a major background. They are removed by requiring that the two pion tracks have an opening angle of <3 rad. Using the energy deposits in the ZDCs, we select events with at least one neutron ($xn$, $xn$), exactly one neutron ($1n$, $1n$), or no neutrons ($0n$, $0n$) in each ZDC, and events with at least one neutron in exactly one ZDC ($xn$, $0n$); the latter two occur only in the topology trigger. A 10% uncertainty arises from the selection of single neutron signals.

The uncorrected transverse momentum spectra of pion pairs for the two-track event samples of the topology triggers ($0n$, $0n$) and the minimum bias trigger ($xn$, $xn$) are shown in Fig. 2. Both spectra are peaked at $p_T < 50$ MeV/c, as expected for coherent coupling. A background model from like-sign combination pairs, normalized to the signal at $p_T > 200$ MeV/c, is not peaked. For comparison, the $p_T$ spectra from Monte Carlo simulations [5] discussed below are shown. They are normalized to the $\rho^0$ signal at $p_T < 150$ MeV/c and added to the background. The $M_{\pi\pi}$ invariant mass spectra (c.f. Figure 4) for both event samples are peaked around the $\rho^0$ mass. We find $131 \pm 14$ ($0n$, $0n$) and $656 \pm 36$ ($xn$, $xn$) events at $p_T < 150$ MeV/c, which we define as coherent $\rho^0$ candidates.

The data contain combinatorial background contributions from grazing nuclear collisions and incoherent photon-nucleon interactions, which are statistically subtracted. Incoherent $\rho^0$ production, where a photon interacts with a single nucleon, yields high $p_T$ $\rho^0$, which are suppressed by the low pair $p_T$ requirement; the remaining small contribution is indistinguishable from the coherent process. A coherently produced background arises from the misidentified two-photon process AuAu $\rightarrow$ AuAu$^{(*)}$AuAu$^{(*)}l^+l^-$. It contributes mainly at low invariant mass $M_{\pi\pi} < 0.5$ GeV/c$^2$. Electrons with momenta $p < 140$ MeV/c can be identified by their energy loss $dE/dx$. About 30 $e^+e^-$ pairs, peaked at low pair $p_T \sim 20$ MeV/c, were detected in the minimum bias data sample [14]. They are extrapolated to the full phase space using a Monte Carlo simulation that describes $e^+e^-$ pair

![FIG. 2 (color online). The $p_T$ spectra of pion pairs for the two-track events selected by (a) the topology trigger ($0n$, $0n$) and (b) the minimum bias trigger ($xn$, $xn$). Points are oppositely charged pairs, and the shaded histograms are the normalized like-sign combinatorial background. The open histograms are simulated $\rho^0$ superimposed onto the background.](image-url)
production by lowest order perturbation theory [15]. Electron-positron pairs contribute 4% ± 1% to the signal at p < 150 MeV/c and M<sub>ll</sub> ± 0.3 GeV/c. For a given M<sub>ll</sub>, muons have lower momenta than the corresponding electrons and are less likely to be detected. Their < 2% contribution to the coherent signal, as well as the contribution from ω decays, are neglected.

The acceptance and reconstruction efficiency were studied using a Monte Carlo event generator that reproduces the expected kinematic and angular distributions for ρ<sup>0</sup> production with and without nuclear excitation [5,16], coupled with a full detector simulation. The ρ<sup>0</sup> decay angle distribution is consistent with s-channel helicity conservation. The ρ<sup>0</sup> production angles are not reconstructed since the AuAu scattering plane cannot be determined. The efficiencies are almost independent of p<sub>T</sub> and the reconstructed invariant mass M<sub>ll</sub>. For the minimum bias trigger, 42% ± 5% of all ρ<sup>0</sup> within |y| < 1 are reconstructed. The topology trigger vetoes the top and bottom of the TPC, reducing the geometrical acceptance. Pions with p<sub>T</sub> < 100 MeV/c do not reach the CTB, effectively excluding pairs with M<sub>ll</sub> < 500 MeV/c<sup>2</sup>. Only 7% ± 1% of all ρ<sup>0</sup> with |y| < 1 are reconstructed in the topology trigger. The p<sub>T</sub> resolution is 9 MeV/c. The M<sub>ll</sub> and rapidity resolutions are 11 MeV/c<sup>2</sup> and 0.01.

The rapidity distribution of ρ<sup>0</sup> candidates (xn, xn) from the minimum bias data is shown in Fig. 3(a). It is well described by the reconstructed events from a simulation, which includes nuclear excitation [5]. The generated rapidity distribution is also shown. The acceptance is small for |y| > 1, so this region is excluded from the analysis. Cross sections are extrapolated from |y| < 1 to the full 4π acceptance by σ<sub>4π</sub>/σ<sub>y<sub>1</sub></sub> = 1.9 for ρ<sup>0</sup> production with nuclear breakup, and σ<sub>4π</sub>/σ<sub>y<sub>1</sub></sub> = 2.7 for ρ<sup>0</sup> production without nuclear breakup. A 15% uncertainty in the extrapolations is estimated by varying the Monte Carlo parameters. Event rapidity and photon energy are related by y = ±(1/2) ln(2E<sub>γ</sub>/M<sub>ll</sub>). After accounting for the ambiguity of photon emitter and scattering target, the average photon energy ⟨E<sub>γ</sub⟩⟩ ~ 50 GeV is independent of rapidity.

The minimum bias data sample has an integrated luminosity of L = 59 mb<sup>−1</sup>. The luminosity was measured by counting hadronic collisions [17]. We assume a total gold-gold hadronic cross section of 7.2 b [7]; its uncertainty dominates the 10% systematic uncertainty of L.

The differential cross section dσ/(γAu → ρAu)/dt ∝ dσ/(γAu → ρAu)/dp<sub>T</sub><sup>2</sup> for the (xn, xn) events is shown in Fig. 3(b). Here, the combinatorial background is subtracted. The photon flux is determined integrating the photon spectrum of a relativistic nucleus over the impact parameter space [5]. In ultraperipheral collisions, dσ/dt reflects not only the nuclear form factor, but also the photon p<sub>T</sub> distribution and the interference of production amplitudes from both gold nuclei. The interference arises since both nuclei can be either the photon source or the scattering target [18]. A detailed study of this effect is beyond the scope of this paper. From a fit to dσ/(AuAu)/dt ∝ e<sup>−bt</sup>, we obtain a forward cross section dσ/(AuAu)/dt|<sub>t=0</sub> = 965 ± 140 ± 230 mb/GeV<sup>2</sup> and an approximate gold radius of R<sub>g</sub> = 1/√b = 7.5 ± 2 fm, comparable to previous results [2].

The dσ/(AuAu → Au<sup>+</sup>Au<sup>−</sup>)/dM<sub>ll</sub> invariant mass spectrum for the (xn, xn) events with pair p<sub>T</sub> < 150 MeV/c is shown in Fig. 4; the (0n, 0n) events have a similar dσ/dM<sub>ll</sub> spectrum. Three different parametrizations are applied:

\[
dσ/dM<sub>ll</sub> = f_pBW(M<sub>ll</sub>) + f_I(M<sub>ll</sub>) + f_p, \quad (1)
\]

\[
dσ/dM<sub>ll</sub> = \left| A \frac{M<sub>ll</sub>\Gamma_p}{M<sub>ll</sub>^2 - M_p^2 + iM_p\Gamma_p} + B \right|^2 + f_p, \quad (2)
\]
\[ \frac{d\sigma}{dM_{\pi\pi}} = f_\rho BW(M_{\pi\pi})(m_{\pi}/M_{\pi\pi})^n + f_p. \]  

Equation (1) is a relativistic Breit-Wigner, \( BW = M_{\pi\pi}M_{\rho}G_{\rho} / [(M_{\rho}^2 - M^2_{\pi\pi})^2 + M_{\rho}^2G_{\rho}^2], \) for \( \rho \) production plus a Söding interference term \[19\], \( I(M_{\pi\pi}) = (M_{\rho}^2 - M_{\pi\pi}^2) / [(M_{\rho}^2 - M_{\pi\pi}^2)^2 + M_{\rho}^2G_{\rho}^2] \), Eq. (2) is a modified Söding parametrization \[20\], and Eq. (3) is a phenomenological Ross-Stodolsky parametrization \[21\]. Here, \( \Gamma_{\rho} = \Gamma_0 \cdot (M_{\rho}/M_{\pi\pi}) \cdot [(M_{\pi\pi}^2 - 4m_n^2)/(M_{\rho}^2 - 4m_n^2)]^{3/2} \) is the momentum-dependent width, and \( f_p \) is a fixed second order polynomial describing the residual background. The fit parameters are given in Table I. The \( \rho \) mass and width are consistent with accepted values \[22\]; they were fixed to reduce the number of degrees of freedom to obtain \( |B/A|, f_1/f_\rho \), and \( n \). Our results are consistent with values found for the same parametrizations in the topography trigger data. Grazing nuclear collisions do not contribute to \( \sigma_{0n,0n}^p \) and \( \sigma_{n,n}^p \), since they yield neutron signals in both ZDCs. From \( \sigma(AuAu \rightarrow Au_n^+Au_n^-\rho^0) \), we estimate \( \sigma(AuAu \rightarrow Au_n^+Au_n^-\rho^0) = 370 \pm 170 \pm 80 \text{ mb} \), \( \sigma(AuAu \rightarrow Au_n^+Au_n^-\rho^0) = 95 \pm 60 \pm 25 \text{ mb} \), and the total cross section for coherent \( \rho \) production \( \sigma(AuAu \rightarrow Au_n^+Au_n^-\rho^0) = 460 \pm 220 \pm 110 \text{ mb} \). Table II compares our results to the calculations of Ref. \[5\]. The calculation for \( \sigma_{n,n}^p \) excludes grazing nuclear collisions; it is therefore compared to our value without the overlap correction. Recent predictions \[24\] are about 50% higher than in Ref. \[5\] without giving specific numbers for \( \sqrt{s_{NN}} = 130 \text{ GeV} \).

In summary, the first measurements of coherent \( \rho \) production with and without accompanying nuclear excitation, \( AuAu \rightarrow Au_n^+Au_n^-\rho^0 \) and \( AuAu \rightarrow AuAu^0 \), confirm the existence of vector meson production in ultra-peripheral heavy-ion collisions. The \( \rho^0 \) production is produced at small transverse momentum, showing the coherent coupling to both nuclei. The cross sections at \( \sqrt{s_{NN}} = 130 \text{ GeV} \) are in agreement with theoretical calculations.

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<table>
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<tr>
<th>Cross section</th>
<th>STAR (mb)</th>
<th>Ref. [5] (mb)</th>
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</thead>
<tbody>
<tr>
<td>( \sigma_{n,n}^p )</td>
<td>28.3 ± 2.0 ± 6.3</td>
<td>27</td>
</tr>
<tr>
<td>( \sigma_{1n,1n}^p )</td>
<td>2.8 ± 0.5 ± 0.7</td>
<td>2.6</td>
</tr>
<tr>
<td>( \sigma_{n,n}^{inc , overlap} )</td>
<td>39.7 ± 2.8 ± 9.7</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>( \sigma_{0n,0n}^p )</td>
<td>95 ± 60 ± 25</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>( \sigma_{0n,0n}^{inc , overlap} )</td>
<td>370 ± 170 ± 80</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>( \sigma_{total}^p )</td>
<td>460 ± 220 ± 110</td>
<td>350</td>
</tr>
</tbody>
</table>

TABLE II. Comparison of predictions from \[5\]. The uncertainties are highly correlated.
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