Ultra-peripheral heavy ion collisions involve long range electromagnetic interactions at impact parameters larger than twice the nuclear radius, where no nucleon-nucleon collisions occur. The first observation of coherent $\rho^0$ production with and without accompanying nuclear breakup, $AuAu \rightarrow Au^*Au^* \rho^0$ and $AuAu \rightarrow AuAu \rho^0$ respectively, and the observation of $e^+e^-$ pair production $AuAu \rightarrow Au^*Au^*e^+e^-$ are presented by the STAR collaboration. The transverse momentum spectra are peaked at low $p_T$, showing the coherent coupling to the nuclei. A clear $\rho^0$ signal is observed in the two pion invariant mass spectrum.

In ultra-peripheral heavy ion collisions, photo-nuclear interactions take place at impact parameters $b$ larger than twice the nuclear radius $R_A$, where no nucleon-nucleon collisions occur. The large charge of a relativistic heavy nucleus is a strong source of quasi-real photons. Exclusive $\rho^0$ meson production $AuAu \rightarrow AuAu\rho^0$ can then be described by the vector meson dominance model: a photon emitted by one nucleus fluctuates to a virtual quark-antiquark pair; this intermediate state scatters diffractively from the other nucleus, emerging as a vector meson. The diagram for this process is shown in Fig. 1a. Here, the gold nuclei remain in their ground state. Additional photon exchange can yield nuclear excitation and the subsequent emission of single or multiple neutrons, as shown in Fig. 1b for the process $AuAu \rightarrow Au^*Au^*\rho^0$.

![Figure 1](image-url)
Photon and Pomeron can couple coherently to the spatially extended electric and nuclear charge of the gold nuclei. A coherence condition follows from the uncertainty principle: a low transverse momentum of $p_T < 2\hbar/R_A$ ($\sim 100$ MeV at RHIC for $R_A \sim 7\text{fm}$), and a maximum longitudinal momentum of $p_\parallel < 2\hbar\gamma/R_A$ ($\sim 6$ GeV at RHIC). The coupling strength of the photon is proportional to the square of the charge $Z^2$ (6241 for Au); the strength of the Pomeron coupling lies between $A^4/3$ for surface coupling to $A^2$ in the bulk limit ($10^3$ to $10^4$ for Au). This leads to large cross sections; for gold collisions at $\sqrt{s_{NN}} = 130$ GeV the $\rho^0$ production cross section is expected to be about 400 mb or 5% of the total hadronic cross section.

It is impossible to determine which nucleus was the photon source or the target, thus the amplitudes for $\rho^0$ production from both ions interfere. Since the $\rho^0$ has negative parity, this interference is destructive. The short-lived $\rho^0$ decay before they travel the distance of the impact parameter $b$, and the interference is believed to be sensitive to the post-decay wave function.

In the year 2000, RHIC collided gold nuclei at a center-of-mass energy of $\sqrt{s_{NN}} = 130$ GeV/nucleon. The STAR detector consists of a 4.2 m long cylindrical time projection chamber (TPC) of 2 m radius. In 2000 the TPC was operated in a 0.25 T solenoidal magnetic field. Particles were identified by their energy loss in the TPC. A central trigger barrel (CTB) of scintillators surrounds the TPC. Two zero degree calorimeters (ZDC) at $\pm 18\text{m}$ from the interaction point are sensitive to the neutral remnants of nuclear breakup.

Ultra-peripheral collisions have a specific experimental signature: the $\pi^+\pi^-$ decay products of the $\rho^0$ meson are observed in an otherwise 'empty' spectrometer. Fig. 2 shows a typical event candidate; the tracks are approximately back-to-back in the transverse plane due to the small $p_T$ of the pair.

Two data sets were used for the analysis of ultra-peripheral events. First the 'minimum bias' data set, where the coincident detection of neutrons from nuclear break up in the ZDCs is used as a trigger. About 800k events were recorded. For the process $AuAu \rightarrow Au^*Au^*\rho^0$, i.e. $\rho^0$ production accompanied by mutual nuclear excitation, events were selected with exactly two tracks of opposite charge forming an common vertex in the interaction region. The tracks are required to have a 3-dimensional opening angle smaller than 3 radians, i.e. they must not be perfectly back-to-back, to reject background.

Figure 2. Display of a typical $\rho^0$ candidate event in the STAR TPC.
from cosmic rays. Fig. 3 shows the transverse momentum spectrum for the selected events (points). A clear peak, the signature for coherent coupling, can be observed at $p_T < 100$ MeV. Those events are compatible with coherently produced $\rho^0$ candidates. A background model from like-sign combination pairs (shaded histogram), which is normalized to the signal at $p_T > 250$ MeV, does not show such a peak. In the invariant mass spectrum of Fig. 3, a clear peak is shown at the $\rho^0$ mass for the signal events at $p_T < 100$ MeV. A clear single-neutron peak was observed for those signal events in the ZDCs. The data contains little background: beam-gas and incoherent photonuclear events are unlikely to deposit energy in both ZDCs; background from grazing nuclear collisions does not show a peak at low $p_T$. Nevertheless, background from mis-identified coherently produced $e^+e^-$ pairs, discussed below, contributes to the invariant mass region around $m(\pi\pi) \sim 0.4$ GeV. This background can be statistically subtracted.

For the analysis of the process $AuAu \rightarrow AuAu\rho^0$ a second data set was collected using a low-multiplicity topology trigger which did not require a ZDC signal. In the level 0 trigger, the CTB was divided into 16 coarse pixels. For a two track topology, hits were required in opposite pixels, while pixels in the top and the bottom acted as a veto to suppress cosmic rays. A fast online reconstruction - the level 3 trigger - further removed background. With this trigger, the STAR collaboration collected about 30k events in 7 hours. The $\rho^0$ candidates from this data set have a transverse momentum and an invariant mass distributions similar to the ones already shown in Fig. 3: a peak at low $P_T < 100$ Mev and a peak of about 300 events around the rho mass. In contrast to the minimum bias data, the topology triggered data had almost no energy deposition in the ZDC consistent with the two gold nuclei remaining in their ground state.
Two-photon interactions include the purely electromagnetic process of electron-positron pair production as well as single and multiple meson production. The coupling \( Z_\alpha \) (0.6 for Au) is large, hence \( e^+e^- \) pair production is an important probe of quantum electrodynamics in strong fields. At momenta below 140 MeV, \( e^+e^- \) pairs are identified by their energy loss in the TPC as shown for the minimum bias data sample in Fig. 4a. Fig. 4b shows the \( p_T \) spectrum for identified \( e^+e^- \) pairs; a clear peak at \( p_T < 50 \) MeV/c identifies the process \( AuAu \rightarrow Au^*Au^*e^+e^- \).

In summary, for the first time, exclusive \( \rho^0 \) production \( AuAu \rightarrow AuAu\rho^0 \) and \( \rho^0 \) production accompanied by nuclear breakup \( AuAu \rightarrow Au^*Au^*\rho^0 \) were observed in ultra-peripheral heavy ion collisions. The \( \rho^0 \) are produced at small perpendicular momentum, showing their coherent coupling to both nuclei. In addition, the coherent electromagnetic process \( AuAu \rightarrow Au^*Au^*e^+e^- \) was observed. In 2001, RHIC will collide gold nuclei at \( \sqrt{s_{NN}} = 200 \) GeV, attempting to reach full design luminosity. Together with new trigger algorithms, this will allow us to collect several orders of magnitude larger statistics than presently available, thus greatly expanding the physics reach of the STAR ultra-peripheral collisions program.

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