Interference and wave function collapse in the reaction $AuAu \rightarrow AuAu\rho^0$

The STAR collaboration

Abstract

In ultra-peripheral heavy ion collisions, a photon from the electromagnetic field of one nucleus can fluctuate to a quark-antiquark pair and scatter from the other nucleus, emerging as a ρ^0. The ρ production is well localized at the two nuclei, forming a 2-source interferometer. The two sources interfere, and ρ^0 production at low transverse momentum is suppressed. We measure this interference in 200 GeV per nucleon Au-Au collisions, and observe interference at $93 \pm 6 \pm x\%$ of the expected level, and find a maximum decoherence, due to wave function collapse or other factors, of x% at the 90% confidence level.

This interference occurs even though the ρ^0 decay before their pre-decay wave functions can overlap. In one interpretation, the interference requires that the post-decay wave functions retain amplitudes for all possible decay modes, long after the decay occurs.

Electromagnetic interactions between relativistic heavy ions are rather simple systems; the ions act as source of fields, and their internal structure is unimportant. A variety of two-photon and photonuclear interactions have been discussed[**?**]. In coherent vector meson production, a photon from the field of one nucleus fluctuates into a quark-antiquark pair which scatters elastically from the other nucleus, emerging as a vector meson. This reaction has a large cross section, about 8-10% of the hadronic cross section for gold-gold collisions at a center of mass energy of 200 GeV per nucleon[**?**][**?**][**?**].

The ρ production occurs at impact parameters b much larger than twice the nuclear radii R_A. Because the scattering involves the short-ranged strong force, the ρ production occurs in or very near (within 1 fm) the two ions, so the system consists of two well-separated sources. Either nucleus 1 emits a photon which scatters off nucleus 2, or vice versa. These two possibilities are indistinguishable, so the amplitudes add; because vector mesons are negative parity, and the amplitudes subtract, with a transverse momemntum (p_T) dependent phase factor to account for the separation. The cross section is[**?**]

$$\sigma = |A_1 - A_2 \exp{(ip_T \cdot b)}|^2 \tag{1}$$

where A_1 and A_2 are the amplitudes for ρ^0 production from the two directions. At mid-rapidity $A_1 = A_2$ and this simplifies to

$$\sigma = \sigma_0[(1 - \cos{(p_T \cdot b)}] \tag{2}$$

where σ_0 is the cross section without interference. The system acts as a 2-slit interferometer, with slit separation b. Of course, b is unmeasurable, and the observed p_T spectrum is obtained by integrating Eq. (1) over b. The p_T spectrum is suppressed for $p_T < \hbar / < \langle b \rangle$. where $\langle b \rangle$ is the median impact parameter.

This interference is of interest because the ρ decay distance, $\gamma\beta c\tau \ll 1$ fm, far less than the median impact parameter of 46 fm. So, the ρ themselves cannot interfere; any interference must involve the decay products. Interference only occurs between identical final states, *i.e.* when the wave functions from the two decays contain non-zero amplitudes for identical $\pi^+\pi^-$ kinematics. Given the huge number of final states, this can only happen if the $\pi^+\pi^-$ system retains amplitudes for all possible decay kinematics after the decay occurs. In other words, the meson decay must not collapse the wave function. With the addition of the amplitudes from the two possible production points, the system can only be described with a non-local (non-factorizing) wave function. Thus, the system manifests the Einstein-Podolsky-Rosen paradox[**?**][**?**] The particles in the interferometer

In this letter we measure this interference in 200 GeV per nucleon gold on gold collisions. We also set limits on possible decoherence due to external factors.

The topology trigger selected exclusive ρ events, by detecting roughly back-to-back pions in a central trigger barrel (CTB) consisting of 240 scintillator slats surrounding the TPC, detecting charged particles with pseudorapidity $|\eta| < 1.0$. The CTB was divided into 4 quadrants, with hits required in opposite quadrants; the top and bottom were used as vetos, to reject cosmic rays. About 1.5 million events were used here. Data from both triggers was processed identically, except that events from the CTB based trigger were distributed more broadly along the TPC axis, and consequently, were accepted in a broader range.

The event selection selected a clean set of ρ events, at some cost in efficiency. Events were required to have exactly two tracks with a vertex within 50 cm longitudinally of the center of the TPC for the minimum bias sample, and 100 cm for the topolgoy sample. The tracks were assumed to be pions, and were required to have a $\pi\pi$ invariant mass $550 MeV < M_{\pi\pi} < 920$ MeV.

The background was estimated by looking at like-sign pion pairs, and was found to be small, x%. The dipion mass spectrum includes a contribution from direct pion production. This contribution was assumed to be the same as in lower energy UPCs, which also matches the contribution seen by the HERA collaborations. Figure 1 shows the rapidity and $M_{\pi\pi}$ distributions of the data, compared with simulation results.

These data includes some direct $\pi^+\pi^-$ pairs [**?**] along with the ρ^0. These channels are indistinguishable, so the two processes interfere. The direct pion rate is relatively small, but the interference shifts the observed ρ mass peak to a lower mass value. The observed shift and direct pion fraction are consistent with earlier studies in AuAu UPCs[**?**] and fixed target photoproduction experiments[**?**] The direct pions should have the same spin/parity and quantum mechanical behavior as the pion pairs from ρ decay, so we do not distinguish between the two sources. With the chosen mass cut, background from misidentified two-photon production of lepton pairs should be very small.

The interference depends on the amplitudes for ρ production by the two nuclei, which themselves depend on the photon energies., Away from $y = 0$, the photon energies differ, $k_{1,2} = M_V/2 \exp(\pm y/2)$, and so the amplitudes differ and the interference is less than maximal. Although it is not expected in the soft-Pomeron model, the the photon energy difference could introduce a small ρ^0 production phase difference, which could affect the interference[**?**]. This paper focuses on the region near mid-rapidity where we assume that this phase difference is small.

To study the interference, we use the variable $t_\perp = p_T^2$. At RHIC energies, the longitudinal component to the 4-momentum transfer is small, so $t \approx t_\perp$. $t_\perp$ is convenient because, without interference, the spectrum dN/dt is well described by an exponential distribution for a wide variety of nuclear models. Our calculations consider a Woods-Saxon distribution for the gold density distribution; the t distribution is well fit by an exponential distribution[**? ?**]. To determine the interference in different rapidity bins, we use a Monte Carlo simulation which follows Refs [**?**] and [**?**].

Figure 2 compares the uncorrected minimum bias data for $0.1 < |\eta| < 0.5$ with simulation with interference ("Int") and without it ("Noint"). The data shows a significant downturn for $t < 0.015$ GeV^2. This drop is also seen in the "Int" simulation.

The efficiency corrected data are shown in Fig. 3. Minimum bias and topology data are shown separately, each with two rapidity bins: $0.1 < |\eta| < 0.5$ and $0.5 < |\eta| < 1.0$. The efficiency is independent of p_T, but p_T smearing (resolution) in the affects the spectrum slightly. The ρ^0 p_T resolution is about 9 MeV/c, compared to the first t bin width of (15 MeV/c)^2. Interference depletes the first few bins, but feeddown from the higher t bins partially repopulates them. We will discuss the accuracy of the data correction later.

The data is fit to the 3-parameter form:

$$\frac{dN}{dt} = a\exp(-bt)[1 + c(R(t) - 1] \tag{3}$$

where $R(t) = Int(t)/Noint(t)$ is the ratio of the t-spectra with and without interference. Here, A is the overall normalization, the slope b is related to the nuclear radius, c gives the degree of spectral modification; $c = 0$ corresponds to no interference while $c = 1$ is the expected interference. This form separates the interference (c) from the nuclear form factor (b).

Table 1 gives the results of the fits. In the small-rapidity samples, where A_1 and A_2 are similar, the interference is much larger. It is also much larger in the minbias data than the topology data. This is because the median impact parameter in the minimum bias data is much smaller than in the topology data.

Trigger	Rapidity	A	b	c	Background (%)
MinBias	$0.1 < \|\eta\| < 0.5$	828 ± 44	301 ± 14	1.007 ± 0.085	0%
MinBias	$0.5 < \|\eta\| < 1.0$	907 ± 54	304 ± 15	0.783 ± 0.128	0%
Topo	$0.1 < \|\eta\| < 0.5$	1243 ± 44	361 ± 10	0.709 ± 0.163	0%
Topo	$0.5 < \|\eta\| < 1.0$	1678 ± 79	368 ± 12	1.217 ± 0.214	0%

TABLE I: Fits to the 4 data sets.

The 4 c values are consistent within errors; the weighted average is $c = 0.93 \pm 0.06$. The b values for the minimum bias and exclusive ρ^0 data differ by 20%: 364 ± 7 GeV^{-2} for the exclusive ρ versus 303 ± 10 GeV^{-2} for the Coulomb breakup events.

The different b values may be attributed to the different impact parameter distributions. The photon flux at an impact parameter b scales as $1/b^2$. When b is only a few times R_A, ρ are more likely to be produced on the side of the target near the photon emitter. The resulting peak in the ρ production amplitude leads to a smaller effective production volume and the smaller b. This near-side skewing will also affect the interference slightly; unfortunately, this effect is not included in current calculations.

We have considered a variety of sources of systematic errors in this measurement. If the efficiency varied with p_T or y in not-understood ways, this could affect the measurement. Likewise, if the p_T resolution was wrong in our simulations, this might affect the t spectrum. We have studied a variety of relevant variables, and found that the vertex position, rapidity distribution, $M_{\pi\pi}$ distribution, and $\pi^\pm$ angular distributions agree well between the data and simulation. In addition, we have turned off the detector simulation, by fitting the uncorrected t spectrum with the raw Monte Carlo output; this reduced c by 0.18, a relatively small change. Most of this change is due to the smearing in the lowest t bins. We have confidence that our detector simulation is at least 75% correct, so we assign an overall 5% systematic error to the detector simulation.

Backgrounds are a small effect. Backgrounds were estimated using like-sign pairs ($\pi^+\pi^+ + \pi^- pi^-$). The like-sign background percentages with $t < 0.01$ GeV^2 region are given in Table 1. They are $\approx 2\%$ of the signal. The like-sign backgrounds should be within a factor of 2 of the true background[**?**]; this leads to an x% systematic error.

Source	Uncertainty (%)
Detector Corrections	5
Backgrounds	3
Fitting	5
R_A	2
Calculations	10
Total	15

TABLE II: Systematic Errors and their size.

The fitting procedure may also introduce some systematic error. $R(t)$ is fit to a 6th order polynomial. When we fit $R(t)$ to 5th and 7th order polynomials, c changed by x%. There could also be some error introduced if the form-factor is not a perfect exponential in t. With the good agreement between the 4 samples, this can not be a large factor. We assign a 5% systematic error due to this. We also consider the effect of using a wrong 'b' value in the simulations. When b is changed by 20% in the input Monte Carlo, the fit output changed by 3% for c and b changed by 1.7%. Overall, we find an 7% systematic error due to the fit. Since these systematic errors are uncorrelated, we add them in quadrature.

With respect to the model in Ref.[**?**], we measure the interference to be $93 \pm 6 \pm xx\%$ as large as expected. For an absolute measurement of interference, we need to consider systematic errors in the model. One problem is the $b-$skewing due to the photon flux variation. This skewing may partly explain the large χ^2 in the large-y Coulomb breakup fit. We estimate that the effective b should be within 10% of the geometric b for the coulomb breakup data, and 3% for the exclusive rho. Overall, we estimate that the uncertainties in the calculations used in the model should be at most a 20% effect. These systematic uncertainties are tabulated in Table 2.

We find that interference is $93 \pm 6 \pm 20\%$ of that expected. Thus, the decoherence $\xi = 1 - c$ due to wave function collapse or environmental factors is is less than 40% at the 90% confidence level.

Because the ρ decays so rapidly, $\gamma\beta c\tau \ll \langle b \rangle$, the ρ decay points are well separated in space-time, so the decays must proceeding independently, and any interference must involve the $\pi^+\pi^-$. Necessarily, the interference must involve identical final states from the two sources. Given the large phase space available for the decays, this is very unlikely for independent decays. However, if the post-decay wave function includes amplitudes for all possible decays, then the amplitudes for identical decays subtract, and the interference is visible. In this picture, because of the two sources, the $\pi^+\pi^-$ wave function is non-factorizable, and thus exhibits the Einstein-Podolsky-Rosen paradox. This latter approach fits the data.

In conclusion, we have observed interference between ρ production by the two ions in gold-gold UPCs. The interference is $93 \pm 6 \pm xx\%$ of that predicted in Ref. [**?**]. This apparent interference between well-separated ρ production point can only be explained via interference between the ρ decay products. This requires a non-local wave function, and is thus an example of the Einstein-Podolsky-Rosen paradox.

We thank the RHIC skydiving team for their support.

[] G. Baur *et al.*, Phys. Rep. **364**, 359 (2002); F. Krauss, M. Greiner and G. Soff, Prog. Part. Nucl. Phys. **39**, 503 (1997).

[] S. Klein and J. Nystrand, Phys. Rev. **C60**, 014903 (1999).

[] C. Adler *et al.*, Phys. Rev. Lett. **89**, 027302 (2002).

[] L. Frankfurt, M. Strikman and M. Zhalov, Phys. Rev. **C67**, 034901 (2003); L. Frankfurt, M. Strikman and M. Zhalov, Phys. Lett. **B537**, 51 (2002).

[] S. Klein and J. Nystrand, Phys. Rev. Lett. **84**, 2330 (2000).

[] A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. **47**, 777 (1935).

[] This situation is analogous to the two-slit interferometer described by T. Sudbery, in *Quantum Concepts in Space and Time*, ed. R. Penrose and C. J. Isham, (Oxford, 1986).

[] S. Klein and J. Nystrand, Phys. Lett. **Axxx**, yyy (2003).

[] M. Anderson *et al.*, Nucl. Instrum & Meth. **B499**, 659 (2003); M. Anderson *et al.*, Nucl. Instrum & Meth. **B499**, 679 (2003).

[] F. S. Bieser *et al.*, Nucl. Instrum & Meth. **B499**, 766 (2003).

[] C. Adler *et al.*, Nucl. Instrum. & Meth. **A470**, 488 (2001).

[] P. Söding, Phys. Lett. **B19**, 702 (1966).

[] T. H. Baur *et al.*, Rev. Mod. Phys. **50**, 261 (1978).

[] A. Baltz, S. Klein and J. Nystrand, Phys. Rev. Lett. **89**, xxxxx(2002).

[] R. C. Stabler, Nature **206**, 922 (1965).

[] M. Vidovic, M. Greiner, C. Best and G. Soff, Phys. Rev. **C47**, 2308 (1993); G. Baur and L. G. Ferreira Filho, Phys. Lett. **B254**, 30 (1991).

[] B. Müller and A. J. Schramm, Nuclear Physics **A523**, 677 (1991).

[] D. Leith in *Electromagnetic Interactions of Hadrons*, ed. A. Donnachie and G. Shaw, Plenum Press, 1978; T. H. Bauer *et al.*, Rev. Mod. Phys. **50**, 261 (1978).

[] M. A. Horne, A. Shimony and A. Zeilinger, Phys. Rev. Lett. **62**, 2209 (1989).

FIG. 1: The rapidity distribution for the exclusive ρ (right) and Coulomb breakup sample (left). The points with error bars are the data, and the histogram are the simulations.

FIG. 2: Raw (uncorrected) $t_\perp$ spectrum for ρ^0 sample for $0.1 < |y| < 0.6$ for the topology data. The histogram is the data, while the solid line is a simulation assuming that there is interference; the dashed line is a simulation without interference. The dashed histogram is the wrong-sign background.

FIG. 3: Efficiency corrected $t_\perp$ spectrum for ρ^0 from (a) mutual dissociation with $0.1 < |y| < 0.6$, (b) mutual dissociation with $0.5 < |y| < 1.0$, (c) topology trigger with $0.1 < |y| < 0.6$ and (d) topology trigger with $0.5 < |y| < 1.0$. The histograms are the data, while the solid line is a simulation assuming that there is interference; the dashed line is a simulation without interference. The dashed histogram is the wrong-sign background.