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# Does particle decay cause wave function collapse: An experimental test

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## Abstract

We describe an experimental test of whether particle decay causes wave function collapse. The test uses interference between two well separated, but coherent, sources of vector mesons. The short-lived mesons decay before their wave functions can overlap, so any interference must involve identical final states. Unlike previous tests of nonlocality, the interference involves continuous variables, momentum and position. Interference can only occur if the wave function retains amplitudes for all possible decays. The interference can be studied through the transverse momentum spectrum of the reconstructed mesons.

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In 1935, Einstein, Podolsky and Rosen (EPR) showed that quantum mechanics required that wave functions can be non-local [1]. When a system is observed, the wave function collapses from one which contains amplitudes for a host of possible outcomes to smaller set of possibilities, in accord with the measurement. This collapse is instantaneous; much has been written about its superluminal nature. Most studies of the EPR paradox have tested Bell's inequality [2] using spin correlations, usually with photons produced in pairs [3]. Experimenters measure the spin correlations using two polarizers with a varying angle between them. Bell found that models with non-local wave functions and models with hidden variables produced different angular correlation spectra. Previous tests of non-locality used discrete variables like 'pseudo-spin' for CP violation, as with studies using the reaction  $\Phi \rightarrow K^+ K^-$  [4].

We describe a very different system that, in contrast to the  $K_L K_S$  system, is sensitive to the collapse of continuous variables in a wave function [5]. Short-lived vector mesons (VMs) are produced with a fixed phase relationship at two separated sources. Even though the mesons do not come from a single source, and, in fact, share no common history [6], the system acts as an interferometer. The meson lifetimes are short compared to the source separation, so the mesons decay before their wave functions can spatially overlap.

Any interference between the two sources must involve the decay products. Interference is only possible between identical final states. With the large phase space for final states, interference can only occur if the wave functions retain amplitudes for all possible decay channels and angular distributions long after the decay takes place [7]. We have previously calculated the interference pattern [8]. This letter will focus on the effects of the wave function collapse and Bell's inequality-like tests, and sketch an alternate derivation of the interference, to emphasize the symmetries of the system.

Figure 1 shows electromagnetic VM production in relativistic heavy ion collisions at large impact parameters,  $\vec{b}$ . A photon from the electromagnetic field of one nucleus fluctuates to a virtual quark-anti-quark pair which elastically scatters from the other nucleus, emerging as a real vector meson [9]. Either nucleus can emit the vector meson. The momentum

transfers from the nuclei are similar, and they remain in the ground state, so it is impossible to determine which nucleus emitted the photon and which is the target.

The electromagnetic interaction (photon) has a long range, while the elastic scattering has a short range, around 0.6 fm [10], far smaller than the  $< 7$  fm radius of a heavy nucleus or the typical impact parameter. So, VM production takes place essentially ‘on top of’ the emitting nucleus, and the two nuclei act as a two-source interferometer.

Electromagnetic VM production is studied at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, where gold ions collide at center of mass energies up to 200 GeV per nucleon. Starting in 2006, the Large Hadron Collider (LHC) at CERN will collide lead ions at a center of mass energy of 5.5 TeV per nucleon.

The cross sections were previously calculated [11] using the Glauber approach [9] with the photon spectrum given by the Weizsäcker-Williams virtual photon method [12]. The calculated photonuclear cross sections agree with data to within 20%. The cross sections are large, about 10% of the hadronic cross section at RHIC, rising to 50% at the LHC. The corresponding production rates, more than  $100 \rho^0/\text{sec}$  at RHIC, rising to  $230,000 \rho^0/\text{sec}$  at the LHC, are large enough that it will be easy to collect adequate statistics to study wave function collapse. Already, the STAR collaboration [13] has observed more than  $10,000 \rho^0$ , which should be enough to observe the interference.

The impact parameters for these interaction are large compared with the nuclear radii,  $R_A$ . For  $\rho$  and  $\omega$  production, the median impact parameter  $\langle b \rangle$  is about 40 fm at RHIC, rising to 300 fm at the LHC; for the  $J/\psi$ ,  $\langle b \rangle$  rises from 23 fm at RHIC to about 50 fm at the LHC. All are much larger than  $R_A \approx 7$  fm for heavy ions. It is possible to select events with smaller  $\langle b \rangle$ , but still with  $b > 2R_A$ , by choosing events where VM production is accompanied by nuclear breakup [14].

The  $\langle b \rangle$  are larger than the distance travelled by most VMs before they decay. The VM lifetimes  $\tau$  range from  $4 \times 10^{-24}$ s for the  $\rho$  up to  $7.5 \times 10^{-21}$ s for the  $J/\psi$ . The VM are produced with typical transverse momentum  $p_T \approx 2\hbar/R_A \approx 60\text{MeV}/c$ ; at mid-rapidity, the longitudinal momentum is zero, so VM have a median decay distance  $d = 2\hbar c\tau/R_A M_V$ .

Except for the  $J/\psi$ ,  $d \ll \langle b \rangle$ ; for the  $J/\psi$  at the LHC,  $d \approx \langle b \rangle$ .

The final state wave function from ion source  $i$  at a time  $t$  can be expressed schematically

$$\psi(t)_i = \exp(-t/2\tau) |V\rangle + (1 - \exp(-t/2\tau)) |DP\rangle \quad (1)$$

where  $\tau$  is the vector meson lifetime,  $|V\rangle$  is the vector meson wave function, and  $|DP\rangle$  is the final state. For stable particles,  $\tau = \infty$ , the decay products drop out, leaving a conventional two-source interferometer.

The interference can be seen by examining the symmetries of the system. The total amplitude  $A_T$  for observing the VM with momentum  $\vec{p}$  at position  $\vec{r}$ , and time,  $t$ , depends on the production amplitude  $A(\vec{p}, \vec{x}, t')$  and a propagator  $P(\vec{p}, \vec{x}, t', \vec{r}, t)$  which transports the meson from  $\vec{x}, t'$  to  $\vec{r}, t$ :

$$A_T(\vec{p}, \vec{r}, t) = \int A(\vec{p}, \vec{x}, t') P(\vec{p}, \vec{x}, t', \vec{r}, t) d\vec{x} dt'. \quad (2)$$

The production amplitude  $A(\vec{p}, \vec{r}, t)$  depends on the electromagnetic field,  $E(\vec{x}, t')$ , nuclear density  $\rho(\vec{x}, t)$  and the amplitude  $f(\vec{p}, \vec{k})$  for a photon with momentum  $\vec{k}$  to fluctuate to a  $q\bar{q}$  pair and scatter from a nucleon, emerging as a vector meson with momentum  $\vec{p}$ :

$$A(\vec{p}, \vec{x}, t') = f(\vec{p}, \vec{k}) \rho(\vec{x}, t') E(\vec{x}, t') \quad (3)$$

The electromagnetic field at a distance  $b$  from a nucleus is a Lorentz-contracted pulse with a width  $b/\gamma$  where  $\gamma$  is the Lorentz boost. When  $\gamma \gg 1$ , the electric and magnetic fields are perpendicular and the overall field may be represented as a stream of almost-real photons, with energies up to  $\hbar\gamma/b$  [12]. The photon amplitude is proportional to  $E(\vec{x}, t')$ . The scattering amplitude is obtained from data; only its symmetries are important here. Absorption of the nascent  $\rho^0$  is neglected, but could be included with an additional position-dependent variable, effectively modifying  $\rho(x, t')$ .

At large distances, the propagator for a VM with energy  $\omega = \sqrt{M_V^2 + |\vec{p}|^2}$  may be modelled with a plane wave. Neglecting, for now, VM decays,

$$P(\vec{p}, \vec{x}, t', \vec{r}, t) = e^{i(\vec{p} \cdot (\vec{r} - \vec{x}) - \omega(t - t'))} \quad (4)$$

The nuclear density is symmetric around the center of mass (origin), giving it positive parity, while the antisymmetric electric field has negative parity):  $\rho(\vec{x}, t') = \rho(-\vec{x}, t')$  and  $E(\vec{x}, t') = -E(-\vec{x}, t')$ . With this, the range of integration in Eq. (2) can be restricted to a single nucleus:

$$A_T(\vec{p}, \vec{r}, t) = \int_{y>0} d\vec{x} dt' \rho(\vec{x}, t') E(\vec{x}, t') e^{i(\vec{p}\cdot\vec{r}-\omega(t-t'))} [f(\vec{p}, \vec{k}) e^{i\vec{p}\cdot\vec{x}} - f(\vec{p}, -\vec{k}) e^{-i\vec{p}\cdot\vec{x}}] \quad (5)$$

The only differences between the two nuclei are the phases  $\pm i\vec{p}\cdot\vec{x}$  and between  $f(\vec{p}, -\vec{k})$  and  $f(\vec{p}, \vec{k})$ . The latter is because the sign of  $p_z$  reduces the symmetry of the system. Of course, interference is only significant when  $|f(\vec{p}, \vec{k})| \approx |f(\vec{p}, -\vec{k})|$  which occurs near  $p_z = 0$ .

The equation simplifies by defining  $\vec{x} = \vec{b}/2 + \vec{x}'$ . The bulk of the cross section is from when the photon couples coherently to the target nucleus, *i.e.* when  $\vec{k}\cdot\vec{x}' \ll \hbar$ , so the exponential phase is constant over the nucleus. Then, the maximum transverse and longitudinal momenta are  $\hbar/R_A$  and  $\gamma\hbar/R_A$ . Emitted photons are subject to similar limits [15]. Near  $p_z = 0$ , the photon momentum, and the momentum exchange due to the scattering are very similar so it isn't possible to determine which nucleus emitted the photon, and which was the scatterer; in fact, at  $\vec{p} = 0$ , the two momentum transfers are equal and opposite.

The electromagnetic pulse lasts a time,  $b/c\gamma$ , which may be slightly longer than one photon period ( $\hbar/\omega$ ). This partial temporal incoherence will reduce the overall production amplitude. There is a pairwise cancellation between space-time volume elements  $d\vec{x} dt'$  at positions  $\vec{x}$  and  $-\vec{x}$ , so the interference is not affected.

With this,  $\vec{p}\cdot\vec{x} = \vec{p}\cdot\vec{b}/2$  and

$$A_T(\vec{p}, \vec{r}, t) = \int_{y>0} d\vec{x}' dt' \rho(\vec{x}', t') E(\vec{x}', t') e^{i(\vec{p}\cdot\vec{r}-\omega(t-t'))} [f(\vec{p}, \vec{k}) e^{i\vec{p}\cdot\vec{b}/2} - f(\vec{p}, -\vec{k}) e^{-i\vec{p}\cdot\vec{b}/2}]. \quad (6)$$

We now introduce a few approximations. The amplitude for production from the first nucleus is  $A_1(\vec{p}, \vec{r}, t) = \int_{y>0} d\vec{x} dt' \rho(\vec{x}, t') E(\vec{x}, t') f(\vec{p}, \vec{k})$  and we define  $c$  to be the ratio of the amplitudes for production from the two nuclei:

$$c(p_z) = \frac{\int_{y>0} d\vec{x} dt' \rho(\vec{x}, t') E(\vec{x}, t') f(\vec{p}, -\vec{k})}{\int_{y>0} d\vec{x} dt' \rho(\vec{x}, t') E(\vec{x}, t') f(\vec{p}, \vec{k})}. \quad (7)$$

The ratio  $f(\vec{p}, -\vec{k})/f(\vec{p}, \vec{k})$  does not vary significantly over the nucleus, so the single nucleus production amplitude factors out of the integral in Eq. (6). The transverse momenta do not affect  $c$ , and  $k_z = M_V^2/4p_z$ . Then,

$$A_T(\vec{p}, \vec{r}, t) = A_1(\vec{p}, \vec{r}, t) \left[ e^{i\vec{p}\cdot\vec{b}/2} - c(p_z)e^{-i\vec{p}\cdot\vec{b}/2} \right]. \quad (8)$$

The amplitude factorizes into a magnitude and an interference term. The  $p_T$  dependence of  $A_1(\vec{p}, \vec{r}, t)$  is dominated by the nuclear form factors, with the bulk of the production having  $p_T < 2\hbar/R_A$ . Most of the uncertainties discussed earlier do not affect the interference term. The time and  $z$  variation in  $E(\vec{x}, t')$  should be largely independent of  $k$ . In the soft Pomeron model, the photon to VM coupling increases slowly with  $k$  and has an almost constant phase. At RHIC, a photon-meson term is also present, but the phase of  $c$  still changes only slowly with  $k$  [9].

The interference is clearest when  $p_z=0$ . Then  $c = 1$  and the approximations introduced in defining  $c$  disappear. The amplitude is  $A_T(\vec{p}, \vec{r}, t) = 2iA_0 \sin(\vec{p}\cdot\vec{b}/2)$ . and the cross section is

$$\sigma \sim |A_T(\vec{p}, \vec{r}, t)|^2 = 2A_0^2[1 - \cos(\vec{p}\cdot\vec{b})]. \quad (9)$$

This formula applies for stable particle emission, such as bremsstrahlung photon emission in  $e^-e^-$  [16] and  $pp$  collisions [17].

For short-lived particles, the situation is more interesting. We can express the cross section in Eq. 9 as a sum of a coherent (interfering) and an incoherent (non-interfering) term

$$2A_0^2[1 - (1 - \eta) \cdot \cos(\vec{p}\cdot\vec{b})], \quad (10)$$

where  $\eta$  measures the degree of decoherence, as has been done for the system  $\Phi \rightarrow K^0\bar{K}^0$  [4,18]. Complete quantum mechanical coherence between the two sources here means  $\eta = 0$ .

If the interference is restricted to the time the system spends in the vector meson (parent) state, then one would expect partial decoherence. According to Eq. 1, only a fraction

$\exp(-(M_V b)/(\omega\tau))$  of the vector mesons will have survived long enough for the amplitude to propagate the distance  $b$  between the nuclei before the decay. This scenario thus corresponds to

$$\eta = 1 - \exp\left(-\frac{M_V b}{\omega\tau}\right). \quad (11)$$

For the  $\rho$ ,  $\omega$ , and  $\phi$ , which all have  $c\tau \ll b$ ,  $\eta \approx 0$  and one expects almost complete decoherence in this scenario. For the  $J/\Psi$ , on the other hand,  $c\tau \approx b$ , so the decoherence would be only partial. This scenario could therefore be distinguished by observing the  $J/\Psi$ , while for the lighter vector mesons it would essentially be indistinguishable from a scenario with no interference.

However, there is a broader issue. A distant observer sees the decay products from the original meson, and most VM have many decay modes. The final state may be written  $|DP \rangle = \sum_j \alpha_j |DP_j \rangle$ , where  $\alpha_j$  is the amplitude for final state  $|DP_j \rangle$ . For example, the  $J/\psi$  can decay to  $e^+e^-$  or  $\pi^+\pi^-\pi^0$ , among many possibilities. The probability for any specific final state is small, less than 7%.

If the wave function contains amplitudes for every possible decay mode, at times  $t \gg \tau$ , the individual particles may be modelled as plane waves and the wave function is

$$\Psi(t) = \int_0^t \frac{dt_d}{2\tau} \left[ e^{i\vec{p}\cdot(\vec{x}_d + \vec{b}/2)} + c e^{i\vec{p}\cdot(\vec{x}_d - \vec{b}/2)} \right] e^{-t_d/2\tau - i\omega t_d} |\sum_j \sqrt{Br_j} \Psi_j \rangle \quad (12)$$

where the decays occur at time  $t_d$  and displacement  $\vec{x}_d = (\vec{p}/M_V)t_d$  from the production points. Here,  $Br_j$  are the branching ratios to different final states, and  $\Psi_j$  is the  $k$ -particle final state

$$\Psi_j = \sum_k e^{i[\vec{p}_k(\vec{x}_k - \vec{x}_d) - \omega_j(t - t_d)]} |\Psi_{jk} \rangle \delta(\sum_k \omega_k - \omega) \delta(\sum_k \vec{p}_k - \vec{p}). \quad (13)$$

Here  $\vec{x}_k$ ,  $\omega_k$  and  $\vec{p}_k$  are the particle positions, energy, and momenta, and  $|\Psi_{jk} \rangle$  includes the particle types and angular distribution. The  $\delta$  functions impose 4-momentum conservation.

If the decay occurs before the two amplitudes overlap, then either the wave function must retain amplitudes for all final states, or the two decays will produce different final states,



and the interference must be small. Also, as Eq. (9) shows, amplitudes for different decay times must also be included. Thus, the presence or absence of interference tests whether particle decay collapses the wave function.

The two source terms in Eq. (12) entangle the final state wave functions. The phases differ by  $\exp[i(\vec{p} \cdot \vec{b} + \delta)]$  where  $\delta$  is the phase of  $c$ . Any measurement on one decay product at least partially collapse the wave function of the others [3]. Detectors could accurately measure either the position or momentum of the  $k$  final state particles. 'Accurately', is compared to the relevant distance ( $b$ ) or momentum ( $\hbar/b$ ) scales. By these metrics, current and planned experiments measure momentum accurately, but not position.

The interference pattern, Eq. (9) can be seen in the reconstructed VM  $p_T$  [8]. Because  $b$  is not generally measurable,  $\sigma$  must be integrated over all  $b$ . Figure 2 shows the expected  $p_T$  spectrum for  $\rho^0$  production at mid-rapidity at RHIC [8]. The large dip for  $p_T < \hbar/\langle b \rangle$  is a distinctive experimental signature.

Alternately, at least in a gedanken experiment, position sensitive detectors could be used to localize the decay to a single nucleus, provided the ion trajectories are known. The decay  $J/\psi \rightarrow e^+e^-$  produces two relativistic electrons that are back-to-back in the transverse plane. For  $p_T = 0$ , a line between the two measured electron positions will intersect one of the ion trajectories. When the electron  $\vec{p}_k$  are perpendicular to  $\vec{b}$  then it is possible to determine which nucleus emitted the VM. The nonzero meson  $p_T$  introduces some uncertainty, but not enough to encompass both ion trajectories. For detectors 500 fm from the collision point, the pointing uncertainty is 16 fm, less than the  $\langle b \rangle \sim 50$  fm for  $J/\psi$  at the LHC.

As with existing tests of Bell's inequality, two detectors, on opposite sides of the collision region could randomly measure either position or momentum. All single-detector measurements are insensitive to what happens in the other detector. However, when both detectors measured position, the production point could be determined, while when both measured momentum, a null at  $p_T = 0$  would be seen, showing the interference. These two possibilities are only compatible if the wave function collapses when a measurement is made, and not earlier, when the meson decays. For  $J/\psi \rightarrow e^+e^-$ , the collapse would have to be

superluminal.

One possible source of decoherence is the decay timing. The VM are produced nearly at rest, but the decay products may be relativistic. The maximum flight time difference from the two sources to a detector is  $b/c$ . If the detectors could resolve this time difference, this could partially localize the production, reducing the coherence.

Since the probability of producing a VM in grazing collisions ( $b = 2R_A$ ) is high, about 1% at RHIC and 3% at the LHC [11], multiple VM production is also observable. Multi-meson final states will exhibit more complicated entanglements, with possibly new behavior.

We have described a 2-source interferometer for short lived particles, and showed that its description requires a non-local wave function. The observation of interference will clearly demonstrate that, after a decay, a systems' wave function includes amplitudes for all possible decay modes and angular distributions, and does not collapse to a specific decay mode until the wave function is externally observed. Measurements of this interference should be available soon. The STAR detector has observed exclusive  $\rho^0$  production in gold collisions at RHIC [13]. Current data should provide higher statistics and an accurate  $\rho^0$   $p_T$  spectrum, probing the EPR paradox for continuous variables.

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FIGURES

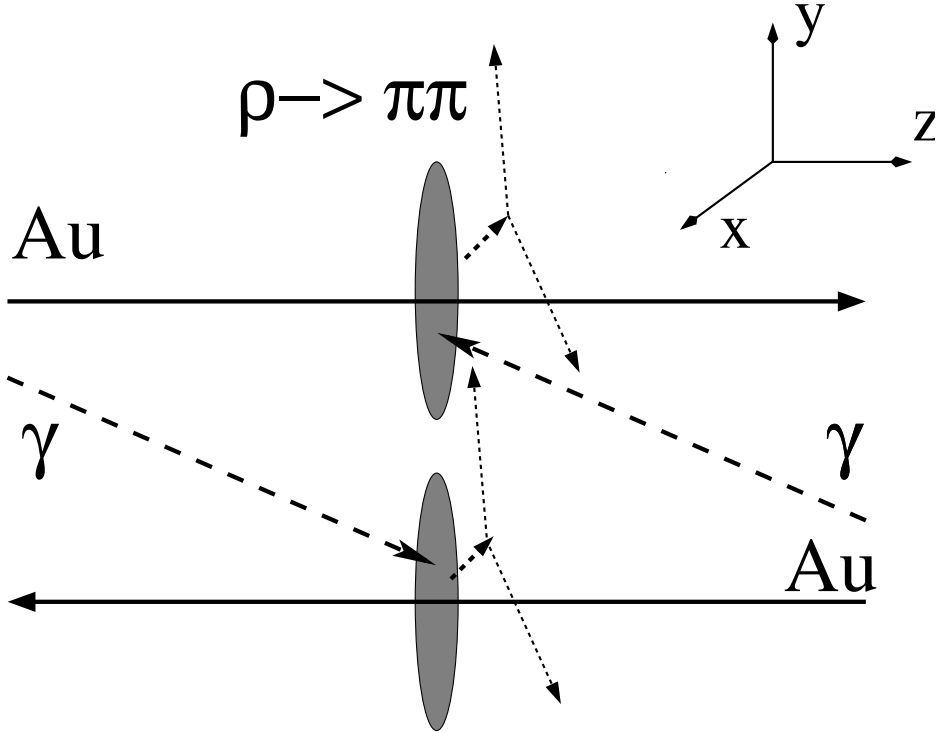


FIG. 1. Diagram showing ultra-peripheral  $\rho^0$  production and decay in heavy ion collisions. The nuclear momenta follow the  $z$  axis, and come closest at  $z = 0$ , when their separation (impact parameter),  $\vec{b}$  follows the  $y$  axis.

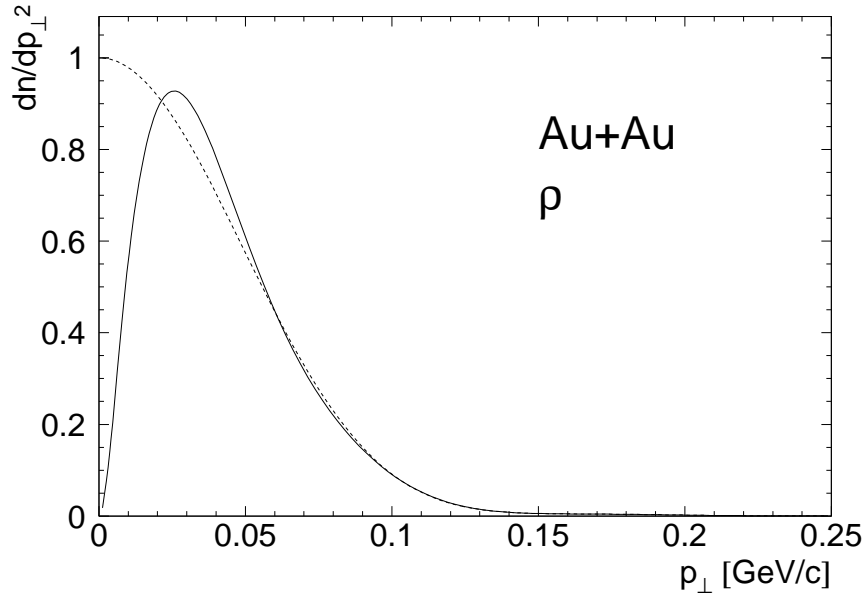


FIG. 2. Perpendicular momentum spectra for  $\rho^0$  production at RHIC, at  $p_z = 0$ , for gold on gold collisions at a center of mass energy of 200 GeV per nucleon. Plotted are  $dN/dp_T$ , with and without interference. The curves are normalized to 1 for  $p_T = 0$  and no interference. The calculation assumes that the impact parameter is not measured, so the interference is washed out, except for  $p_T < 25$  MeV/c.