New type of double-slit interference experiment at Fermi scale (Postprint)

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Abstract

A new approach utilizing polarized photon-gluon collisions, reported by the STAR Collaboration, is employed to perform tomography of ultrarelativistic nuclei. The collision can be treated as a double-slit experiment at the Fermi scale, and resolves a mystery lasting over 20 years regarding the extraction of nuclear radius via vector meson photoproduction.

Full Text

Preamble

A new approach employing polarized photon-gluon collisions, reported by the STAR Collaboration, enables tomography of ultrarelativistic nuclei. This collision system can be treated as a double-slit experiment at the Fermi scale and resolves a mystery lasting over 20 years regarding the extraction of nuclear radii via vector meson photoproduction.

Gluons, as the propagators of the strong interaction, bind quarks inside nucleons such as protons and neutrons. Through the strong interaction, quarks and gluons are confined within the nuclear core rather than existing as free particles. Quantum chromodynamics (QCD) represents the most successful theory describing this strong interaction based on our current understanding. Despite this success, QCD does not provide a complete explanation for why gluons are not confined within the bounds of individual protons and neutrons in a nucleus, nor does it fully describe the momentum-dependent parton distribution functions (PDFs) of gluons in a proton. To understand the nature of gluons within nuclear matter, mapping the dynamical distribution of gluons inside nuclei has become one of the most urgent goals in contemporary experimental nuclear physics research.

Now published in *Science Advances* [**?**], the STAR Collaboration has reported a novel approach using polarized photon-gluon collisions to perform tomography of ultrarelativistic nuclei. The work was primarily contributed by a joint team from Brookhaven National Laboratory, Shandong University, and the University of Science and Technology of China, led by James Daniel Brandenburg, Zhangbu Xu, Chi Yang, and Wangmei Zha. This study resolves a mystery persisting for over 20 years concerning the extraction of nuclear radii via vector meson photoproduction. Even more remarkably, a new form of quantum interference has been observed between two dissimilar particles, demonstrating that this type of polarized photon-gluon collision can be treated as a double-slit experiment at the Fermi scale [**?**]. The observation also suggests possible entanglement between dissimilar particles.

To study gluons, nuclear physicists can effectively shine light on nuclei. These photons can be emitted via charged particles moving at relativistic velocities, such as in $e+p$, $e+A$, and $A+A$ collisions. Although no electron-ion collider yet exists, ultra-peripheral $A+A$ collisions (UPCs)—where both nuclei pass each other without "breaking"—enable such research in ultrarelativistic heavy-ion collisions. This technique is analogous to positron emission tomography (PET) used in medical imaging but at the Fermi scale. Recent measurements in UPCs at RHIC [**?**, **?**] and LHC \cite{5–7} have shown that these quasi-real photons generated from high-energy nuclear interactions at relativistic speeds can be treated as real photons in all observable quantities. Furthermore, measurements from the STAR Collaboration [**?**] demonstrate that these photons are linearly polarized in the transverse plane, as shown in [Figure 1: see original paper]. In photonuclear interactions, the polarization vector of the spin-1 photon is transferred directly to the produced vector meson (such as ρ^0) and subsequently transferred into the orbital angular momentum (OAM) of the daughter particles. This results in an alignment between the momentum of daughter particles and the vector meson spin direction, manifesting as an azimuthal $\cos 2\phi$ modulation between them [**?**].

The key sub-detectors responsible for the success of this ultrarelativistic nuclear tomography are the Time Projection Chamber (TPC) and Time-Of-Flight (TOF) systems. Both detectors were realized through joint efforts between the STAR China group and US groups. The TPC upgrade was recently completed [**?**], while the TOF project was finished more than ten years ago [**?**]. The TPC reconstructs three-dimensional tracks, providing transverse momentum (p_T) and energy loss (dE/dx) information for particle identification, while the TOF rejects contamination from e^+e^-, pp, and K^+K^- pairs. With the combined capabilities of both subsystems, the STAR Collaboration performed precise measurements of the $\rho^0 \to \pi^+ + \pi^-$ photoproduction process, enabling observation of the azimuthal $\cos 2\phi$ modulation effect caused by ρ^0 spin alignment.

It is noteworthy that spin alignment has become a new and important topic in the heavy-ion community, as it may illuminate the magnitude of local fluctuations in the strong force field \cite{11–13}. A very recent STAR measurement on the vector meson ϕ, composed of a strange quark and its antimatter partner, reveals a surprising preference in its spin alignment [?].

In these measurements, because the polarization direction is constrained, the gluon density can be studied two-dimensionally rather than as an average. In previous works, extracted nuclear radii via vector meson photoproduction were consistently larger than expected, puzzling the field for over 20 years. This puzzle has now been solved using 2D imaging techniques that remove the effects from photon transverse momentum. The nuclear radii of Au and U have been calculated via this new 2D imaging method. This approach has the potential to bridge research in current ultrarelativistic heavy-ion collisions, which primarily focus on properties of the extremely hot and dense medium (hot QCD), with future electron-ion collisions focusing on nuclear structure (cold QCD). The measurements demonstrate that spin-induced OAM effects open a new pathway for quantitatively mapping nuclear geometry and gluon distributions in heavy ions, extending the physical applications of ultrarelativistic heavy-ion collisions.

An additional intriguing finding is that measurements of nonzero ρ^0 spin alignment in $Au + Au$ and $U + U$ collisions demonstrate an entirely new quantum interference behavior between dissimilar particles. Simply by selecting momentum directions along and perpendicular to the photon's motion, as shown in [Figure 1: see original paper], an interference pattern can be observed in the momentum phase beyond the azimuthal $\cos 2\phi$ modulation. These spin alignment effects were observed only in $Au + Au$ and $U + U$ collisions, not in $p + Au$ collisions where the photon emitter and target nucleus (Pomeron emitter) are distinguishable. Considering the ρ^0 lifetime (approximately 1 fm) and the average impact parameter of the collisions (approximately 20 fm), this quantum interference may serve as an excellent example of entanglement-enabled intensity interferometry (E2I) between nonidentical particles [?]. A recent study in the quantum optics field is based on entanglement between lasers with different wavelengths [?], while the STAR measurement shows entanglement between π^+ and π^-. In the particle physics domain, spin entanglement phenomena have also been measured between double-strange baryons Ξ^- and $\bar{\Xi}$ via e^+e^- colliders, aiming to probe charge-parity symmetry and weak phases [?]. The implications and applications of these discoveries may extend beyond our current understanding.

[Figure 1: see original paper] illustrates the interference pattern in the ρ^0 photoproduction process $\rho^0 \to \pi^+ + \pi^-$ measured in UPCs at RHIC-STAR. The interference principle is similar to the double-slit experiment. The two colliding ultrarelativistic heavy ions pass each other with an impact parameter larger than their diameters without "breaking." In the photoproduction process, one nucleus could act as either the photon or Pomeron emitter while the other serves the opposite role. The photoproduced ρ^0 in UPCs decays into a π^+ and π^- pair before its wave function can interact with the other nucleus. The interference occurs between π^+ and π^- rather than between two ρ^0 mesons or between π^+ and π^- from the same mother particle. The interference effect plots in the figure are from Ref. [?].

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Note: Figure translations are in progress. See original paper for figures.