Nuclear Science and Techniques (2023) 34:16
https://doi.org/10.1007/s41365-023-01167-6

RESEARCH HIGHLIGHT

New type of double-slit interference experiment at Fermi scale

Yu-Gang Ma[1,2]

Received: 19 January 2023 / Revised: 20 January 2023 / Accepted: 20 January 2023 / Published online: 30 January 2023

A new approach that using polarized photon–gluon collisions reported by STAR Collaboration is used to do tomography of the ultrarelativistic nucleus. The collision can be treated as a double-slit experiment at Fermi scale and solves a mystery last over 20 years in extracting the nuclear radius via vector meson photoproduction.

Gluons, which are propagators of strong interactions, bind to quarks inside nucleons, such as protons and neutrons. Owing to strong interactions, quarks and gluons are constrained within the nuclear core instead of existing as free particles. Quantum chromodynamics (QCD) is the most successful theory that describes this strong interaction based on our current understanding. However, it does not provide a perfect explanation of why gluons are not confined within the bounds of protons and neutrons in a nucleus or description of the momentum-dependent parton distribution functions (PDFs) of gluons in a proton. To understand the nature of gluons inside nuclear matter, mapping the dynamic distribution of gluons inside nuclei is one of the most urgent goals of recent research on experimental nuclear physics.

In *Science Advances* [1], the STAR Collaboration reported a new approach that uses polarized photon–gluon collisions for performing tomography of the ultrarelativistic nuclei. This work was mainly contributed by a joint team of 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. A mystery last over 20 years in extracting the nuclear radius via vector meson photoproduction has been solved. Interestingly, a new type of quantum interference has been observed between two dissimilar particles, indicating that this type of polarized photon-gluon collisions can be treated as a double-slit experiment at the Fermi scale [2]. This observation also indicates a possible entanglement between dissimilar particles.

In studying gluons, nuclear physicists can shed light on the nuclei. The photons emitted by charged particles move at relativistic velocity, such as in e + p, e + A, and A + A collisions. Although there is no electron-ion collider, ultra-peripheral A + A collisions (UPCs), where both nuclei pass each other without "breaking", make the research available in ultrarelativistic heavy-ion collisions. The technique is similar to the positron emission tomography (PET) used in medical imaging, but at the Fermi level. Recent measurements of UPCs at RHIC [3, 4] and LHC [5–7] showed that these expected quasi-real photons generated from high-energy nuclear interactions at relativistic speed can be treated as real photons in all possible observables. Furthermore, measurements from the STAR [4] Collaboration demonstrated that these photons were linearly polarized in the transverse plane, as shown in Fig. 1. In photonuclear interactions, the polarization vector of spin-1 photons is transferred directly to the produced vector meson (such as ρ^0) and is further transferred into the orbital angular momentum (OAM) of the daughter particles. This results in an alignment between the momentum of the daughter particles and the vector meson spin direction, which is an azimuthal $\cos 2\phi$ modulation between them [8].

The key subdetectors responsible for the success of the ultrarelativistic nucleus tomography are the time projection chamber (TPC) and time-of-flight (TOF). Both subdetectors are attributed to joint efforts between the STAR China group and USA groups. The TPC upgrade was recently completed [9], and the TOF project was completed more than ten years ago [10]. The TPC was used to reconstruct 3D tracks, providing transverse momenta (p_{T}) and energy loss ($\mathrm{d}E/\mathrm{d}x$) information for particle identification, whereas the TOF was used to reject contamination from e^+e^-, pp and K^+K^- pairs. Owing to the joint support of both subsystems, the STAR Collaboration made a

✉ Yu-Gang Ma
mayugang@fudan.edu.cn

1 Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China

2 Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai 200438, China

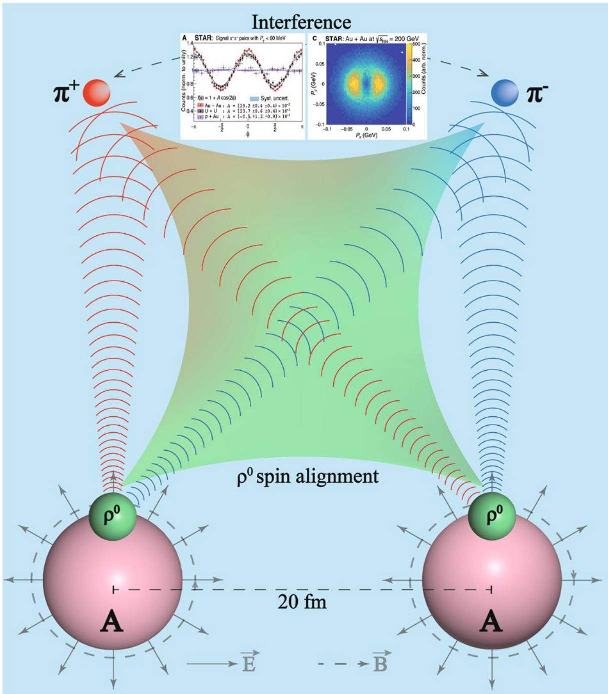

Fig. 1 (Color online) Illustration of the interference pattern in the ρ^0 photoproduction process $\rho^0 \rightarrow \pi^+ + \pi^-$ measured in UPCs at RHIC-STAR. The principle of the interference is similar to a double-slit experiment. The two collided ultrarelativistic heavy ions passed each other with an impact parameter larger than their diameters without "breaking." In the photoproduction process, one nucleus could be either the photon or the Pomeron emitters, whereas the other one acted vice versa. The photoproduced ρ^0 in UPCs decays to π^+ and π^- pair before its wave functions can interact with the other one. Interferences occur between π^+ and π^- instead of between two ρ^0 or between π^+ and π^- from the same mother particle. The interference effect plotted in the figure is from Ref. [1]

precise measurement of the $\rho^0 \rightarrow \pi^+ + \pi^-$ photoproduction process, providing observations of an azimuthal $\cos 2\phi$ modulation effect caused by the ρ^0 spin alignment. It is worth mentioning that spin alignment is a hot and important topic in heavy-ion community because it might shed light on the strength of local fluctuations in strong forces [11–13]. A recent measurement of STAR on a vector meson called ϕ, which was composed of a strange quark and its antimatter partner, revealed a surprising preference on its spin alignment [14].

In the measurements, because the polarization direction is constrained, the density of gluons can be studied two-dimensionally instead of being measured as an average. In previous studies, the nuclear radii extracted through vector meson photoproductions were always larger than the expected, which remained unsolved for over 20 years. Using the 2D imaging technique, the issue was solved by removing the effects of the photon transverse momentum and two-source interference. Furthermore, by comparing the extracted nuclear radii and previous results of nuclear charge radii [15] , the neutron skin depths of Au and U were calculated using this new 2D imaging method. This method has the potential to bridge the research in the current ultrarelativistic heavy-ion collisions, which mainly focuses on the properties of extremely hot and dense media (hot QCD), and the future electron-ion collisions focusing on nuclear structure (cold QCD). The measurements demonstrate that spin-induced OAM effects open a new way to quantitatively map nuclear geometry and gluon distribution in heavy ion, extending the physical applications of ultrarelativistic heavy-ion collisions.

Interestingly, measurements of nonzero ρ^0 spin alignment in Au + Au and U + U collisions demonstrate an entirely new quantum interference behavior between dissimilar particles. By simply selecting the momentum direction along and perpendicular to the photon motion, as shown in Fig. 1, an interference image can be observed in the momentum phase, in addition to the azimuthal $\cos 2\phi$ modulation. These spin alignment effects are only observed in Au + Au and U + U collisions, not in p + Au collisions, where the photon emitter and target nuclei (Pomeron emitter) are distinguishable. Considering the lifetime of ρ^0 (approximately 1 fm) and the average impact parameter of the collisions (approximately 20 fm), this quantum interference could be a good example of entanglement-enabled intensity interferometry (E^2I^2) between nonidentical particles [16]. A recent research in the quantum optics field was based on the entanglement between lasers with different wavelengths [17], whereas what was measured by STAR was the entanglement between π^+ and π^-. In particle physics, the spin entanglement phenomenon between the double-strange baryons Ξ^- and $\overline{\Xi}^+$ via e^+e^- collider was also determined, with the aim of probing the charge–parity symmetry and weak phases [18]. The significance and applications of these discoveries may go beyond our current understandings.

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