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RESEARCH HIGHLIGHT

Probing QCD confinement with spin–spin correlation in proton–proton collisions

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An important feature of quantum chromodynamics (QCD) is that the strong force grows as the distance between partons increases, which confines partons into hadrons, commonly known as QCD confinement. Perturbative QCD (pQCD) does not work at large distance, such as the length scale of a hadron, which is the regime of non-perturbative QCD. The detailed QCD mechanisms through which confinement occurs from partons to hadrons (usually known as hadronization), and how it manifests itself in partonic structure of hadrons (usually known as parton distribution), remain unresolved puzzles of first-principle QCD calculations.

Spin, as a fundamental degree of freedom, plays a critical role in QCD and often brings surprises. For example, the large transverse polarization of Λ hyperons observed in unpolarized hadron–hadron and hadron–nucleus collisions in the 1970 s [1, 2] could not be described by pQCD [3]. Similarly, sizable transverse single-spin asymmetries have also been observed for the hadrons produced in transversely polarized hadron collisions since the 1970s [4], which again cannot be explained by pQCD [3]. Important progress has been achieved in recent years, and these two phenomena can now be described under the high-twist framework and/or transverse momentum-dependent (TMD) framework with non-perturbative TMD parton distributions and fragmentation functions [5–7]. These two frameworks are proven to work at different scales in different processes and describe the same physics in the overlap region [8, 9].

Another famous spin puzzle is the spin structure of the proton, which is also a non-perturbative question in QCD. In 1987, EMC measurements indicated that quark spin contributions only account for a very small fraction of the proton spin [10]. This is in stark contrast to the expectation from the naive quark model under the SU(6) picture [11] that 100% of the proton spin arises from the valence quark spin, triggering the so-called spin crisis. After approximately 40 years of efforts in both experiments and theory, we know that there are also significant contributions from the gluon spin, sea quark spin, and orbital angular momentum that are related to the TMD distribution functions [12, 13]. Worldwide facilities, including the RHIC at BNL, JLab, COMPASS at CERN, and HERMES at DESY, have been dedicated to studying the proton spin structure [14], to be continued with the proposed facilities such as EIC [15] and EicC [16].

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is the world's first and only polarized proton–proton collider. The RHIC is capable of proton–proton collisions at $\sqrt{s} = 200$ GeV and 500 GeV, thus providing unique opportunities to study the above-mentioned fundamental questions, including QCD confinement and proton spin structure [17, 18].

In high-energy proton–proton collisions, virtual quark–antiquark pairs can be liberated from the QCD vacuum. These virtual pairs, including strange quark–antiquark pairs, are initially quantum spin-entangled and later undergo quark confinement to form hadrons such as $\Lambda/\bar{\Lambda}$ hyperons, whose properties can serve as probes into QCD confinement. The Λ–$\bar{\Lambda}$ pair is expected to be inherited from spin-correlated strange quark–antiquark pairs. The spin correlation of Λ–$\bar{\Lambda}$ pair can reveal the spin states of the strange quark–antiquark pair, as the strange valence quark carries 100% of the Λ spin under the naive quark model. Fortunately, the spin polarization of the Λ hyperon can be measured via the

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angular distribution of the decay daughter proton in its rest frame, as illustrated in Fig. 1.

Spin correlation analysis and results — In a recent article published in *Nature* [19], the STAR Collaboration reported the first evidence of spin correlations in Λ–$\bar{\Lambda}$ hyperon pairs in *pp* collisions at $\sqrt{s}$ = 200 GeV. A relative correlation signal of (18±4)% was observed, which links the spin-correlated quark pairs in the QCD vacuum to their final-state hadron counterparts. This work was mainly conducted by a team at the Brookhaven National Laboratory, led by Zhoudunming Tu and Jan Vanek. Crucially, this correlation vanishes when the hyperon pairs are widely separated in rapidity and azimuthal space, consistent with the decoherence of the quantum system.

Λ and $\bar{\Lambda}$ hyperons are reconstructed through their weak decays, $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ at STAR. High-purity hyperon samples were selected and paired to extract the spin correlation, which is determined from the following angular distribution of the decay daughters of the hyperon pair [20],

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^\star} = \frac{1}{2}[1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos\theta^\star], \quad (1)$$

where $P_{\Lambda_1\Lambda_2}$ is the spin correlation signal of the Λ hyperon pair, α_1 and α_2 are the weak decay parameters, and $\theta^\star$ is the angle between the two (anti-)protons which are boosted into the rest frames of the parent hyperons [20].

Figure 2 shows the results of spin–spin correlation $P_{\Lambda,\bar{\Lambda}}$ between Λ and $\bar{\Lambda}$, versus their separation $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$ in the rapidity and azimuthal space [19]). A significant correlation is observed when the Λ–$\bar{\Lambda}$ pair is close in the phase space ($\Delta R < 1$). This magnitude is compatible with the expectations from a spin–triplet $s\bar{s}$ state in simple quark model descriptions, including SU(6) and the Burkardt–Jaffe model, both shown in Fig. 2. No spin correlation is observed within the uncertainties for the Λ-Λ or $\bar{\Lambda}$–$\bar{\Lambda}$ pairs, consistent

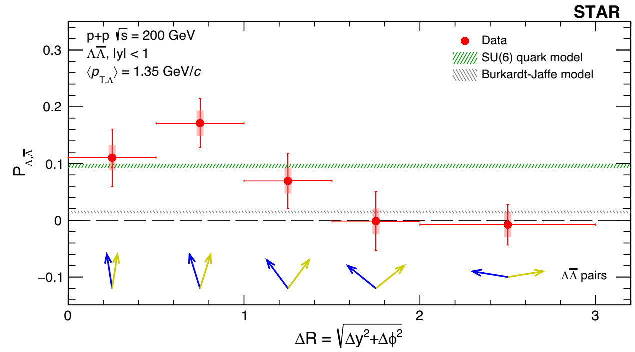

Fig. 2 (Color online) Spin correlation $P_{\Lambda_1\Lambda_2}$ as a function of pair separation ΔR. The data were compared with the predictions from the SU(6) quark model and Burkardt–Jaffe model. Statistical uncertainties are denoted by error bars, and systematic uncertainties are represented by shaded boxes. The blue and yellow arrows are used to illustrate the separation of the $\Lambda\bar{\Lambda}$ pairs. (Figure taken from [19])

with the absence of an initial correlated source q–q or $\bar{q}$–$\bar{q}$. As a null check, the K_S^0–K_S^0 pair showed no correlation, as expected.

Physics implication — The measurement provides an experimental window into the earliest non-perturbative stage of hadron formation. The persistence of the spin correlation suggests that a part of the quantum state of the virtual s–$\bar{s}$ pair survives the confinement process, leaving a measurable imprint in the final hyperons. This connection between vacuum quark–antiquark fluctuations and hadron spin opens a novel avenue for probing confinement. In particular, the observed ΔR dependence of the spin correlation indicates a stronger spin correlation in the short range, most probably when they come from parton's hadronization. This can be further verified with the spin correlation of the hyperon pair associated with jet production in *pp* collisions.

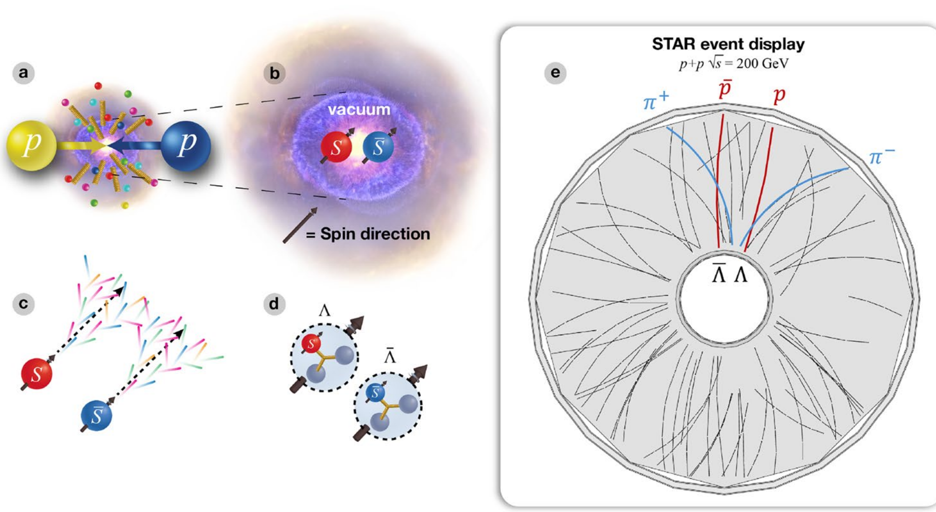

Fig. 1 (Color online) Illustration of tracing the QCD evolution of the spin of an $s\bar{s}$ pair into a $\Lambda\bar{\Lambda}$ hyperon pair and its measurement in STAR. **a** Relativistic *pp* collisions excite the QCD vacuum and liberate quark pairs; **b** some are spin–triplet $s\bar{s}$ pairs; **c** confinement drives their hadronization; **d** some $s\bar{s}$ pairs form $\Lambda\bar{\Lambda}$ hyperons whose spins are accessible through weak decays; **e** STAR reconstructs the decay daughters to determine the Λ and $\bar{\Lambda}$ spin correlation. (Figure taken from [19])

Conceptually, this work brings quantum information ideas—entanglement, decoherence, and spin correlation—into high-energy QCD studies and provides a new experimental paradigm for exploring the dynamics and interplay of quark confinement and entanglement. The vanishing of the correlation at large separation offers an experimentally accessible measure of decoherence in a strongly interacting non-perturbative system.

Outlook — The first results of the spin correlation of hyperon pair invite follow-up studies in multiple directions. Measurements at higher energies, different collision systems (p+A or A+A), or using multi-strange hyperons (Ξ, Ω) could reveal the dependence of spin-state survival on the system size and hadronization environment. In particular, the spin–spin correlation of hyperon pairs in heavy-ion collisions can provide further information on the properties of the guark–gluon plasma (QGP) and even the QCD phase transition, going beyond the global polarization effect in A+A collisions [21–25]. On the theoretical side, quantitative modeling of spin-state evolution during confinement—possibly connecting QCD-based fragmentation models, TMD evolution, and quantum information measures—will be essential for interpreting the magnitude and scale dependence of the observed effects. Overall, this study represents a milestone that links QCD vacuum fluctuations, hadron formation, and spin phenomena within a unified experimental framework.

The RHIC spin program has produced a remarkable breadth of exciting results over the years, utilizing unique polarized $p+p$ collisions [26–28]. These explorations are demonstrated clearly in the flagship measurements of the gluon and sea quark helicity distributions [17]. The STAR measurements of $W^{\pm}$ single-spin asymmetry, for the first time, concluded that there is a clear flavor asymmetry between the helicity distributions of $\bar{u}$ and $\bar{d}$ [29, 30]. The double-spin asymmetry measurements of the reconstructed jets revealed a significant contribution ($\sim$ 40%) of the gluon spin to the proton spin [28, 31]. The $\Lambda/\bar{\Lambda}$ spin transfer and polarization measurements in $p+p$ collisions at RHIC [32–36] provide sensitivities to strange quark polarization and the polarized fragmentation functions. Recent measurements of transverse spin asymmetries with transversely polarized $p+p$ collisions [37–39] have deepened our understanding of the three-dimensional structure of nucleons, in particular the transverse momentum-dependent (TMD) parton distribution functions and fragmentation functions.

Recently, the landmark observation of global hyperon polarization in heavy-ion collisions by STAR [40, 41], confirming the predictions made 20 years ago [42, 43], has established spin measurement as a new tool for QGP studies [21, 25]. The observed global spin alignment of the vector meson indicates a possible spin correlation of the quark–antiquark pair, which could naturally lead to a spin correlation of the hyperon pair [22, 23, 41]. The above-discussed spin correlation study in $p+p$, $p+A$ and $A+A$ opens a new avenue for both cold and hot QCD studies.

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