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Abstract

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Global Spin Alignment of Vector Mesons and Strong Force Fields in Heavy-Ion Collisions

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Introduction

Particles and fields represent two fundamental forms of matter in nature. Particles are excitations or quanta of their corresponding fields, characterized by quantum numbers such as mass, charge, spin, and parity. Photons, for instance, are quanta of electromagnetic fields that mediate electromagnetic forces among charged particles. At high energy scales in collisions, gluons emerge as quanta of color fields that mediate interactions among quarks, the elementary particles of strong interaction. At low energy scales, strong interaction is often described by mesons as effective degrees of freedom of quarks and gluons, a concept first proposed by Yukawa in 1935 through analogy with electromagnetic fields [?]. We now understand that nuclear forces as strong interactions at low energies involve many meson field components [?, ?], including σ , π , ρ , ω , etc. As the energy scale increases in nuclear reactions, other meson fields carrying strangeness quantum numbers may become relevant, such as K , ϕ , etc. As quanta of strong force fields, all these mesons with their specified quantum numbers were discovered before the 1960s. Due to their short Compton wavelengths, experimentally it is far easier to detect particles than wave-like fields, which are elusive and strongly fluctuating.

Recently, for the first time, the imprint of a strong force field was detected through the global spin alignment of vector mesons in heavy-ion collisions by the STAR experiment [?]. This represents another breakthrough following the measurement of global spin polarization of Λ hyperons in heavy-ion collisions [?]. The global spin polarization arises from the initial orbital angular momentum (OAM) in nuclear collisions, which is partially converted to local OAM or vorticity, leading to hadron polarization through spin-orbit coupling in the interaction [?]. The spin alignment of vector mesons in heavy-ion collisions along the OAM direction was first proposed by Liang and Wang several years ago [?]. The observable is the 00 element ρ_{00} of the spin density matrix for vector mesons, which can be measured through the angular distribution of their strong decay daughters in the meson's rest frame [?]. The STAR data for ρ_{00} show a surprisingly large positive deviation from 1/3—orders of magnitude larger than predictions from conventional mechanisms [?]. In Ref. [?], Sheng, Oliva, and Wang proposed that local correlation or fluctuation of the ϕ meson field can produce a large positive deviation for ρ_{00} from 1/3, thereby providing a possible explanation. Such ϕ fields may originate from non-perturbative strong interaction coupled to s and \bar{s} quarks and are connected with vacuum properties of quantum chromodynamics (QCD) [?, ?].

Vector Meson Spin Alignment

The spin state of a system of spin- S particles can be described by the spin density matrix $\hat{\rho}$, which is a $(2S + 1) \times (2S + 1)$ complex Hermitian matrix for spin- S particles with unit trace. The number of independent real variables in $\hat{\rho}$ is $4S(S + 1)$. For example, for spin-1/2 particles, there are 3 independent real variables corresponding to a polarization vector \mathbf{P} , as in $\hat{\rho} = (1/2)(1 + \boldsymbol{\sigma} \cdot \mathbf{P})$, where $\boldsymbol{\sigma}$ are

Pauli matrices. For spin-1 particles such as vector mesons, there are 8 independent real variables corresponding to a polarization vector \mathbf{P} (3 variables) and a symmetric traceless tensor \mathbf{T} (also called tensor polarization, 5 variables). As a spin-1/2 particle, the Λ hyperon's spin polarization can be measured through its parity-violating weak decay $\Lambda \rightarrow p\pi^-$, since the preferred direction of the daughter proton's momentum aligns with its spin in the rest frame. However, this approach does not work for vector mesons, as they primarily decay through strong interaction in which parity is conserved. Consequently, the measurable elements of the spin density matrix are its tensor components T , and ρ_{00} is associated with these components. For the ϕ meson's strong decay $\phi \rightarrow K^+K^-$, the daughter particle's polar angular distribution is given by:

$$\frac{dN}{d\cos\theta} \propto [1 - \rho_{00} + (3\rho_{00} - 1)\cos^2\theta]$$

We observe that ρ_{00} appears in the coefficient of \cos^2 , which can be determined by measuring the polar angle distribution. If $\rho_{00} = 1/3$, the distribution is constant, indicating that daughter particles are emitted isotropically. If $\rho_{00} \neq 1/3$, the probabilities of the vector meson in the three spin states are not equal, and the emission of daughter particles becomes anisotropic. For $\rho_{00} = 1/3$, the polar angle distribution assumes a cigar/disc shape (as shown in Fig. 1 [Figure 1: see original paper]). Correspondingly, if $\rho_{00} > 1/3$, the vector meson has a larger probability of being in the spin state $\lambda = 0$, so its average polarization vector (not the spin) aligns with the spin quantization axis. If $\rho_{00} < 1/3$, the vector meson has a larger probability of being in the spin states $\lambda = \pm 1$, and its average polarization vector aligns in the plane perpendicular to the spin quantization axis. The quantity is thus referred to as the spin alignment of the vector meson.

Experimental Results

In Ref. [?], ϕ and K^0 mesons are observed by pairing their decay daughters K^+K^- and $K\pi$, respectively, with subtraction of combinatorial background and application of event mixing and rotation methods. Detailed studies show that both techniques effectively break the correlation between pairs in real events, and the yields of ϕ and K^0 from the two techniques are consistent [?]. The spin quantization direction is chosen as the normal direction of the second-order event plane constructed from charged particles collected by the STAR Time Projection Chamber (TPC). The polar angle distribution from Eq. (1) is then analyzed, and ρ_{00} is extracted after correction for detection efficiency and acceptance. The spin quantization direction can be constructed using different detectors such as the shower maximum detector and the beam-beam counter, and all yield consistent results on the global spin alignment of ϕ and K^{*0} [?]. In the following discussion, we focus on results with respect to the TPC event plane.

Figure 2 [Figure 2: see original paper] shows the ρ_{00} data for ϕ and K^{*0} mesons

in $\sqrt{s_{NN}} = 11.5$ to 200 GeV measured in Au+Au collisions by the STAR collaboration [?], from a dedicated Beam Energy Scan program and multiple years of high-statistics event collection in Au+Au collisions at 200 GeV. Centrality categorizes events according to the observed number of tracks in each collision. Here, 0% centrality corresponds to exactly head-on collisions that produce the most tracks, while 100% centrality corresponds to barely glancing collisions that produce the fewest tracks. The STAR measurements presented in Fig. 2 are for the centrality interval of 20% to 60%, where one expects the largest OAM among collisions and a better signal-to-noise ratio in the experimental analysis. A complete set of results for centrality and transverse momentum dependence can be found in Ref. [?].

The STAR data show $\hat{\phi}_{00} = 0.3512 \pm 0.0017(\text{stat.}) \pm 0.0017(\text{syst.})$ and $\hat{K^0}_{00} = 0.3356 \pm 0.0034(\text{stat.}) \pm 0.0043(\text{syst.})$, obtained by averaging over results at energies from 11.5 to 62.4 GeV for ϕ , and from 11.5 to 54.4 GeV for K^0 [?]. Taking the total uncertainties as the sum in quadrature of statistical and systematic uncertainties, the results suggest that $\hat{\phi}_{00}$ is above 1/3 with a significance of 7.4σ , indicating significant global spin alignment for the ϕ meson. However, the values of $\hat{K^0}_{00}$ are consistent with 1/3. Measurements in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [?] in the p_T bin nearest to the mean p_T for STAR data in the range from 1.0 to 5.0 GeV/c are also shown for comparison. They are consistent with the STAR data, where the magnitude of the spin alignment for both ϕ and K^0 lies at 1/3 at the highest beam energies within large uncertainties.

Quark Coalescence Model

The quark coalescence model (QCM) serves as a convenient theoretical tool for describing hadron production or hadronization in heavy-ion collisions. Therefore, one can calculate the spin density matrix for vector mesons in terms of those for quarks and antiquarks within QCM [?, ?]. A non-relativistic QCM provides the simplest and most transparent framework for this purpose [?, ?].

In QCM, the meson's spin density operator can be constructed as $\hat{M} = \hat{q} \hat{\bar{q}}$, where \hat{q} and $\hat{\bar{q}}$ are spin density operators of the quark and antiquark in spin and momentum space, respectively. The elements $\rho(x, p)$ can be obtained by projecting \hat{M} onto two meson spin and momentum states and then performing a Fourier transformation with respect to the relative momentum of the two states. The ρ_{00} for the ϕ meson in phase space reads [?]:

$$\rho_{00}^{\phi}(x, p) \approx \frac{\langle P_q^y(x_1, p_1) P_{\bar{q}}^y(x_2, p_2) \rangle}{\langle P_q(x_1, p_1) \cdot P_{\bar{q}}(x_2, p_2) \rangle}$$

where $x_1 = x + \Delta x/2$, $x_2 = x - \Delta x/2$, $p_1 = p/2 + \Delta p$, $p_2 = p/2 - \Delta p$, the average is taken over Δx and Δp weighted by the ϕ meson's wave function, $P_q(x_1, p_1)$ and $P_{\bar{q}}(x_2, p_2)$ are spin polarization vectors of the quark and

antiquark respectively, and the spin quantization direction is taken along the y direction.

Equation (2) clearly shows that the vector meson's spin alignment is determined by the local correlation of the quark's and antiquark's polarization functions $P_q(x_1, p_1)$ and $P_{\bar{q}}(x_2, p_2)$ within the phase space limited by the meson's wave function.

Local Correlation of ϕ Fields

It is well known that fermions such as quarks at rest have magnetic moments proportional to their spins that become polarized along the direction of the magnetic field. For moving fermions, the electric field contributes through $\mathbf{p} \times \mathbf{E}$ (the spin-orbit coupling or spin-Hall effect). Similarly, vorticity fields and vector meson fields can also polarize quarks and antiquarks. For s and \bar{s} quarks that form the ϕ meson, the spin polarization vector is:

$$P_{q/\bar{q}} = \frac{\boldsymbol{\omega} \times \mathbf{p}}{2m_q E_p T} + \frac{\mathbf{E}_\phi \times \mathbf{p}}{T}$$

where T is the effective temperature of the quark matter when s and \bar{s} combine into the ϕ meson, and $\boldsymbol{\omega}$ are the electric and magnetic parts of the thermal vorticity tensor, and \mathbf{E}_ϕ and \mathbf{B}_ϕ are the electric and magnetic parts of the ϕ field, respectively. Here we neglect effects from electromagnetic fields since they dissipate quickly in the late stage of matter evolution in heavy-ion collisions. Effects from vorticity fields can also be neglected because their magnitudes, inferred from measured Λ polarization, are too small to account for the observed ϕ_{00} , though their terms are retained in Eq. (3) for contrast with ϕ field terms. The main difference between vorticity field terms and ϕ field terms in Eq. (3) is the sign for antiquarks: vorticity fields do not distinguish quarks from antiquarks, whereas ϕ fields do (similar to electromagnetic fields). As we shall see, this distinction is essential for obtaining a large vector meson spin alignment ϕ_{00} in the coalescence of s and \bar{s} into the ϕ meson.

Substituting Eq. (3) into Eq. (2), one finds that $\hat{\phi}_{00}$ depends on the local correlation of ϕ fields within the ϕ meson's wave function. A more rigorous approach based on relativistic QCM has been formulated using the closed-time-path (Schwinger-Keldysh) method in quantum field theory [?, ?]. The result obtained for $\hat{\phi}_{00}$ reads [?, ?]:

$$\rho_{00}^\phi(t, x, p) \approx \frac{1}{3} + C_1 \left[\frac{1}{2} \boldsymbol{\omega}' \cdot \boldsymbol{\omega}' - (\boldsymbol{\epsilon}_0 \cdot \boldsymbol{\omega}')^2 \right] + C_2 \left[\frac{1}{2} \mathbf{E}'_\phi \cdot \mathbf{E}'_\phi - (\boldsymbol{\epsilon}_0 \cdot \mathbf{E}'_\phi)^2 \right] + C_2 \left[\frac{1}{2} \mathbf{B}'_\phi \cdot \mathbf{B}'_\phi - (\boldsymbol{\epsilon}_0 \cdot \mathbf{B}'_\phi)^2 \right]$$

where the primed fields are in the ϕ meson's rest frame, and C_1 and C_2 are functions of m_s (strange quark mass) and m_ϕ (ϕ meson mass). We see that

all terms appear as squares of fields. The momentum dependence of $\hat{\phi}_{00}$ can be obtained by rewriting the expression in terms of fields in the lab frame using Lorentz transformation. By taking averages over space-time on the hadronization hyper-surface of the ϕ meson, one obtains $\hat{\phi}_{00}$ as functions of momentum that can be compared with STAR data [?]. The parameters appear in the form $g^2 E^2 \phi / T^2$ and $g^2 B^2 \phi / T^2$ and reflect local fluctuations of ϕ fields [?]. If we assume that local field fluctuations differ in the transverse (labeled as i) and longitudinal (labeled as z) directions with respect to the beam direction in heavy-ion collisions, then $\hat{\phi}_{00}$ depends on two parameters: $F^2 = g^2 E^2 \{\phi, i\} / T^2 = g^2 B^2 \{\phi, i\} / T^2$ and $T = g^2 E^2 \{\phi, z\} / T^2 = g^2 B^2 \{\phi, z\} / T^2$. The values of these two parameters are determined by fitting STAR data on ϕ_{00} as functions of collision energies in Fig. 2. With the fitted parameter values, one can predict the transverse momentum spectra of $\hat{\phi}_{00}$ at all available collision energies, which are in good agreement with STAR data [?].

Summary and Outlook

An unexpectedly large global spin alignment of ϕ mesons has been observed by the STAR Collaboration [?] in relativistic heavy-ion collisions. Using the quark coalescence model for hadron production, Refs. [?, ?, ?] provide a good interpretation of the data [?]. According to this interpretation, such a large global spin alignment of ϕ mesons is induced by local correlation or fluctuation of strong force fields on the hadronization hyper-surface. The average values $E^2 \phi$ and $B^2 \phi$ reflect the local fluctuation of ϕ fields and are expected to be calculable using lattice QCD.

These studies open a new avenue for investigating properties of strongly interacting quark matter as well as non-perturbative properties of strong interaction. Furthermore, relativistic heavy-ion collisions are often called “small bang” in contrast to the Big Bang of the universe. In this analogy, hadronization on the freeze-out hyper-surface corresponds to the stage in the early universe when particles decoupled from interactions during the Big Bang. The vector meson’s spin alignment is similar to polarization modes of cosmic microwave background radiation.

We note that such an explanation remains subject to debate and requires further verification. More systematic studies in both experiments and theory are needed to clarify the deep physics behind these phenomena.

Conflict of Interest

The authors declare that they have no conflict of interest.

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References

- [1] Hideki Yukawa. On the Interaction of Elementary Particles I. Proc. Phys. Math. Soc. Jap., 17:48–57, 1935.
- [2] Shoji Sawada, Tamotsu Ueda, Wataro Watari, and Minoru Yonezawa. One Boson Exchange Model in Proton-Proton Scattering: An Approach to the Strong Interaction. Prog. Theor. Phys., 28:991–1025, 1962.
- [3] Aneesh Manohar and Howard Georgi. Chiral Quarks and the Nonrelativistic Quark Model. Nucl. Phys. B, 234:189–212, 1984.
- [4] M. S. Abdallah et al. Pattern of global spin alignment of ϕ and K^0 mesons in heavy-ion collisions. *Nature*, 614(7947):244–248, 2023.
- [5] L. Adamczyk et al. Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid. *Nature*, 548:62–65, 2017.
- [6] Zuo-Tang Liang and Xin-Nian Wang. Globally polarized quark-gluon plasma in non-central $A+A$ collisions. *Phys. Rev. Lett.*, 94:102301, 2005. [Erratum: *Phys. Rev. Lett.* 96,039901(2006)].
- [7] Zuo-Tang Liang and Xin-Nian Wang. Spin alignment of vector mesons in non-central $A+A$ collisions. *Phys. Lett.*, B629:20–26, 2005.
- [8] Xin-Nian Wang. Vector meson spin alignment by the strong force field. *Nucl. Sci. Tech.*, 34:15, 2023.
- [9] B. I. Abelev et al. Spin alignment measurements of the $K^0(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev.*, C77:061902, 2008.
- [10] Xin-Li Sheng, Lucia Oliva, and Qun Wang. What can we learn from the global spin alignment of ϕ mesons in heavy-ion collisions? *Phys. Rev. D*, 101(9):096005, 2020. [Erratum: *Phys. Rev. D* 105, 099903 (2022)].
- [11] Edward V. Shuryak. The Role of Instantons in Quantum Chromodynamics. I. Physical Vacuum. *Nucl. Phys. B*, 203:93, 1982.
- [12] Mikhail A. Shifman, A. I. Vainshtein, and Valentin I. Zakharov. QCD and Resonance Physics. Theoretical Foundations. *Nucl. Phys. B*, 147:385–447, 1979.
- [13] Shreyasi Acharya et al. Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions. *Phys. Rev. Lett.*, 125:012301, 2020.
- [14] Xin-Li Sheng, Zuo-Tang Liang, and Qun Wang. Global spin alignments of vector meson in heavy ion collisions. *Acta. Phys. Sin.* (in Chinese), 72:072502, 2023.
- [15] Xin-Li Sheng, Lucia Oliva, Zuo-Tang Liang, Qun Wang, and Xin-Nian Wang. Spin alignment of vector mesons in heavy-ion collisions. 5 2022.
- [16] Xin-Li Sheng, Lucia Oliva, Zuo-Tang Liang, Qun Wang, and Xin-Nian

Wang. Relativistic spin dynamics for vector mesons. 6 2022.

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