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Exploring the impact of strong-force fields on ϕ-meson spin alignment within a quantum relativistic transport approach

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Abstract. The unexpected pattern of global spin alignment of vector mesons observed in relativistic heavy-ion collisions for different particle species has posed a serious challenge to theoretical interpretation, as it cannot be explained solely by conventional polarization sources such as vorticity and electromagnetic fields. Fluctuations of strong-force fields may be the key to solving this puzzle. In these proceedings, we review our calculations of the spin density matrix for flavorless vector mesons. The large spin alignment observed for ϕ mesons at lower energies may arise from strong-force fields that polarize the strange quarks and antiquarks, which form polarized mesons via coalescence at hadronization. The strength of the effective ϕ field can be inferred from the experimental data on ϕ-meson spin alignment.

1 Introduction

Heavy-ion collisions (HICs) at high energy create a deconfined state of quarks and gluons, named Quark-Gluon Plasma (QGP). In the last decade, the experimental collaborations reported exciting measurements on spin polarization: a preferential orientation of particle spins along a specific direction offers a powerful probe of the underlying QGP dynamics [1, 2], particularly the role of intense fields produced in the collision. The observation of global polarization of Λ baryons along the system's angular momentum by STAR Collaboration at the Relativistic Heavy Ion Collider (RHIC) [3] represented the first experimental evidence of vorticity in the QGP, recognizing it as the most vortical fluid ever observed in nature. Polarization measurements were then extended to vector mesons: STAR reported a spin alignment consistent with zero in K^{*0} mesons, but a surprisingly large positive alignment in ϕ mesons [4]. This pattern cannot be explained by conventional polarization sources such as vorticity or electromagnetic (EM) fields [5]. We have proposed that fluctuations and correlations of strong-force fields may be responsible for the observed ϕ-meson spin alignment [6].

2 Relativistic spin Boltzmann equation for vector mesons

A relativistic spin Boltzmann equation (SBE) for vector mesons is derived [7] from the Kadanoff-Baym equations [8] for Wigner functions, incorporating an effective quark-meson

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model [9] for describing the strong interaction and the quark coalescence process [10, 11] as hadronization mechanism. The SBE describes the phase-space evolution of the matrix-valued spin dependent distribution (MVSD) of the vector meson $f^V_{\lambda_1\lambda_2}$, where $\lambda_1, \lambda_2 = -1, 0, +1$ denote its spin states along the spin quantization direction. In the dilute gas limit the SBE for the vector meson's MVSD can be expressed as [7]

$$k \cdot \partial_x f^V_{\lambda_1\lambda_2}(x, \mathbf{k}) = \frac{1}{8}\left[\epsilon^*_\mu(\lambda_1, \mathbf{k})\epsilon_\nu(\lambda_2, \mathbf{k})C^{\mu\nu}_{\rm coal}(x, \mathbf{k}) - C_{\rm diss}(\mathbf{k})f^V_{\lambda_1\lambda_2}(x, \mathbf{k})\right], \tag{1}$$

where $k^\mu = (E^V_{\mathbf{k}}, \mathbf{k})$ is the on-shell four-momentum of the vector meson. The collision kernel in the SBE is constituted by the gain and loss terms, $C^{\mu\nu}_{\rm coal}$ and $C_{\rm diss}$ respectively, which correspond to the coalescence and dissociation processes. The dissociation kernel is independent of the MVSDs of the quark, antiquark and vector meson; hence, it is independent on the quark polarization. The coalescence kernel instead depends on the MVSDs for the quark and antiquark, which involves the unpolarized distribution $f_{q/\bar{q}}$ and the spin polarization four-vector $P^\mu_{q/\bar{q}}$ for the quark/antiquark [12–14]. In terms of the latters, $C^{\mu\nu}_{\rm coal}$ reads [6, 7]:

$$\begin{aligned} C^{\mu\nu}_{\rm coal}(x, \mathbf{k}) = &\int \frac{d^3\mathbf{p}'}{(2\pi\hbar)^2}\frac{1}{E^{\bar{q}}_{\mathbf{p}'}E^q_{\mathbf{k}-\mathbf{p}'}}\delta\left(E^V_{\mathbf{k}} - E^{\bar{q}}_{\mathbf{p}'} - E^q_{\mathbf{k}-\mathbf{p}'}\right)f_{\bar{q}}(x, \mathbf{p}')f_q(x, \mathbf{k}-\mathbf{p}') \\ &\times \mathrm{Tr}\left\{\Gamma^\nu\left(p' \cdot \gamma - m_{\bar{q}}\right)\left[1 + \gamma_5\gamma \cdot P^{\bar{q}}(x, \mathbf{p}')\right]\Gamma^\mu\left[(k - p') \cdot \gamma + m_q\right][1 + \gamma_5\gamma \cdot P^q(x, \mathbf{k}-\mathbf{p}')]\right\}, \end{aligned} \tag{2}$$

where $p'^\mu = (E^{\bar{q}}_{\mathbf{p}'}, \mathbf{p}')$ and $k^\mu - p'^\mu$ denote the on-shell four-momenta of the antiquark and the quark respectively, and $m_{\bar{q}} = m_q$ are their masses. The $q\bar{q}V$ vertices appear in the form $\Gamma^\alpha \approx g_V B(\mathbf{k} - \mathbf{p}', \mathbf{p}')\gamma^\alpha$, where g_V is the coupling constant of the vector meson and quark-antiquark, and $B(\mathbf{k} - \mathbf{p}', \mathbf{p}')$ denotes the Bethe-Salpeter wave function of the vector meson. Assuming thermal equilibrium, the spin polarization four-vectors as phase space distributions for quarks and antiquarks are given by

$$P^\mu_{q/\bar{q}}(x, \mathbf{p}) \approx \frac{1}{4m_{q/\bar{q}}}\epsilon^{\mu\nu\rho\sigma}p_\nu\left[\omega_{\rho\sigma} \pm \frac{g_V}{(u \cdot p)T_h}F^V_{\rho\sigma}\right], \tag{3}$$

where T_h is the hadronization temperature, u^μ is the local four-velocity of the medium, $\omega_{\rho\sigma}$ is the thermal vorticity field and $F^V_{\rho\sigma}$ is the effective vector-meson field, corresponding to long-wavelength components of the strong-force fields [6, 7].

By solving the SBE, we obtain the spin density matrix for vector mesons as phase-space distribution. After proper normalization, the resulting spin density matrix is fully determined by the coalescence kernel (2). Therefore, the SBE describes the polarization transfer from constituent quarks and antiquarks to vector mesons at the hadronization stage of HICs.

3 Global spin alignment of ϕ mesons from strong-force fields

We focus on ϕ mesons created through coalescence of strange quark and antiquark and evaluate their spin density matrix in terms of the fields in the laboratory frame of the collision: $\boldsymbol{\varepsilon}$ and $\boldsymbol{\omega}$ denote the electric and magnetic part of $\omega_{\mu\nu}$; $\mathbf{E}_\phi$ and $\mathbf{B}_\phi$ the electric and magnetic part of $F^{\mu\nu}_\phi$. After choosing a spin quantization direction, the 00 element of the spin density matrix for ϕ mesons has the form:

$$\rho^\phi_{00}(x, \mathbf{k}) \approx \frac{1}{3} + \frac{1}{3}\sum_{i=1,2,3}\left\{I_{B_i}(\mathbf{k})\left[\omega_i^2 - \frac{4}{m_\phi^2}\left(\frac{g_\phi B^\phi_i(x)}{T_h}\right)^2\right] + I_{E_i}(\mathbf{k})\left[\varepsilon_i^2 - \frac{4}{m_\phi^2}\left(\frac{g_\phi E^\phi_i(x)}{T_h}\right)^2\right]\right\} \tag{4}$$

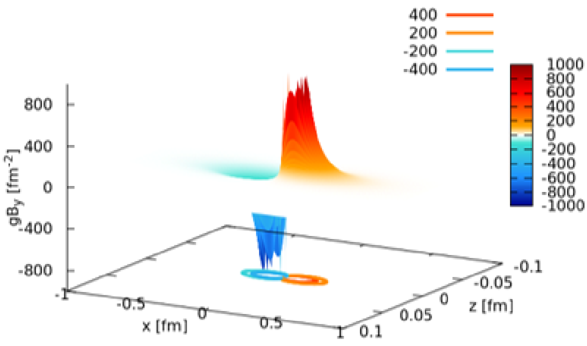

Figure 1. Profile on the $x - z$ plane of the y component of the magnetic part of the effective vector ϕ field, $g_\phi B_y$, generated by a single strange charge moving at constant velocity along the z axis.

where the coefficients I depend only on the ϕ-meson mass and momentum components; see Ref. [7] for their explicit expressions. We see from Eq. (4) that in the ρ_{00}^{ϕ} there is a cancellation of all mixed terms of different fields and different components of the same field. Only short-distance correlations between the same components of a given field determine the spin alignment of vector mesons. This remarkable result makes the ϕ meson a powerful analyzer of field fluctuations through its spin observables: any spatial anisotropy of field fluctuations in the meson's rest frame with respect to the spin quantization direction will induce spin alignment, i.e., $\rho_{00} - 1/3 \neq 0$. The contributions from the vortical and EM fields to the ϕ meson spin alignment are of order $10^{-5} - 10^{-3}$ [5], much smaller than that observed by STAR Collaboration [4]. Therefore, we support the idea that the dominant effect is induced by strong-force fields.

The vector ϕ field is an effective description of the strong interaction between the strange quark-antiquark pair constituting the ϕ meson and the strange quarks and antiquarks in the surrounding medium. This field, having a vanishing mean value, is dominated by fluctuations. However, it induces a sizable contribution to the spin alignment of ϕ meson because the polarizations of the constituent s and $\bar{s}$ are strongly correlated. Like electric charges in motion can generate an EM field, strange charges in motion can generate an effective ϕ vector field. In analogy to EM fields, the ϕ field can polarize s and $\bar{s}$, but with a larger magnitude due to larger value of the corresponding coupling constant: $\alpha_\phi = g_\phi^2/(4\pi) \sim O(1)$, about two orders of magnitude larger than $\alpha_{EM} = e^2/(4\pi) \simeq 1/137$. The vector meson field can be computed in a similar way as the EM field, with some additional complexity due to the presence of the vector meson mass [15]. The result for the B_y^ϕ component generated by a single strange charge moving at constant relativistic velocity along the z direction is illustrated in Fig. 1, and can be compared to the correspondent calculation for the EM field produced by a single electric charge, see Fig. 1 of Ref. [16].

The result in Eq. (4) has also a remarkable factorization form: the field fluctuations are spacetime functions separated by the momentum functions $I(\mathbf{k})$. The advantage of this factorized form is that, once the momentum averages of the coefficients are determined (weighted by ϕ-meson momentum spectra taking into account the azimuthal anisotropy), the spacetime averages of the unknown strong-force field strengths at hadronization can be considered as model parameters to be extracted from the experimental data for the momentum-integrated ρ_{00}^{ϕ}. STAR has measured ρ_{00}^{ϕ} with respect to different spin quantization axes [4]: the out-of-plane direction, i.e., the direction of the global orbital angular momentum in HICs, and the in-plane direction, that is, along the impact parameter axis; see data on the upper left panel of Fig. 2. We choose as two independent parameters the transverse and longitudinal fluctuations of the effective ϕ field: $\langle (g_\phi B_{x,y}^\phi/T_h)^2\rangle = \langle (g_\phi E_{x,y}^\phi/T_h)^2\rangle \equiv F_T^2$ and $\langle (g_\phi B_z^\phi/T_h)^2\rangle = \langle (g_\phi E_z^\phi/T_h)^2\rangle \equiv F_z^2$. The extracted parameters are shown in the bottom left

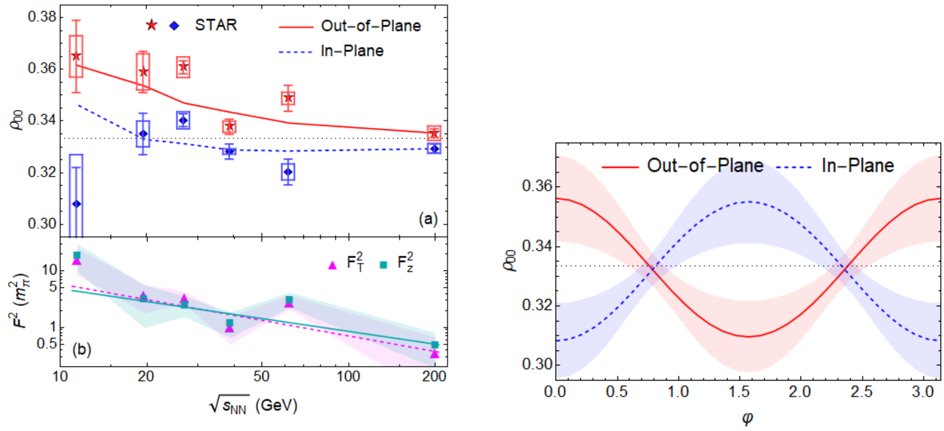

Figure 2. Left panel: collision energy dependence of the ϕ-meson spin alignment in the out-of-plane (red) and in-plane (blue) directions measured by STAR [4] (a) and our extraction of the effective ϕ-meson field strengths (b). Right panel: our prediction for the azimuthal-angle dependence of the ϕ-meson spin alignment. Figures adapted from Ref. [6].

panel of Fig. 2. The field fluctuations strengths F_T^2 and F_z^2 are of the same order and have a strong beam energy dependence, ranging from about 0.5 m_π^2 at $\sqrt{s_{NN}}$ = 200 GeV to more than one order of magnitude larger at 11.5 GeV. Once the field fluctuation parameters have been determined, the momentum dependence of the spin alignment can be calculated [6]. Our findings for the transverse momentum dependence of ρ_{00}^{ϕ} are in fair agreement with STAR data, while our prediction for its azimuthal angle dependence (right panel of Fig. 2) can serve as a test of model validity in future experiments. This would also allow further exploration of the role of strong-force fields on spin polarization observables.

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