

New method to clarify the contribution of the chiral magnetic effect in small collision systems $p^\uparrow + A$ involving a transversely polarized proton

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In this Letter, we propose a new experimental method to check the contribution of the chiral magnetic effect (CME). With experimental data of deep inelastic scattering (DIS) involving transversely polarized proton, we have calculated the three-dimensional charge density inside the polarized proton, which is found to have a significant violation to spherical symmetry. Then we have calculated the property of electromagnetic field (EM field) generated by a single transversely polarized proton ($p^\uparrow$). Based on them, the EM fields generated in small collision system $p^\uparrow + A$ are studied. We find that the orientation of this EM field has a significant dependence on the polarization direction of the proton, and the correlator ($\Delta\gamma$) has also significant dependence on the angle between the reaction plane and polarization direction. As background contributions are canceled comparing two collision geometry schemes, only the contribution of CME remains.

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In recent years, it has been recognized that there may be a Charge conjugation Parity (CP) violation effect [1–6] due to the quantum anomalous fluctuation of quantum chromodynamics (QCD) vacuum. This effect can be observed as chiral magnetic effect (CME) in quark-gluon plasma (QGP) with existing strong magnetic fields [3,4]. In a high energy heavy ion collision experiment, QGP is produced since the extreme environment needed for the phase transition is satisfied, and a strong magnetic field is also produced in noncentral heavy ion collisions [7–14]. So heavy ion collisions are an excellent place to study CME. A charge asymmetry (charge separation) along the magnetic field is induced by the CME, which provides a way to study the quantum anomaly of QCD vacuum topology.

In order to study the charge separation, a three-point correlator γ is introduced [15],

$$\gamma_{\alpha\beta} = \langle \cos(\Phi_\alpha + \Phi_\beta - 2\Phi_{RP}) \rangle, \quad (1)$$

where Φ_α and Φ_β are azimuthal angles of charged particles α and β , Φ_{RP} is the azimuthal angle of the reaction plane respective to the laboratory frame. To cancel charge-independent backgrounds, the difference of correlator $\Delta\gamma = \gamma_{OS} - \gamma_{SS}$ is used [5], where γ_{OS} represents for opposite charge particle

pair, γ_{SS} represents for same charge particle pair. The contribution of CME into correlator can be expressed as [16,17]

$$\Delta\gamma_{CME} \propto B^2 \cdot \cos[2(\Phi_B - \Phi_{RP})], \quad (2)$$

where Φ_B is the azimuthal angle of magnetic field. However, a large amount of QCD background effects is also included in $\Delta\gamma$ which is related to QGP flow v_2 [18–23]. It is a huge challenge to clarify the contributions of CME and background correspondingly in experiment data of $\Delta\gamma_{exp}$:

$$\Delta\gamma_{exp} = \Delta\gamma_{CME} + \Delta\gamma_{BG}. \quad (3)$$

In this Letter, we propose a new method to check and clarify the contribution of CME in small collision systems involving a transversely polarized proton $p^\uparrow + A$

In our previous work [24], employing a physical charge-profile model to describe the inner charge distribution of a proton, we calculated the property of an electromagnetic field produced in small system $p + A$. We find that there is a significant azimuthal correlation between Φ_B and Φ_{RP} . Here, we forward our study to a transversely polarized proton.

In deep inelastic scattering (DIS) onto transversely polarized nucleon experiment [25], the plane charge distribution of a polarized proton is given by

$$\begin{aligned} \rho_T^N(\mathbf{b}) &= \rho_0^N(b) - \sin(\phi_b - \phi_s) \\ &\times \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M_N} J_1(bQ) \frac{G_M(Q^2) - G_E(Q^2)}{1 + \tau}. \end{aligned} \quad (4)$$

The first term in it is the plane charge distribution of an unpolarized proton, which is also given by the DIS experiment [26]

$$\rho_0^N(\mathbf{b}) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) \frac{G_E(Q^2) + \tau G_M(Q^2)}{1 + \tau}, \quad (5)$$

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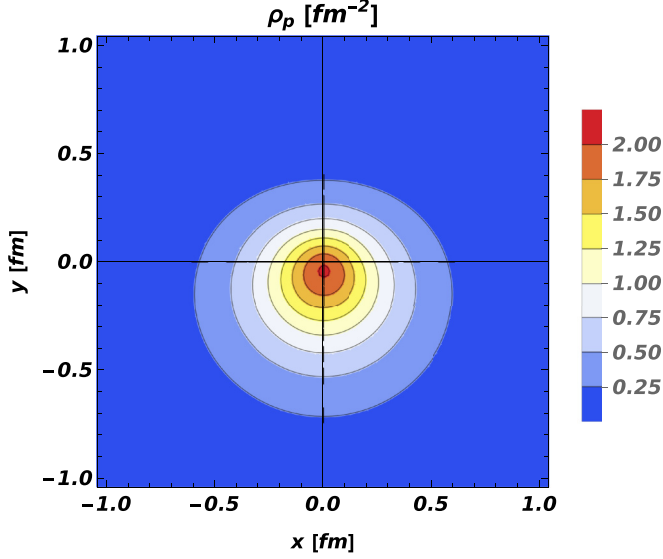


FIG. 1. Plane charge density in a proton polarized along $+x$ direction.

where $\tau = \frac{Q^2}{4M^2}$, M is the mass of proton, J_0 and J_1 are cylindrical Bessel functions. The electric form factor G_E and magnetic form factor G_M of the proton are given in the following parametrized form [27–29]:

$$G_E \frac{G_M}{\mu_p} = \frac{1 + \sum_{i=1}^n a_i^{E,M} \tau^i}{1 + \sum_{i=1}^{n+2} b_i^{E,M} \tau^i}. \quad (6)$$

With these parametrization, the plane charge density of a proton polarized along $+x$ direction is shown in Fig. 1.

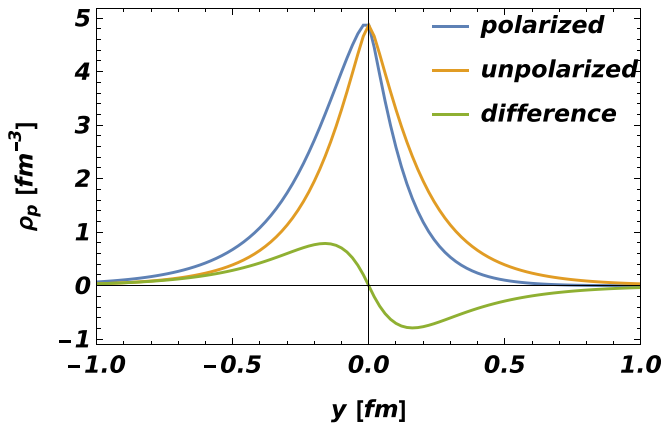


FIG. 2. The three-dimensional charge profiles in an unpolarized proton (orange curve) and a proton polarized along $+x$ (blue curve) as function of y at $x = 0$ and $z = 0$.

we can see that the center of charge moved along $-y$ direction.

The origin of this asymmetry is not clear now. It could be related perhaps with the Siverts effect [30], i.e., the asymmetry in the transverse momentum distribution of partons in a polarized proton. And/or it could be explained as a synchronization effect, the energy density of a transversely polarized proton could be modified in tilted light front coordinates [31].

With this plane charge distribution in a polarized proton, we can derive its three-dimensional (3D) charge profile using the same method in [24]. Shown in Fig. 2, we compare the 3D charge profile of a polarized proton and an unpolarized proton. Their difference defined as $\rho_{\text{pol}} - \rho_{\text{unpol}}$, also shown in this figure. We can see that there is a significant violation to spherical symmetry in 3D charge profile as our expectation.

Using Lienard-Wiechert potential, we can calculate the spatial distribution of the electromagnetic field generated by a single flying polarized proton:

$$e\mathbf{E}(t, \mathbf{r}) = \frac{e^2}{4\pi} \sum_n Z_n(\mathbf{R}) \frac{\mathbf{R}_n - \mathbf{R}_n \mathbf{v}_n}{(R_n - \mathbf{R}_n \cdot \mathbf{v}_n)^3} (1 - v_n^2),$$

$$e\mathbf{B}(t, \mathbf{r}) = \frac{e^2}{4\pi} \sum_n Z_n(\mathbf{R}) \frac{\mathbf{v}_n \times \mathbf{R}_n}{(R_n - \mathbf{R}_n \cdot \mathbf{v}_n)^3} (1 - v_n^2). \quad (7)$$

Here, Z_n is the n th particle charge number, v_n is its velocity. $\mathbf{R}_n = \mathbf{r} - \mathbf{r}_n$ is the relative position of the field point $\mathbf{r}$ and the source point $\mathbf{r}_n$ which is the n th particle at the position with a delay time of $t_n = t - |\mathbf{r} - \mathbf{r}_n|$ [11].

We set the proton polarized along $+x$ axis still and flying with a relativistic heavy ion collider (RHIC) energy scale ($E = 100$ GeV) along $+z$ direction. $t = 0$ is set as the proton just flying through the origin of coordinate $z = 0$. Shown in Fig. 3 is the magnetic field produced by this polarized proton at $t = 0$. Left panel of it showed the vector stream (vector) and strength (color) on plane with $z = 0$, while the right panel showed them on a plane with $z = 1/\gamma$ fm with a Lorentz factor $\gamma = E/m_p$.

To compare the magnetic field produced by polarized and unpolarized protons, we defined $\Delta \mathbf{B} = \mathbf{B}_{\text{pol}} - \mathbf{B}_{\text{unpol}}$. The results are shown in Fig. 4. We can see that the intensity of $\Delta \mathbf{B}$ is the same order of the strength of $\mathbf{B}$ within the circle of proton size, which will be the overlap region in small collision system $p + A$.

So, let us move from a flying single polarized proton to small collision system $p^\uparrow + \text{Au}$ at RHIC energy $\sqrt{s} = 200$ GeV. The collision geometry is set as the momentum of the proton being in the $+z$ direction, while the Au nuclei being in the $-z$ direction. And the polarization is fixed as $+x$ direction. Impact parameter is defined as the vector point from center of Au to center of proton. Since the azimuthal angle of reaction plane Φ_{RP} is random in each event, we showed an illustration of one event with $\Phi_{RP} \neq 0$ in Fig. 5. In our following calculation, just four collision geometry schemes are investigated with $\Phi_{RP} = 0, \pi/2, \pi$, and $3\pi/2$, respectively, illustrated in Fig. 6.

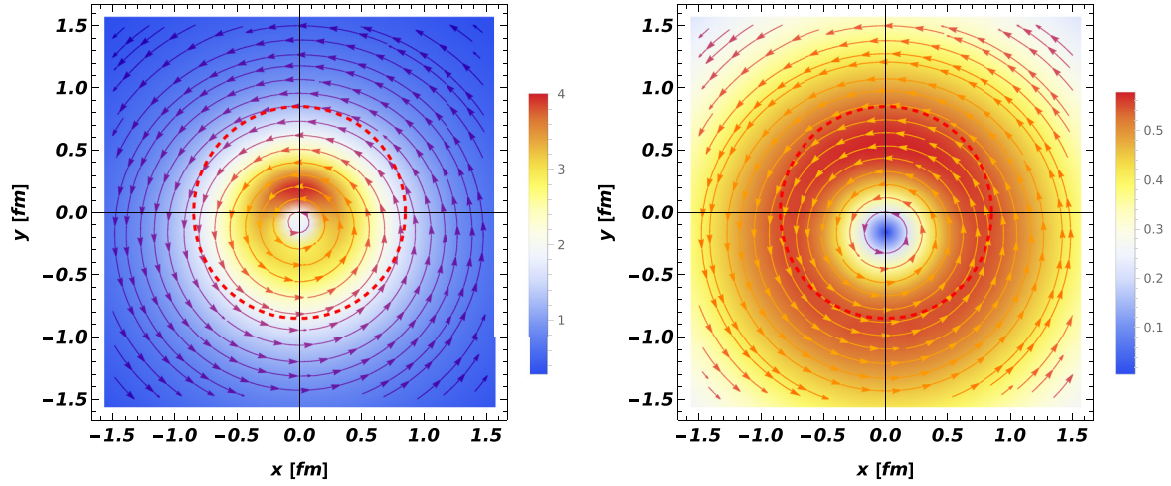


FIG. 3. The distribution of magnetic field $\mathbf{B}$ on plane with $z = 0$ (left panel), and $z = 1/\gamma$ fm (right panel) at $t = 0$. A red circle with $r = 0.85$ fm is shown together, which is typical radii of proton.

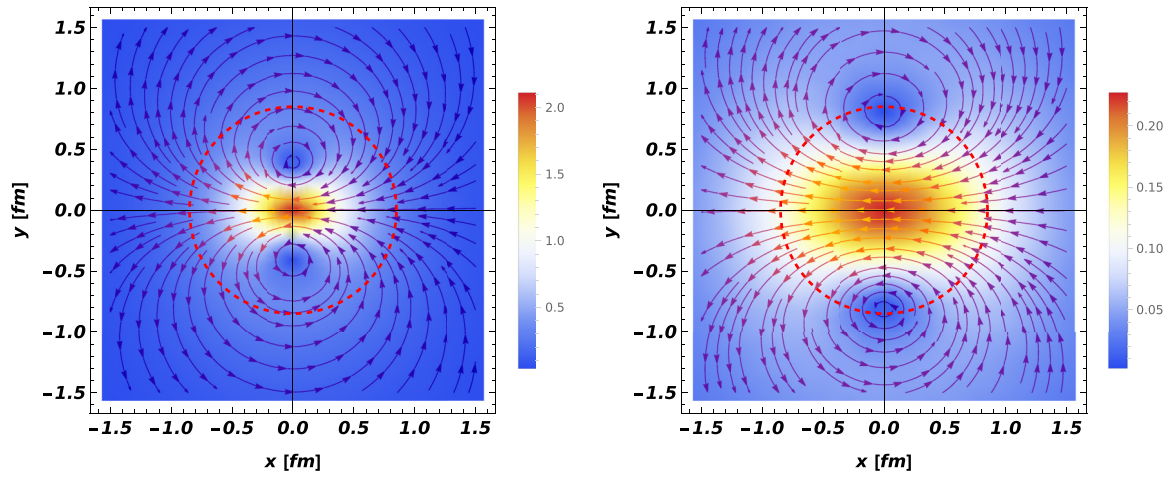


FIG. 4. The distribution of magnetic field difference $\Delta \mathbf{B}$ on plane with $z = 0$ (left panel), and $z = 1/\gamma$ fm (right panel) at $t = 0$. A red circle with $r = 0.85$ fm is shown together, which is typical radii of proton.

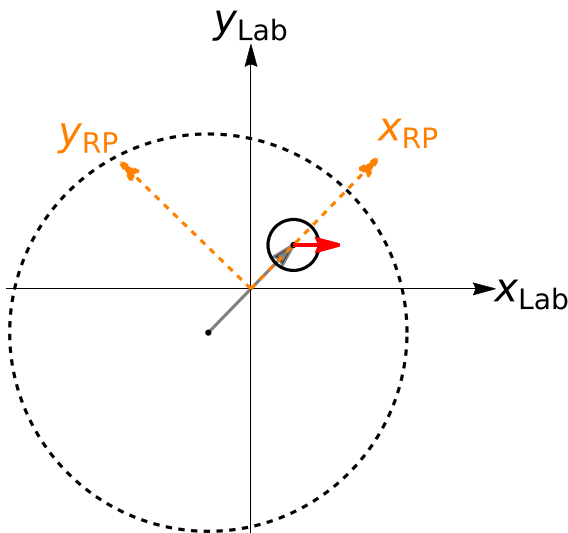


FIG. 5. An illustration of collision geometry of $p^\dagger + \text{Au}$ with $\Phi_{RP} \neq 0$.

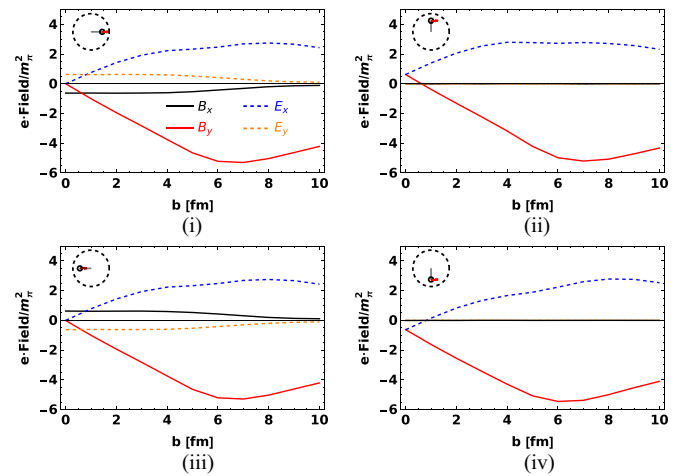


FIG. 6. The strength of electromagnetic fields B_x , B_y , E_x , and E_y as function of impact parameter b in four collision geometry schemes.

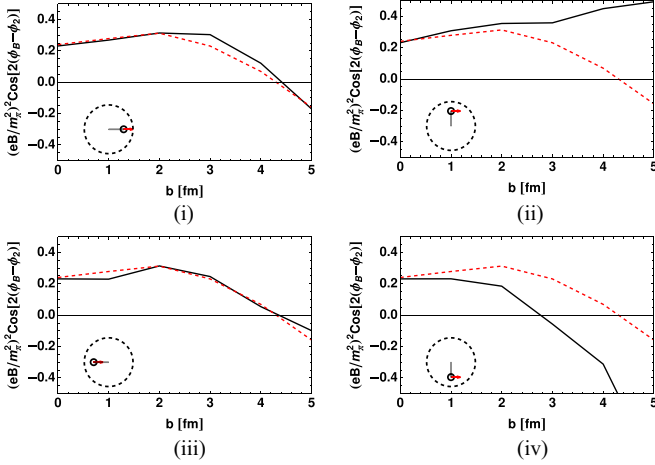


FIG. 7. $B^2 \cdot \cos[2(\Phi_B - \Phi_2)]$ as function of impact parameter b in four collision geometry schemes. The red dashed curve in each panel is result of unpolarized $p + \text{Au}$ collisions, as a comparison.

Then HIJING model [32,33] is employed to simulate the $p + A$ collision process event by event in each collision scheme. In our calculation of electromagnetic fields, the 3D unsymmetrical charge profile is used for the transversely polarized projectile proton, and 3D symmetrical charge profile is used for nucleons in target Au.

Our results of electromagnetic fields on the center of the overlap region averaged over events are shown in Fig. 6 for the four schemes. Components of $\mathbf{B}$ and $\mathbf{E}$ are projected into the frame of the event plane. So, we can see that the value of B_y is always negative as our expectation.

In order to get the CME signal we calculated the correlator as Eq. (8). Here, Φ_2 is the azimuthal angle of the event plane which is determined by all participant nucleons in each event [34]. Although the difference between Φ_{RP} and Φ_2 is small, the correlator as Eq. (8) is more convenient to compare with

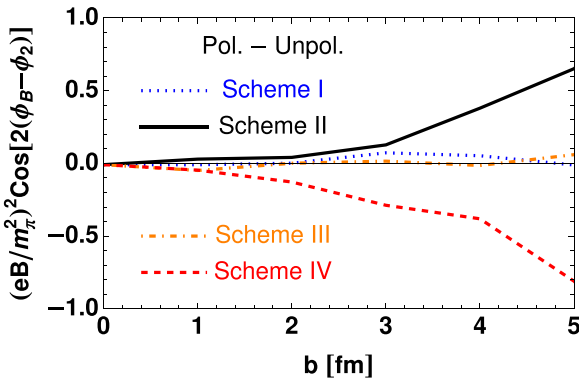


FIG. 8. Difference of $B^2 \cdot \cos[2(\Phi_B - \Phi_2)]$ between unpolarized $p + A$ and polarized $p + A$ in four schemes, as function of impact parameter b .

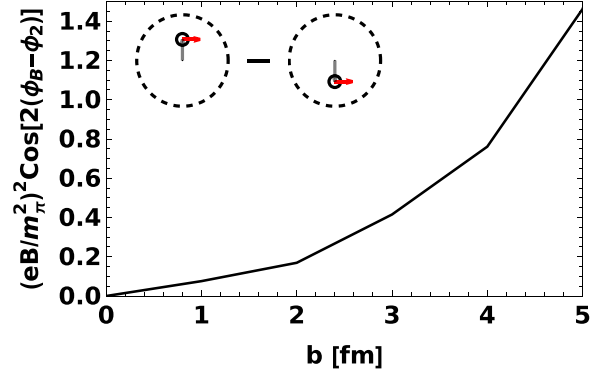


FIG. 9. Difference of $B^2 \cdot \cos[2(\Phi_B - \Phi_2)]$ between scheme II and scheme IV, as function of impact parameter b .

possible future experiment data

$$\Delta\gamma_{\text{CME}} \propto B^2 \cdot \cos[2(\Phi_B - \Phi_2)]. \quad (8)$$

The results of correlators as function of impact parameter b in the four schemes are shown in Fig. 7. In each scheme, the correlator is not zero at small b because of the fluctuation of $\mathbf{B}$ is not vanished in each event. Also, the result of unpolarized $p + A$ collisions is shown in each panel as a red curve, which shows the results of scheme I and scheme III are similar with unpolarized result, while scheme II and scheme IV give significant deviation from the unpolarized result. These features are shown in Fig. 8 directly as the difference between polarized and unpolarized $p + \text{Au}$ collisions.

Especially, we noticed that there is a significant difference between scheme II and scheme IV. These two schemes correspond to the azimuthal angle of impact parameter b lying on the $+y$ and $-y$ sectors, respectively, in the laboratory frame. People can distinguish these two schemes in experiment with zero degree calorimeters on RHIC. It is more obvious to see the difference of CME correlators between schemes II and IV $\Delta\gamma_{\text{CMEII}} - \Delta\gamma_{\text{CMEIV}}$, shown in Fig. 9. The difference in these two schemes increases with impact parameter, and reach a same order of Au + Au collision. So, if QGP is produced in small collision system, and CME exist here, its contribution to correlator will be much different between scheme II and scheme IV. On the other hand, background flow effects can be canceled completely even if not negligible when we check the difference between experiment data of scheme II and scheme IV:

$$\begin{aligned} \Delta\gamma_{\text{II}} - \Delta\gamma_{\text{IV}} &\propto (\Delta\gamma_{\text{CMEII}} + \Delta\gamma_{\text{BGII}}) - (\Delta\gamma_{\text{CMEIV}} + \Delta\gamma_{\text{BGIV}}) \\ &\propto \Delta\gamma_{\text{CMEII}} - \Delta\gamma_{\text{CMEIV}}. \end{aligned} \quad (9)$$

So this $p^\uparrow + A$ small collision system can provide us an ideal method to check the contribution of CME.

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