Anisotropy of Photon Production: Initial Eccentricity or Magnetic Field

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Recent measurements of the azimuthal anisotropy of direct photons in heavy-ion collisions at the energies of Relativistic Heavy Ion Collider show that it is of the same order as the hadronic one. This finding appears to contradict the expected dominance of photon production from a quark-gluon plasma at an early stage of a heavy-ion collision. A possible explanation of the strong azimuthal anisotropy of the photons, given recently, is based on the presence of a large magnetic field in the early phase of a collision. In this Letter, we propose a method to experimentally measure the degree to which a magnetic field in heavy-ion collisions is responsible for the observed anisotropy of photon production. The experimental test proposed in this Letter may potentially change our understanding of the nonequilibrium stage and possible thermalization in heavy-ion collisions.

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In contrast to hadronic observables, which strongly are influenced by the final state of the fireball created in a heavy-ion collision, the "direct" photons leave the fireball almost without interacting with the medium [1–3], and, thus, they may play an important role in unraveling the properties of hot and dense matter. According to expectations, based on the large yield of thermal photons, photon production is believed to be dominated by the hottest phase, quark-gluon plasma at the early stage of a collision at the top energies in Relativistic Heavy Ion Collider (Brookhaven) and the Large Hadron Collider (CERN). Measurements from the PHENIX Collaboration showed that the observed temperature of photon radiation at energy $\sqrt{s} = 200$ GeV in heavy-ion collisions is about $T_{\mathrm{ave}} \approx 220$ MeV [4]. This value can be considered as an average over the entire evolution of the matter created in heavy-ion collisions. It is higher than the temperature of the phase transition and thus it supports the picture of photon production from the quark-gluon stage of the collision. An alternative explanation of the apparent high temperature of the photon source is the formation of prethermal glasma shining photons early in a collision [5]. In both scenarios, we would expect that the photons' azimuthal anisotropy, characterized by the second Fourier component

$$v_2^\gamma(p_t) = \frac{\int d\phi \cos(2\phi) \frac{dN^\gamma}{dp_t d\phi}}{\frac{dN^\gamma}{dp_t}} \tag{1}$$

is small [6], because, at the early quark-gluon plasma stage, the evolving medium does not develop an appreciable amount of azimuthal anisotropy. Others studied this phenomenon in hydrodynamic calculations that well describe hadron production and hadron azimuthal anisotropy. The hydrodynamic calculations [7], as expected, demonstrated that the photon v_2^γ is almost an order of magnitude smaller than the one of hadrons. Taking into account fluctuating initial conditions or viscosity does not significantly increase v_2^γ. However, recent measurements by the PHENIX Collaboration revealed that the anisotropy of produced photons is very close to that of hadrons [8]. This finding might be explained in several ways. For instance, van Hees and collaborators [9] investigated how the fireball's evolution is constrained by the photon azimuthal anisotropy. To describe the photon spectra it was required to introduce a large acceleration of the fireball's expansion; this, however, is not present in conventional hydrodynamical calculations. Alternatively, we can assume that another unknown mechanism exists that is responsible for photon anisotropy. Such a mechanism was recently proposed in Ref. [10]. It is based on the presence of a large highly anisotropic magnetic field in heavy-ion collisions that could serve as a natural source of the photons' anisotropy. It is maximal at the early stage of a collision, thereby allowing us to reconcile the large thermal yield of photons with significant azimuthal anisotropy.

The importance of the magnetic field was recognized in Ref. [11], wherein the chiral magnetic effect [11–13] was proposed and studied. The results of Refs. [11,14,15] showed that in noncentral heavy-ion collisions the amplitude of magnetic field can reach very high values up to a few $m_\pi^2 \approx 10^{18}$ Gauss. This field is large at the time of the collision and decreases inversely proportional to the square of time [16]. The magnetic field essentially is anisotropic and, on average, points in the direction perpendicular to the reaction plane. It also was demonstrated [15] that event-by-event fluctuations of the magnetic (and electric) field may play an important role on the level of relevant observables.

According to the calculations of several researchers [10,17,18], photons are emitted in the direction perpendicular to the magnetic field. Different microscopic mechanisms of this emission were proposed recently, including the synchrotron radiation of photons from moving charged

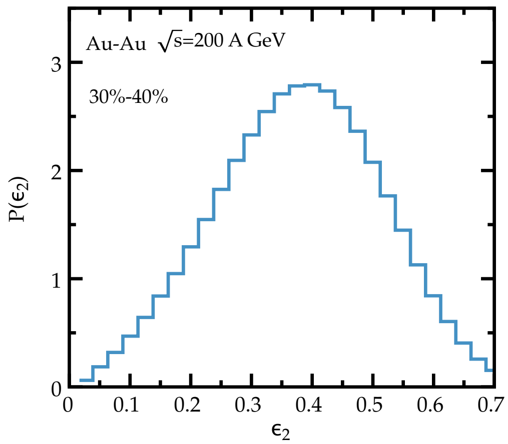

FIG. 1 (color online). Probability distribution of the participant eccentricity ϵ_2 for the centrality class 30%–40% in Au-Au collisions at $\sqrt{s} = 200$ GeV.

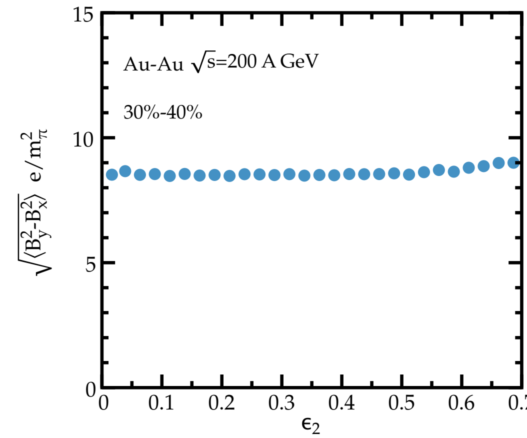

FIG. 2 (color online). Dependence of the magnetic field asymmetry as a function of the initial eccentricity. B_y and B_x denote the out-of-plane and in-plane components of the magnetic field.

quarks [17], and that reflecting the scale anomaly of QCD $\times$ QED [10] and owing to the axial anomaly [18]. The last two mechanisms generate photons even in the case of a vanishing quark number, which is probably a good approximation for the early stage when the magnetic field is significant. The estimates given in Ref. [10] showed that photon production from the conformal anomaly makes a considerable contribution to v_2^γ and potentially can describe the measured data.

The question arises as to how this could be experimentally established if the photons responsible for azimuthal asymmetry are produced from hadronic sources (or more generally from a nonzero eccentricity of the fireball), or from the quark-gluon plasma in the presence of a high magnetic field at early times. In this Letter, we propose an observable that can single out the mechanism responsible for producing the azimuthal anisotropy of photons in heavy-ion collisions. We also discuss other experimental signatures that may help to clarify the situation.

To proceed further, we first recall some properties of the magnetic field in heavy-ion collisions. First, the major contribution to the magnetic field originates from the spectator protons of the colliding nuclei. The charged particles produced may influence the magnetic field; however, this effect is not expected to suffice to overcome the field of spectators at early times (see, e.g., transport model calculations in Ref. [19]). Second, at a given centrality class the average magnetic field almost is independent of the fluctuating shape of the interaction region and the eccentricity ϵ_2 of the initial state; this problem was studied in more detail in Ref. [20].

This feature will allow us to distinguish between different mechanisms of v_2^γ production. It is noteworthy that, in the first approximation, the eccentricity and the magnetic field are linear growing functions of the impact parameter. Thus both mechanisms responsible for v_2^γ, hadronic flow and magnetic field, generate approximately the same qualitative dependence of v_2^γ on centrality. Consequently, this dependence cannot be used as a discriminative test of photon production.

It is commonly accepted that hadronic flow in nucleus-nucleus collisions is defined by the initial state's eccentricity, ϵ_2. The initial state's eccentricity is not only defined by the geometry of the collision, but also by Glauber and "intrinsic" fluctuations (see, e.g., Refs. [21,22]). The first are related to the fluctuations of the nucleon positions in the colliding nuclei, while the second represents the fluctuations of the energy deposition from interacting nucleons and their constituents. Consequently, even in peripheral collisions the initial eccentricity ϵ_2 strongly fluctuates, leading to a broad range of values, as detailed in Ref. [20] where this problem was studied in the context of the chiral magnetic effect [11]. In Fig. 1 we show the probability distribution of events as a function of the eccentricity ϵ_2 for the centrality class 30%–40% in Au-Au collisions at $\sqrt{s} = 200$ GeV. This result is obtained by using the standard Glauber model for the initial state [23]. As seen in Fig. 1 the eccentricity distribution is quite wide, so we expect the same behavior for measured hadronic elliptic flow, denoted in this letter by v_2^π. In Fig. 2 the magnetic field asymmetry $\langle B_y^2 - B_x^2 \rangle^{1/2}$, entering to the photon production rate of Ref. [10], is shown. The calculations are performed by taking into account fluctuating proton positions in colliding nuclei. As seen in Fig. 2 the magnetic field is almost independent of the initial eccentricity for a given centrality class. We also checked that with a good precision, the average magnetic field $\langle B_y \rangle$ coincides with $\langle B_y^2 - B_x^2 \rangle^{1/2}$.

Essentially, there are two competing mechanisms that can contribute greatly to v_2^γ. The first "hadronic" mechanism [9] is related to the initial anisotropy of the fireball ϵ_2:

$$v_2^\gamma \propto \epsilon_2. \tag{2}$$

The second mechanism reflects the presence of a strong magnetic field in the initial stage of a collision, where

$$v_2^\gamma \propto \langle B_y^2 - B_x^2 \rangle, \tag{3}$$

in the case of the scale anomaly of QCD $\times$ QED [10] and the axial anomaly [18], and

$$v_2^\gamma \propto \langle B_y \rangle, \tag{4}$$

for synchrotron radiation, as discussed in Ref. [17]. Here, B_y and B_x, respectively, denote the out-of-plane and in-plane components of the magnetic field.

Owing to eccentricity fluctuations at a given centrality class (or even at a given impact parameter), see Fig. 1, we can select events with different values of the hadronic elliptic flow v_2^π, while centrality fixes the magnetic field, as we demonstrated in Fig. 2. In the limiting case, viz., in noncentral collisions of a certain centrality, we may select events with zero eccentricity and, consequently, with zero hadronic flow. This choice will eliminate contribution from Eq. (2). If the magnetic field is responsible for the photon azimuthal anisotropy via Eq. (3) or (4), we still would observe a nonzero v_2^γ even for vanishing hadronic v_2^π.

Thus, the following three points summarize our idea to determine the mechanism of v_2^γ:

First, we choose a relatively narrow centrality class (e.g., 30%–40%) defined by the number of particles in the midrapidity region, or, if possible, by measuring forward neutrons and protons.

Given the centrality class, in each event we measure the value of the elliptic flow, v_2^π, for all pions in the hydrodynamic region (say $p_t < 1$ GeV). It is commonly accepted that v_2^π reflects the initial eccentricity ϵ_2 of the fireball in the transverse direction. Because of the fluctuations in positions of the participants, we obtain a broad range of ϵ_2 and, consequently, v_2^π.

Finally, we measure the elliptic flow for photons $v_2^\gamma(p_t)$ for different values of v_2^π. The magnetic field mainly is determined by the number of participants or spectators, and is rather independent of the fluctuating values of ϵ_2 in a given narrow centrality class; see Fig. 2. If v_2^γ results solely from the initial eccentricity then it should be proportional to v_2^π. On the contrary, if the magnetic field dominates v_2^γ, it should be independent of v_2^π.

Figure 3 illustrates this idea, wherein we present three possible situations: The photon anisotropy v_2^γ is generated solely by the initial anisotropy; v_2^γ is generated by the magnetic field, and both mechanisms are present with equal strengths.

Before concluding, several comments are warranted. The measurement discussed in this Letter is best suited for midcentral and peripheral collisions, where both the elliptic flow and fluctuations of the initial eccentricity are expected to be maximal. Also, the measurement should be performed for various values of photon transverse momenta. Possibly, different mechanisms of generating v_2^γ may be applicable in different p_t regions. Finally, the analysis should be performed in a narrow centrality class, e.g., 30%–40%, so allowing us to neglect the correlation between v_2^π and the impact parameter (and consequently, the value of the magnetic field) [24].

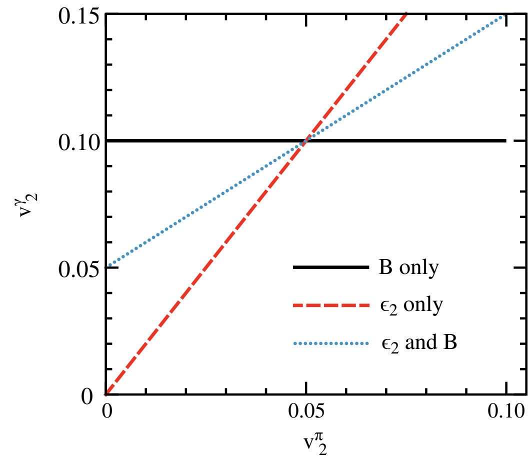

FIG. 3 (color online). Elliptic flow for photons $v_2^\gamma(p_t)$ at a given p_t as a function of the integrated elliptic flow for pions v_2^π for three possible scenarios. (i) Dashed (red) line: $v_2^\gamma(p_t)$ is dominated by the initial eccentricity ϵ_2. Here $v_2^\gamma(p_t)$ should be proportional to v_2^π since $v_2^\pi \propto \epsilon_2$. (ii) Solid (black) line: $v_2^\gamma(p_t)$ is generated solely by the strong magnetic field. In this case $v_2^\gamma(p_t)$ should be approximately independent of v_2^π since the magnetic field at a given narrow centrality class weakly depends on the fluctuating value of eccentricity ϵ_2. (iii) Dotted (blue) line: The case with equal contribution of ϵ_2- and $\vec{B}$-generated $v_2^\gamma(p_t)$. In this schematic plot we assume that, averaged over centrality class C, $v_2^\pi|_C = 0.05$, and $v_2^\gamma(p_t)|_C = 0.1$.

As was suggested in Ref. [10], another probe for illuminating the mechanism of photon production lies in the study of U-U collisions. The deformed shape of the U nucleus may allow us to separate the eccentricity of the initial condition from the magnitude of the magnetic field [25].

Other crucial tests that can be performed to test the role of the magnetic field in heavy-ion collisions include the following:

The violation of scaling $v_4/v_2^2 \sim 1$, which was observed for charged hadrons at PHENIX [26]. According to Ref. [10] the anisotropic contribution to the photon production rate in a magnetic field is proportional to k_x^2 which only gives the second harmonics for azimuthal angle distribution. Thus, we expect $v_4^\gamma/(v_2^\gamma)^2 \ll 1$ for photons produced in a magnetic field.

While measurements of v_4^γ require high statistics, it is sufficient to measure v_3^γ, which in the first approximation is zero for photons produced in a magnetic field.

In conclusion, we reiterate that the recent PHENIX data on the photons' azimuthal anisotropy raise new challenging problems for the theoretical description of heavy-ion collisions. These data either question the conventional picture of early thermalization and subsequent hydrodynamics of heavy-ion collisions, or infers the existence of a new mechanism of photon production, i.e., contingent upon the magnetic field that can create substantial photon azimuthal anisotropy. In this Letter, we proposed a measurement of elliptic flow of photons $v_2^\gamma(p_t)$ as a function of integrated elliptic flow of pions v_2^π, in a given narrow centrality class, e.g., 30%–40%. This measurement will test both mechanisms of photon production due either to the initial eccentricity or the strong magnetic field. We hope that the proposed measurement would be useful both at Relativistic Heavy Ion Collider and the Large Hadron Collider and, eventually, would allow us to solve the puzzle of a large photon azimuthal anisotropy in heavy-ion collisions. We again stress that this may radically change our understanding of the nonequilibrium stage and thermalization in heavy-ion collisions.

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