Azimuthal Asymmetry of Direct Photons in High Energy Nuclear Collisions

S. Turbide,[1] C. Gale,[1] and R. J. Fries[2]

[1]*Department of Physics, McGill University, Montréal, Canada H3A 2T8*
[2]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*

(Received 22 August 2005; published 26 January 2006)

We show that a sizable azimuthal asymmetry, characterized by a coefficient v_2, is to be expected for large p_T direct photons produced in noncentral high energy nuclear collisions. This signal is generated by photons radiated by jets interacting with the surrounding hot plasma. The anisotropy is out of phase by an angle $\pi/2$ with respect to that associated with the elliptic anisotropy of hadrons, leading to negative values of v_2. Such an asymmetry, if observed, could be a signature for the presence of a quark gluon plasma and would establish the importance of jet-plasma interactions as a source of electromagnetic radiation.

DOI: 10.1103/PhysRevLett.96.032303 PACS numbers: 25.75.−q, 12.38.Mh

At the Relativistic Heavy Ion Collider (RHIC) and soon at the Large Hadron Collider (LHC), nuclei are collided at ultrarelativistic energies in order to create a new state of matter: the quark gluon plasma (QGP) [1]. Emitted particles that only interact through the electroweak interactions are very unlikely to interact again despite the dense medium which is created. Thus they are able to carry to the detectors information about the state of the system at the time they were created [2]. Photons and leptons thus constitute a unique class of penetrating probes.

The two most interesting sources of photons are those where the plasma is directly involved in the emission. These are the thermal radiation from the hot QGP [3] and the radiation induced by the passage of high energy jets through the plasma [4–6]. The thermal radiation is emitted predominantly with low transverse momentum p_T and has to compete with photon emission from the hot hadronic gas at later times [7,8]. Photons from jets are an important source at intermediate p_T, where they compete with photons from primary hard scatterings between partons of the nuclei [9]. They probe the thickness of the medium: the longer the path of the jet, the more photons are emitted.

Obviously, measuring photons from either of the sources involving the quark gluon plasma would be an important step toward establishing its existence and would provide a stringent test of the reaction dynamics. We refer the reader to [6] for a discussion of the different photon sources. Recently, the PHENIX Collaboration at RHIC published their first results on direct photons measured in Au + Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV [10]. Note that direct photons here are defined as the total inclusive photon yield minus the photons originating from the decay of hadrons like π^0 and η. The sources discussed above will contribute to the direct photon signal. The data cover the intermediate and high-p_T range where thermal photons are not a leading source. This makes it particularly attractive to look for photons from jet-plasma interactions.

Nuclear collisions at finite impact parameter $b > 0$ start out in an initial state which is not azimuthally symmetric around the beam axis. Instead, the initial overlap zone of the two nuclei has an "almond" shape. Therefore, particle spectra measured in the final state are not necessarily isotropic around the beam axis. It has been argued that the translation of the original space-time asymmetry into a momentum space anisotropy can reveal important information about the system [11]. Two different mechanisms are important here: hydrodynamic pressure for the bulk of the matter, at low- to intermediate-p_T, and a simple optical-depth argument for intermediate- to high-p_T particles. We introduce a novel third mechanism in this Letter.

Let us define the reaction plane as the plane spanned by the beam axis and the impact parameter of the colliding nuclei. For the bulk of the matter, the initial space-time asymmetry leads to an anisotropic pressure gradient which is larger where the material is thinner, i.e., in the event plane. This translates into a larger flow of matter in this direction. The anisotropy is analyzed in terms of Fourier coefficients v_k defined from the particle yield $dN/p_T dp_T d\phi$ as [12]

$$\frac{dN}{p_T dp_T d\phi} = \frac{dN}{2\pi p_T dp_T}[1 + \sum_k 2v_k(p_T)\cos(k\phi)], \quad (1)$$

where the angle ϕ is defined with respect to the event plane. At midrapidity all odd coefficients vanish for symmetry reasons, leaving the coefficient v_2 to be the most important one. Its size determines the ellipsoidal shape of the anisotropy. It is clear that the elliptic asymmetry coefficient v_2 is always positive for hadrons at low and intermediate p_T due to the hydrodynamic flow. On the other hand, jets lose more energy when they are born into a direction where the medium is thicker, i.e., out of the reaction plane. The stronger jet quenching leads to fewer hadrons at intermediate and high p_T emitted into this direction. This "optical v_2" is not associated with flow but with absorption and implies positive v_2 for hadrons from jets. Measurements at RHIC for several hadron species confirm this behavior [13].

In this Letter, we discuss v_2 of direct photons. We concentrate on intermediate and high p_T and the v_2 from all the relevant processes. We define a mechanism that works by absorption of particles or jets going through the medium as optical. It turns out that in some cases a new inverse-optical mechanism is in place for photons: there are more of them emitted into the direction where the nuclear overlap zone is thicker, thus leading to a situation where the anisotropy is shifted by a phase $\pi/2$. Correspondingly, v_2 is negative in this case.

Let us now discuss the different contributions to the direct photon spectrum. Direct photons from primary hard Compton and annihilation processes $a + b \rightarrow \gamma + c$ are produced symmetrically with

$$\frac{dN^{\mathrm{N-N}}}{p_T dp_T d\phi} = T_{AB} f_{a/A} \otimes \sigma_{a+b\rightarrow\gamma+c} \otimes f_{b/B}. \tag{2}$$

Here $\sigma_{a+b\rightarrow\gamma+c}$ is the cross section between partons, $f_{a/A}$, $f_{b/B}$ are parton distribution functions in the nuclei A and B, and T_{AB} is the overlap factor of the nuclei. The primary hard direct photons do not suffer any final state effect and do not exhibit any elliptic asymmetry.

Jets from processes $(a + b \rightarrow c + d)$ are also produced symmetrically; however, they are quenched once they start to propagate through the plasma. This is the optical mechanism that leads to positive v_2 for hadrons fragmenting from jets. We expect photons fragmenting from such jets in the vacuum ($c \rightarrow c + \gamma$, after c propagated through the medium) to exhibit the same anisotropy. Their yield at midrapidity is given by

$$\frac{dN^{\mathrm{jet-frag}}}{p_T dp_T d\phi} = \sum_f \frac{dN^f(\phi)}{dq}\bigg|_{q=p_T/z} \otimes D_{f/\gamma}(z, p_T), \tag{3}$$

where $dN^f(\phi)/dq$ is the distribution of jet partons f with momentum q traveling into the direction given by the angle ϕ, and $D_{f/\gamma}$ is the photon fragmentation function.

The interaction of jets with the medium can also produce photons in different ways: (i) scattering off plasma components can induce photon bremsstrahlung, (ii) hard leading partons may annihilate with thermal ones $(q + \bar{q} \rightarrow \gamma + g)$, or they can participate in Compton scattering $[q(\bar{q}) + g \rightarrow q(\bar{q}) + \gamma]$. The latter case is also called jet-photon conversion, because the cross section is dominated by transfer of the entire jet momentum to the photon, $\mathbf{p}_\gamma \approx \mathbf{p}_{\mathrm{jet}}$. The jet-photon conversion yield at midrapidity is given by [14]

$$\frac{dN^{\mathrm{jet\text{-}th}}}{p_T dp_T d\phi dy} = \int d^4x \frac{\alpha \alpha_s T^2}{8\pi^2} \sum_q \left(\frac{e_q}{e}\right)^2 f_q(x; p_T, \phi, y) \times \left[2 \ln \frac{4E_\gamma T}{m^2} - C\right] \tag{4}$$

with $C = 2.332$ and $m^2 = 4\pi\alpha_s T^2/3$. The distribution of jet partons $f_q(x; p_T, \phi, y)$ at a space-time point x is determined from the time dependent spectrum of jet partons propagating in the plasma, $dN^q/dq(\tau)$, as discussed in [4,6]. The time dependence is governed by the energy loss through induced gluon radiation, obtained with the complete leading order description by Arnold, Moore, and Yaffe (AMY) [15]. It is clear that an anisotropy in ϕ is introduced by the different path lengths for jets traveling in and out of the event plane, leading to an increased probability for a jet-photon conversion in the direction where the medium is thicker. Such an inverse-optical effect has not been observed before.

Medium-induced bremsstrahlung $(q \rightarrow \gamma + q)$ is implemented directly in the AMY formalism through splitting functions $d\Gamma^{q\rightarrow q\gamma}/dkdt$. The photon yield from this process is obtained by

$$\frac{dN^{\mathrm{jet-br}}}{dp_T d\phi} = \int d^2 r_\perp \mathcal{P}(\mathbf{r}_\perp) \int_0^d dt dk \frac{dN^q}{dq} \frac{d\Gamma^{q\rightarrow q\gamma}(q, k)}{dkdt}. \tag{5}$$

Here $\mathcal{P}(\mathbf{r}_\perp)$ is the spatial distribution of hard processes creating jets in the transverse plane and $d = d(\mathbf{r}_\perp, \phi)$ is the distance the jet has to travel from $\mathbf{r}_\perp$ into the direction of the angle ϕ to leave the fireball. Again it is obvious that the probability for induced bremsstrahlung to occur increases with the path length d of the jet. Hence these photons are preferentially emitted into the direction where the medium is thicker, leading to negative v_2.

Finally, thermal photon emission constitutes another contribution to the direct photon spectrum. Thermal photons emitted by the medium are not prone to any optical effects, but the emitting matter experiences the anisotropic hydrodynamic push. However, the emission of intermediate and large p_T photons peaks strongly at very early times where the temperature is highest [16]. We verified that at the time the system generates significant radial and elliptic flow the rate of thermal photons at intermediate and high p_T is negligible.

Let us summarize what we have so far. We identified two processes, induced bremsstrahlung from jets and jet-photon conversion, that we expect to exhibit an inverse-optical anisotropy ($v_2 < 0$). Photons from fragmentation show the regular optical anisotropy ($v_2 > 0$), while primary hard and thermal photons do not contribute to v_2 at intermediate and high p_T.

To quantify our arguments, we carry out a numerical calculation for Au + Au collisions at RHIC ($\sqrt{s_{NN}} =$ 200 GeV). Photon spectra at midrapidity with their dependence on the azimuthal angle ϕ are calculated as described above for three different centrality classes. Our modeling of the nuclear collision is introduced in [6]. The initial conditions are constrained by $\tau_i T_i^3 \sim dN(b)/dy/A_\perp(b)$, where the charged particle pseudorapidity densities dN/dy can be found in [17] and $A_\perp$ is the overlap area of the nuclei in the transverse plane. With fixed initial time $\tau_i = 0.26$ fm/c, the initial temperatures are $T_i = 370$, 360, and 310 MeV for centrality classes 0%–20%, 20%–40%, and 40%–60%, respectively. Comparing with measured photon spectra, a good agreement is obtained for all centrality classes. Details will appear elsewhere [18]. The coefficients v_2 can then be calculated by using

$$v_2(p_T) = \frac{\int d\phi \cos(2\phi) dN/dp_T d\phi}{dN/dp_T}. \tag{6}$$

Figure 1 shows the coefficient v_2 as a function of p_T for Au + Au collisions at RHIC and for the centrality classes 0%–20%, 20%–40%, and 40%–60%. The dotted lines give the results for primary hard direct photons and photon fragmentation. As expected, photons from fragmentation lead to a positive v_2 which is diluted by adding primary hard photons. The solid lines are the results when bremsstrahlung, jet-photon conversion, and thermal photons are also included. They meet our expectations for v_2 of direct photons including all sources discussed above. The v_2 for induced bremsstrahlung and jet-photon conversion is indeed negative. Together they are able to overcome the positive v_2 from fragmentation, leading to an overall negative elliptic asymmetry for direct photons at moderate p_T. Only above 8 GeV/c the direct photon v_2 is again positive, because the yield of photons from fragmentation is dominating over medium-induced bremsstrahlung [6] in this range. The dashed lines in Fig. 1 show the v_2 for direct photons with no jet energy loss included. In this case, fragmentation photons do not exhibit an anisotropy and the elliptic asymmetry is only due to jet-photon conversion. Measurements of v_2 with sufficient accuracy could therefore constrain models for jet energy loss. The absolute size of v_2 is not large, about 2%–3% for the 20%–40% centrality bin around $p_T = 4$ GeV/c and up to 5% for the more peripheral bin. The reason is that the signal is diluted by isotropic photons (primary hard and thermal) and partially canceled between the optical and inverse-optical mechanisms. We also checked the dependence of v_2 on the temperature of the medium by varying the initial temperature T_i with $\tau_i T_i^3$ kept constant. The resulting changes are small: a change in T_i of 40% generates a shift in v_2 of less than 20%.

In Fig. 2 we show some v_2 signals that should be detectable at RHIC in the near future. The dotted lines show v_2 for inclusive photons before background subtraction. In this case the v_2 signal is dominated by contributions from decaying π^0 and η hadrons. The resulting v_2 is positive and larger in magnitude. Only hadrons from fragmentation have been included. However, it has been shown that hadron production up to a p_T of 4 to 6 GeV/c receives significant contributions from recombination of quarks [19]. The dot-dashed lines show the v_2 of inclusive photons if decays of π^0 and η from recombination are included, using [19] with parameters consistent with our jet-fragmentation calculation. Data on v_2 for inclusive photons have been measured by the PHENIX Collaboration [20]. Our calculations for the total inclusive photons including decays from recombined hadrons agree well with their results.

A very exciting option for the future is the possibility to experimentally distinguish between direct photons associated with jets and isolated direct photons. Photons from jet-fragmentation and induced bremsstrahlung are in the former category, while the latter includes primary hard and thermal photons, and photons from jet-photon conversion. The dashed line in Fig. 2 shows the result for the fragmentation and bremsstrahlung processes only. They contribute with different signs and one notes a characteristic change of sign from negative values at low p_T to larger positive values, up to 5%, at large p_T, where fragmentation domi-

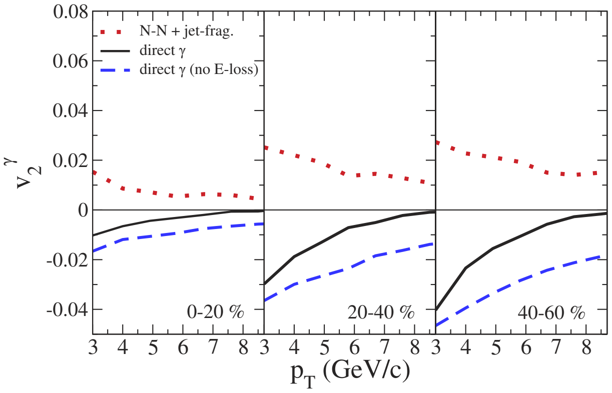

FIG. 1 (color online). Photon v_2 as a function of p_T for Au + Au collisions at RHIC. Three different centrality bins are given. The dotted lines show v_2 for primary hard photons and jet fragmentation only, and the solid lines show all direct photons. Energy loss is included in both cases. The dashed line is the same as the solid line but without energy loss of jets taken into account.

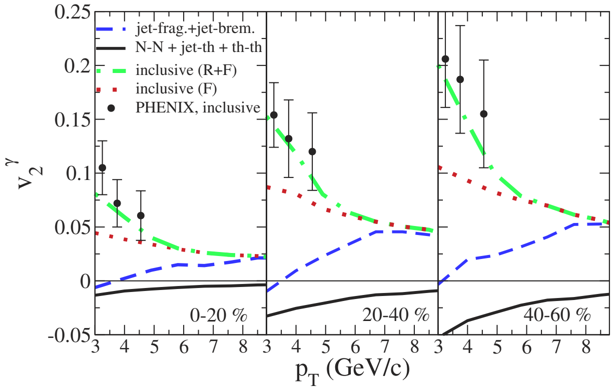

FIG. 2 (color online). v_2 as a function of p_T for Au + Au collisions at RHIC. The dashed line shows jet-fragmentation and induced bremsstrahlung only while the solid lines give jet-photon conversion, primary hard, and thermal photons. The dotted line shows direct photons and the background from decay of neutral mesons coming from jets. The dot-dashed line adds photons from decay of recombined pions as well and can be compared to the inclusive photon v_2 measured by PHENIX [20].

nates. The solid line shows the v_2 of all isolated direct photon processes, including primary hard direct photon, thermal, and jet-photon conversion. Jet-photon conversion is the only source of an anisotropy, so that the resulting v_2 is relatively large and negative.

We briefly mention here that the inverse-optical mechanism for photon v_2 could be also at work for jets going through hadronic matter. Possible examples are hadronic processes after hadronization of the jet, e.g., $\rho + \pi \rightarrow \gamma + \pi$, as well as Compton, annihilation, and bremsstrahlung processes with partons in surrounding hadrons before hadronization. In the first case the p_T of the interacting jet hadron will be smaller than the original p_T of the jet due to energy loss and hadronization, shifting the emitted photons to smaller p_T. In the second case the yield will ultimately depend on the unknown parton content of the hot hadron phase. However, the Compton and annihilation yields have a T^2 dependence at intermediate p_T, hence any reasonable assumption of the parton content and the temperature of the hadronic phase will lead to small yields at intermediate p_T. The admixture of photon v_2 from jet-hadron interactions is therefore suppressed.

To summarize, we present the first calculation of the lowest order azimuthal asymmetry coefficient v_2 for direct photons in high energy nuclear collisions. Jets interacting with a deconfined quark gluon plasma provide photons exhibiting an inverse-optical anisotropy with characteristic negative values of v_2. An experimental confirmation would emphasize the existence of a quark gluon plasma and confirm jet-medium interactions as important sources of photons at intermediate p_T. The v_2 signal is generally of order 3%–5% and should be experimentally accessible at RHIC. Even more promising would be a separation of direct photons emitted in a jet from isolated photons. Both sources carry their own characteristic p_T dependence for v_2. The arguments presented here for direct photons immediately apply to production of lepton pairs as well. Dileptons from annihilation of jets in the medium and from medium-induced virtual photon bremsstrahlung [21] should also exhibit negative v_2.

We thank B. Cole and S. Jeon for stimulating discussions, and G. D. Moore for his help with details of the AMY energy loss. R. J. F. thanks the nuclear theory group at McGill University for their hospitality while part of this work was carried out. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada, by le Fonds Nature et Technologies du Québec, and by DOE Grant No. DE-FG02-87ER40328.

[1] J. W. Harris and B. Müller, Annu. Rev. Nucl. Part. Sci. **46**, 71 (1996).

[2] E. L. Feinberg, Nuovo Cim. A **34**, 391 (1976).

[3] J. I. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D **44**, 2774 (1991); **47**, 4171(E) (1993); R. Baier, H. Nakkagawa, A. Niegawa, and K. Redlich, Z. Phys. C **53**, 433 (1992); P. K. Roy, D. Pal, S. Sarkar, D. K. Srivastava, and B. Sinha, Phys. Rev. C **53**, 2364 (1996); P. Aurenche, F. Gelis, R. Kobes, and H. Zaraket, Phys. Rev. D **58**, 085003 (1998); P. Arnold, G. D. Moore, and L. G. Yaffe, J. High Energy Phys. 12 (2001) 009.

[4] R. J. Fries, B. Müller, and D. K. Srivastava, Phys. Rev. Lett. **90**, 132301 (2003).

[5] B. G. Zakharov, JETP Lett. **80**, 1 (2004); R. J. Fries, B. Müller, and D. K. Srivastava, Phys. Rev. C **72**, 041902 (2005).C. Gale, T. C. Awes, R. J. Fries, and D. K. Srivastava, J. Phys. G **30**, S1013 (2004).

[6] S. Turbide, C. Gale, S. Jeon, and G. D. Moore, Phys. Rev. C **72**, 014906 (2005).

[7] L. Xiong, E. V. Shuryak, and G. E. Brown, Phys. Rev. D **46**, 3798 (1992); V. V. Goloviznin and K. Redlich, Phys. Lett. B **319**, 520 (1993); C. Song, Phys. Rev. C **47**, 2861 (1993).

[8] S. Turbide, R. Rapp, and C. Gale, Phys. Rev. C **69**, 014903 (2004).

[9] J. F. Owens, Rev. Mod. Phys. **59**, 465 (1987).

[10] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **94**, 232301 (2005).

[11] J. Y. Ollitrault, Phys. Rev. D **46**, 229 (1992).

[12] S. Voloshin and Y. Zhang, Z. Phys. C **70**, 665 (1996).

[13] C. Adler *et al.* (STAR Collaboration), Phys. Rev. Lett. **90**, 032301 (2003); S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **91**, 182301 (2003).

[14] C. Y. Wong, *Introduction to High-Energy Heavy Ion Collisions* (World Scientific, Singapore, 1994).

[15] P. Arnold, G. D. Moore, and L. Yaffe, J. High Energy Phys. 11 (2001) 057; J. High Energy Phys. 06 (2002) 030.

[16] P. F. Kolb and U. Heinz, nucl-th/0305084.

[17] B. B. Back *et al.* (PHOBOS Collaboration), Phys. Rev. C **65**, 061901 (2002).

[18] S. Turbide and C. Gale, Proceedings for the Particles and Nuclei International Conference (PANIC05), Santa Fe, New Mexico, hep/0512200 [J. Phys. G (to be published)].

[19] R. J. Fries, B. Müller, C. Nonaka, and S. A. Bass, Phys. Rev. C **68**, 044902 (2003).

[20] S. S. Adler *et al.* (PHENIX Collaboration), nucl-ex/0508019 [Phys. Rev. Lett. (to be published)].

[21] D. K. Srivastava, C. Gale, and R. J. Fries, Phys. Rev. C **67**, 034903 (2003); S. Turbide, C. Gale, D. K. Srivastava, and R. J. Fries, hep-ph/0601041.