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Azimuthal asymmetry of direct photons in intermediate energy heavy-ion collisions

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ABSTRACT

Hard photon emitted from energetic heavy ion collisions is of very interesting since it does not experience the late-stage nuclear interaction, therefore it is useful to explore the early-stage information of matter phase. In this work, we have presented a first calculation of azimuthal asymmetry, characterized by directed transverse flow parameter F and elliptic asymmetry coefficient v_2, for proton–neutron bremsstrahlung hard photons in intermediate energy heavy-ion collisions. The positive F and negative v_2 of direct photons are illustrated and they seem to be anti-correlated to the corresponding free proton's flow.

The properties of nuclear matter at different temperatures or densities, especially the derivation of the Equation-of-State (EOS) of nuclear matter, are one of the foremost challenges of modern heavy-ion physics. Since heavy ion collisions provide up to now the unique means to form and investigate hot and dense nuclear matter in the laboratory, many experimental and theoretical efforts are under way towards this direction. Because of their relatively high emission rates, nucleons, mesons, light ions and intermediate mass fragments, produced and emitted in the reactions, are conveniently used to obtain information on the reaction dynamics of energetic heavy ion collisions. However, these probes interact strongly with the nuclear medium such that the information they convey may bring a blurred image of their source. Fortunately, energetic photons offer an attractive alternative to the hadronic probes [1]. Photons interacting only weakly through the electromagnetic force with the nuclear medium are not subjected to distortions by the final state (neither Coulomb nor strong) interactions. They therefore deliver an undistorted picture of the emitting source. For hard photons, defined as γ-rays with energies above 30 MeV in this Letter, many experimental facts supported by model calculations [1–3] indicate that in intermediate energy heavy-ion collisions they are mainly emitted during the first instants of the reaction in incoherent proton–neutron bremsstrahlung collisions, $p+n \to p+n+\gamma$, occurring within the participant zone. This part of hard photons are called as direct photon. Direct hard photons have thus been exploited to probe the pre-equilibrium conditions prevailing in the initial high-density phase of the reaction [4,5]. Aside from the dominant production of hard photons in first-chance p–n collisions, a significant hard-photon production in a later stage of heavy-ion reactions, called as thermal photons, are also predicted by the *Boltzmann–Uehling–Uhlenbeck* (*BUU*) theory [6,7]. These thermal photons are emitted from a nearly thermalized source and still originate from bremsstrahlung production by individual p–n collisions, which was also confirmed by the experiments at last decade [8,9].

In this work, we take the *BUU* transport model improved by Bauer [10]. The isospin dependence was incorporated into the model through the initialization and the nuclear mean field. The nuclear mean field U including isospin symmetry terms is parameterized as

$$U(\rho,\tau_z)=a\left(\frac{\rho}{\rho_0}\right)+b\left(\frac{\rho}{\rho_0}\right)^{\sigma}+C_{\text{sym}}\frac{(\rho_n-\rho_p)}{\rho_0}\tau_z, \tag{1}$$

where ρ_0 is the normal nuclear matter density; ρ, ρ_n, and ρ_p are the nucleon, neutron and proton densities, respectively; τ_z equals 1 or -1 for neutrons and protons, respectively; The coefficients

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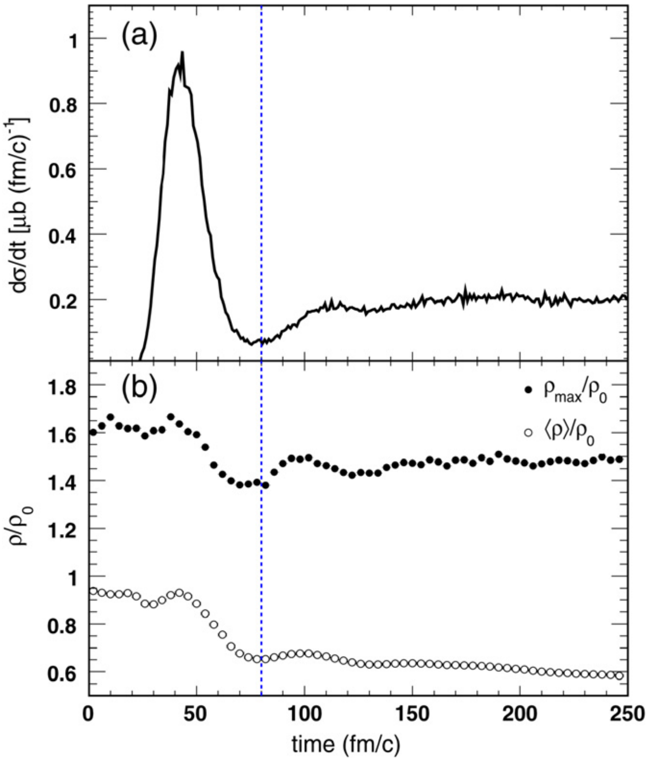

Fig. 1. (a) Time evolution of hard photon production rate for the reaction ^{40}Ca + ^{40}Ca collisions at 30 MeV/nucleon for semi-central events (40–60%). (b) Time evolution of reduced maximum density $\rho_{\max}/\rho_0$ (closed circles) and reduced average density $\langle\rho\rangle/\rho_0$ (open circles) of the whole reaction system in the same reaction. The blue dashed line represents the time when the system ends up till the first expansion stage, and in the panel (a) it separates direct photons (on the left side) and thermal photons (on the right side). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

a, b and σ are parameters for nuclear equation of state. C_{sym} is the symmetry energy strength due to the density difference of neutrons and protons in nuclear medium, which is important for asymmetry nuclear matter (here $C_{\text{sym}} = 32$ MeV is used), but it is trivial for the symmetric system studied in the present work.

For the calculation of the elementary double-differential hard photon production cross sections on the basis of individual proton–neutron bremsstrahlung, the hard-sphere collision was adopted from Ref. [11], and modified as in Ref. [12] to allow for energy conservation. The double differential probability is given by

$$\frac{d^2\sigma^{\text{elem}}}{dE_\gamma\, d\Omega_\gamma} = \alpha \frac{R^2}{12\pi} \frac{1}{E_\gamma}\left(2\beta_f^2 + 3\sin^2\theta_\gamma \beta_i^2\right). \tag{2}$$

Here R is the radius of the sphere, α is the fine structure constant, β_i and β_f are the initial and final velocity of the proton in the proton–neutron center of mass system, and θ_γ is the angle between incident proton direction and photon emitting direction. More details for the model can be found in Ref. [10].

In this Letter, we simulate the reaction of ^{40}Ca + ^{40}Ca collisions at 30 MeV/nucleon, and use the EOS with the compressibility K of 235 MeV ($a = -218$ MeV, $b = 164$ MeV, $\sigma = 4/3$) for the nuclear mean field U. As a first attempt to extract the photon's azimuthal asymmetry, we only take the semi-central events (40–60%) as an example in this Letter.

In Fig. 1 we show the time evolution of production rate of bremsstrahlung hard photons as well as the time evolution of system densities, including both maximum (closed circles) and average density (open circles). We found that hard-photon production is sensitive to the density oscillations of both the maximum and the average density during the whole reaction evolution. When the density of collision system increases, that is in the compression stage, the system produces more hard photons. In contrary, when the system expends, the hard photon production decreases. Actually, the density oscillations of the colliding heavy ions systems can be observed in the experiments via hard-photon interferometry measurements [6,13]. Apparently, hard photons are mostly produced at the early stage of the reaction. Combining the time evolution of the nuclear density, we know that this part of hard photons are dominantly emitted from the stage of the first compression and expansion of the system. Thereafter we call these photons, emitted before the time of the first maximum expansion of the system ($t = 80$ fm/c in this reaction), as direct photons (on the left side of blue dashed line in Fig. 1(a)). It is also coincident with the definition of direct photons above. And we call the residual hard photons produced in the later stage as thermal photons (on the right side of blue dashed line in Fig. 1(a)). So in the simulation, we can identify the produced photon as direct or thermal photon by the emitting time. Because of the sensitivity to the density oscillations of colliding system, hard photon may be sensitive to the nuclear incompressibility [6,7].

It is well known that collective flow is an important observable in heavy ion collisions and it can bring some essential information of the nuclear matter, such as the nuclear equation of state [14–23]. Anisotropic flow is defined as the different nth harmonic coefficient v_n of the Fourier expansion for the particle invariant azimuthal distribution [15]:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi), \tag{3}$$

where ϕ is the azimuthal angle between the transverse momentum of the particle and the reaction plane. Note that the z-axis is defined as the direction along the beam and the impact parameter axis is labelled as x-axis. Anisotropic flows generally depend on both particle transverse momentum and rapidity, and for a given rapidity the anisotropic flows at transverse momentum p_t ($p_t = \sqrt{p_x^2 + p_y^2}$) can be evaluated according to

$$v_n(p_t) = \langle \cos(n\phi) \rangle, \tag{4}$$

where $\langle \cdots \rangle$ denotes average over the azimuthal distribution of particles with transverse momentum p_t, p_x and p_y are projections of particle transverse momentum in and perpendicular to the reaction plane, respectively. The first harmonic coefficient v_1 is called directed flow parameter. The second harmonic coefficient v_2 is called the elliptic flow parameter v_2, which measures the eccentricity of the particle distribution in the momentum space.

In relativistic heavy-ion collisions azimuthal asymmetry of hard photons have been recently reported in the experiments and theoretical calculations [24–27]. It shows a very useful tool to explore the properties of hot dense matter. However, so far there is still neither experimental data nor theoretical prediction on the azimuthal asymmetry of hard photons in intermediate energy heavy ion collisions. Does the direct photon also exist azimuthal asymmetry so that it leads to non-zero directed transverse flow or elliptic asymmetry parameters in the intermediate energy range? Moreover we know that direct photons mostly originate from bremsstrahlung produced in individual proton–neutron collisions, and free nucleons are also emitted from nucleon–nucleon collisions. Does the azimuthal asymmetry of the direct photons correlate with the one of free nucleons? To answer the above question, we focus on the azimuthal asymmetry analysis for both photons and protons in this Letter.

Fig. 2 shows the time evolution of the directed flow parameter v_1 and elliptic flow parameter v_2 for hard photons and free protons. Before we take further calculation and explanation, people should be cautious about the word of "flow" for photons. Since

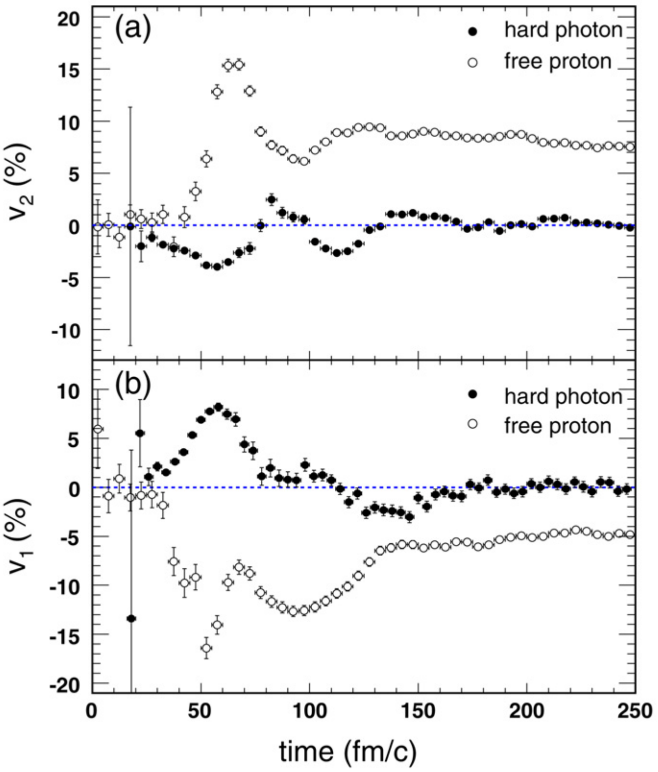

Fig. 2. The time evolution of v_2 (a) and v_1 (b) for hard photons (closed circles) and free protons (open circles).

flow is associated with collectivity caused by multiple interactions, which are exhibited by the nucleons, but not by the photons. The photon emission pattern is basically a result of the nucleon flow, and not a photon flow per se. However, in order to compare the results between photons and protons, we still called v_1 as directed flow parameter and v_2 elliptic flow parameters for photons somewhere in texts. Considering the nearly symmetric behavior for directed flow parameter (v_1) versus rapidity, here we calculate the average v_1 over only the positive rapidity range, which can be taken as a measure of the directed transverse flow parameter. For emitted protons (open circles in the figure) which are experimental measurable and are identified in our BUU calculation as those with local densities less than $\rho_0/8$, the onset of flows occurs around $t = 30$ fm/c before that the system is mostly in fusion stage and protons are seldom emitted. The negative directed flow parameter v_1 of free protons essentially stems from the attractive mean field. Up till $t \sim 120$ fm/c when the system is in the freeze-out stage, the directed flows become saturate. For the elliptic asymmetry parameter v_2 of free protons, the positive values indicate of the preferential in-plane emission driven by the rotational collective motion due to the attractive mean filed. Similarly, the elliptic asymmetry parameter becomes saturate in the freeze-out stage. However, there are obvious difference for proton–neutron bremsstrahlung photons (solid circles in the figure) in comparison to protons. Contrary to the negative directed transverse flow and positive flow, directed photons shows the positive v_1 and the negative v_2 before $t = 80$ fm/c, i.e. the azimuthal anisotropy is shifted by a phase of $\pi/2$. The times corresponding to the peak or valley values of flows roughly keep synchronized with the compression or expansion oscillation of the system evolution. For the late-stage thermal photons after $t = 170$ fm/c the azimuthal asymmetry vanishes, i.e. v_1 and v_2 fades-out.

From the above calculations, we learn that thermal photons in the later stage of reaction are emitted from a more thermalized system, they prefer more isotropic emission (i.e. the vanishing "flow" parameters) than direct ones produced in the pre-equilibrium stage. Thereafter we only consider direct photons to discuss the azimuthal asymmetry results. For protons, we take the values of flows when the system has been already in the freeze-out time at 180 fm/c.

The directed transverse flow parameter at mid-rapidity can be also defined by the slope [28]: $F = \frac{d\langle p_x\rangle}{d(y)_{\text{c.m.}}}|_{(y)_{\text{c.m.}}=0}$, where $(y)_{\text{c.m.}}$ is the rapidity of particles in the center of mass and $\langle p_x\rangle$ is the mean in-plane transverse momentum of photons or protons in a given rapidity region. In Fig. 3(a) and (b), we show $\langle p_x\rangle$ plotted versus the c.m. rapidity $y_{\text{c.m.}}$ for direct photons (a) as well as $\langle p_x\rangle$ plotted versus the reduced c.m. rapidity $(y/y_{\text{beam}})_{\text{c.m.}}$ for free protons (b). The errors shown are only statistical. A good linearity was seen in the mid-rapidity region $(-0.5, 0.5)$ and the slope of a linear fit can be defined as the directed transverse flow parameter. The extracted value of the directed transverse flow of direct photons is about $+3.7$ MeV/c, and that of free protons is about -12.4 MeV/c. Thus direct photons do exist the directed transverse asymmetry even though the absolute value is smaller than the proton's flow, and its sign is just opposite to that of free protons.

As Eq. (3) shows, elliptic flow is defined as the second harmonic coefficient v_2 of an azimuthal Fourier expansion of the particle invariant distribution. In order to extract the value of elliptic asymmetry coefficient v_2 and reduce the error of fits, we fit the azimuthal distribution to the 4th order Fourier expansion. Shown in Fig. 3(c) and (d), direct photons demonstrate out-of-plane enhancement and the v_2 is about -2.7%. Whereas, for free protons, azimuthal distribution displays the preferential in-plane emission and the v_2 is about $+7.2\%$. Furthermore, we can extract the transverse momentum dependence of the elliptic asymmetry coefficient v_2. Fig. 4 shows v_2 of direct photons (a) and free protons (b) as a function of transverse momentum p_T. Similar to the directed transverse flow parameter, the values of elliptic asymmetry coefficient v_2 of direct photons and free protons also have the opposite signs at this reaction energy, i.e. reflecting a different preferential transverse emission in the direction of out-of-plane or in-plane, respectively. Meanwhile, the absolute values of v_2 for photons are smaller than the proton's values as the behavior of transverse flow. Except the opposite sign, we see that both v_2 have similar tendency with the increase of p_T, i.e., their absolute values increase at lower p_T, and become gradually saturated, especially for direct photons.

To explain the above anti-correlation of anisotropic emission between direct photons and free protons, we should note that direct photons originate from the individual proton–neutron collisions. As Eq. (2) shows, we can roughly consider that in the individual proton–neutron center of mass system, in directions perpendicular to incident proton velocity, i.e. $\theta_\gamma = \pi/2$, the probability of hard photon production is much larger than that in the parallel direction, i.e. $\theta_\gamma = 0$, which is in agreement with the theoretical calculations and the experiments [29,30], that causes hard photon preferential emission perpendicular to the motion plane of corresponding nucleons. As a whole, the azimuthal anisotropy of hard photons is shifted by a phase of $\pi/2$ with respect to that associated with the anisotropy of nucleons, leading to the opposite signs of the values of F and v_2 between them. Consequently, azimuthal anisotropic emission of hard photon and free nucleon are anti-correlated, presenting the opposite behavior.

In conclusion, we have presented a first calculation of azimuthal asymmetry, both directed and elliptic asymmetry, for direct photons produced by proton–neutron bremsstrahlung from intermediate energy heavy-ion collisions. It was, for the first time, pre-

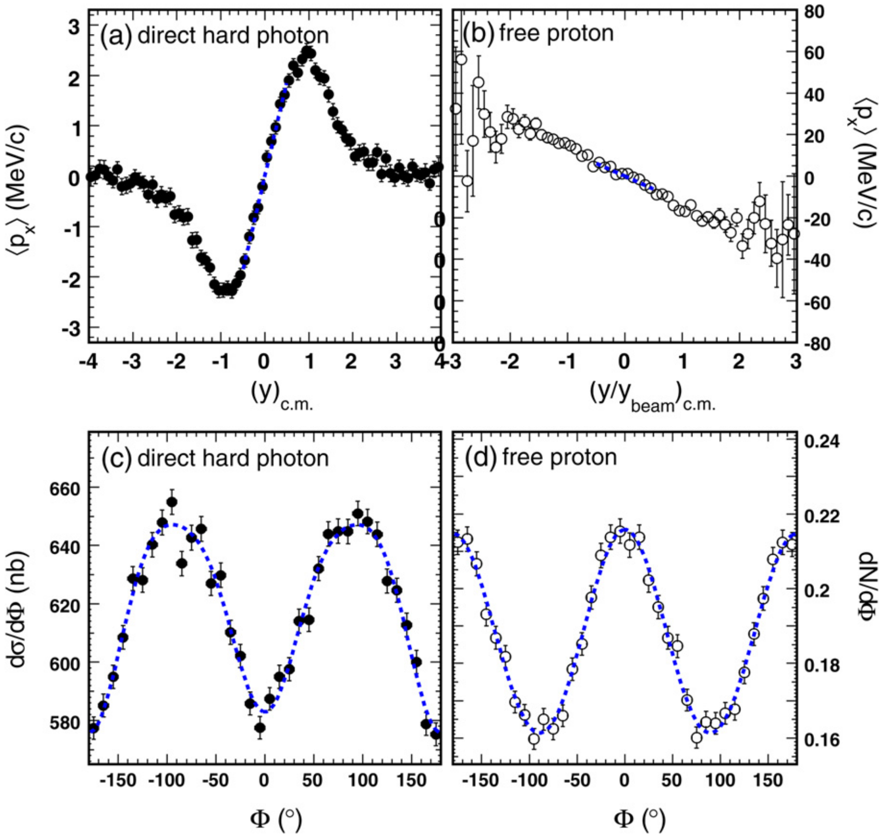

Fig. 3. (a) Average in-plane transverse momentum of direct photons as a function of c.m. rapidity for semi-central events (40–60%). The dashed line segment is a fit over the mid-rapidity region $-0.5 \leqslant y_{\mathrm{c.m.}} \leqslant 0.5$. (b) Same as the panel (a) but for free protons. The dashed line segment is a fit over the mid-rapidity region $-0.5 \leqslant (y/y_{\mathrm{beam}})_{\mathrm{c.m.}} \leqslant 0.5$. (c) and (d) are the azimuthal distributions of direct photons and free protons, respectively, and both of them are fitted to the 4th order Fourier expansion.

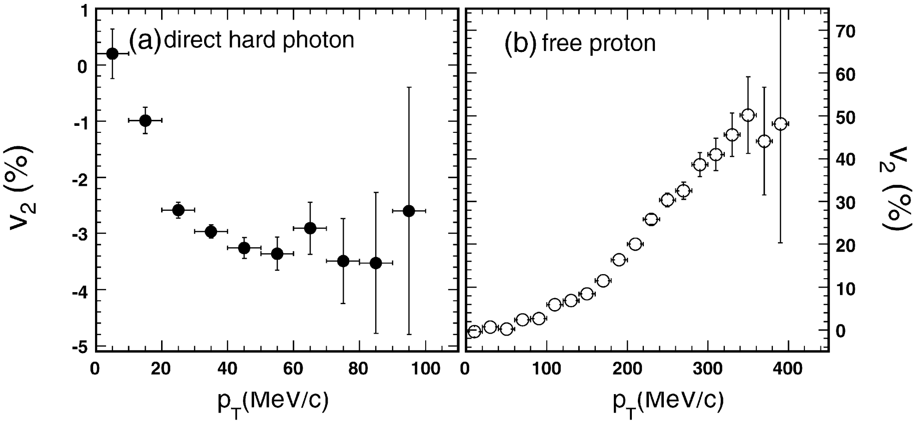

Fig. 4. v_2 as a function of transverse momentum (p_T) for direct photons (a) and free protons (b).

sented that in the intermediate energy heavy-ion collisions the proton–neutron bremsstrahlung hard photon shows non-zero directed transverse flow parameter and elliptic asymmetry coefficient which have opposite sign to the corresponding free proton flow parameters. The time evolutions of azimuthal parameters v_1 and v_2 of hard photons exhibit rich structures as the density oscillation of the system during the pre-equilibrium and thermalization stage of reaction system. Therefore direct photons can server for a good probe to nuclear matter properties. Considering that hard photons are dominantly produced by individual neutron–proton bremsstrahlung, so they are sensitive to the in-medium neutron–proton cross section, but not to the in-medium proton–proton or neutron–neutron cross section, that can be advantaged in the isospin dependent study of in-medium nucleon–nucleon cross section by direct photons. Of course, systematic studies of the influences from equation of state, in-medium nucleon–nucleon cross section, impact parameter and incident energy, etc., on the azimuthal asymmetry of direct photon should be carried out. The progress along this line is underway.

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