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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

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

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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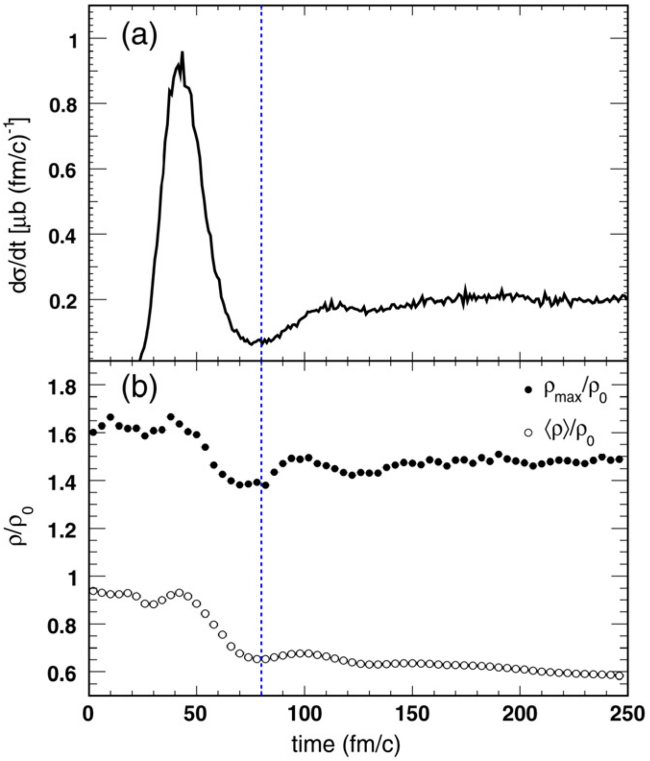

Fig. 1. (a) Time evolution of hard photon production rate for the reaction ^{40}Ca + ^{40}Ca collisions at 30 MeV/nucleon for semi-central events (40–60%). (b) Time evolution of reduced maximum density $\rho_{\max}/\rho_0$ (closed circles) and reduced average density $\langle\rho\rangle/\rho_0$ (open 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

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

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