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# Impact parameter and beam energy dependence for azimuthal asymmetry of direct photons and free protons 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 calculated the impact parameter and beam energy dependence for azimuthal asymmetry, characterized by directed transverse flow parameter $F$ and elliptic asymmetry coefficient $v_2$, of direct photons and the corresponding free protons in intermediate energy heavy-ion collisions. It is further shown the anti-correlated azimuthal asymmetry between direct photons and free protons.

**Key words** hard photon, azimuthal asymmetry, BUU, impact parameter dependence, energy dependence

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## 1 Introduction

One of the main goals of nuclear physics is to study properties of the dense and hot nuclear matter, especially the derivation of the nuclear Equation-of-State (EOS). Nuclear collisions provide the only means to compress nuclear matter to high density within a laboratory environment. The pressures that result from the high densities achieved during such collisions strongly influence the motion of ejected matter and provide the sensitivity to the EOS that is needed for its determination. In comparison with the conventional hadronic probes, 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 and therefore deliver an undistorted picture of the emitting source[1]. Since the last two decades, many model calculations and experimental facts [1—9] have indicated that in intermediate energy heavy-ion collisions hard photons defined as photons with energies above the Giant Dipole Resonance domain, above 30 MeV in this paper, mainly originate from incoherent proton-neutron bremsstrahlung collisions, $p+n \rightarrow p+n+\gamma$. These hard photons are emitted from two distinct sources. The first and dominant component denoted as direct photon is associated with the first-chance proton-neutron collisions in the initial phase of the heavy-ion reaction. The second one originates from the secondary proton-neutron collisions in the later stage of the reactions when the di-nuclear system is thermalizing, accordingly called as thermal photon. Because of their distinct emission sources, direct photons and thermal photons can deliver the thermodynamic information of the hot and dense nuclear matter formed during the various stages of the heavy-ion collisions.

## 2 BUU model and motivation

Our study is based on the Boltzmann-Uehling-

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Uhlenbeck (BUU) transport model which incorporates the isospin dependent initialization and isospin dependent potential. The nuclear mean field $U$ including isospin symmetry terms is parameterized as

$$U(\rho,\tau_z)=a\left(\frac{\rho}{\rho_0}\right)+b\left(\frac{\rho}{\rho_0}\right)^{\sigma}+C_{\mathrm{sym}}\frac{(\rho_{\mathrm{n}}-\rho_{\mathrm{p}})}{\rho_0}\tau_z, \quad (1)$$

where $\rho_0$ is the normal nuclear matter density; $\rho$, $\rho_{\mathrm{n}}$, and $\rho_{\mathrm{p}}$ are the nucleon, neutron and proton densities, respectively; $\tau_z$ equals 1 or $-1$ for neutrons and protons, respectively; The coefficients $a$, $b$ and $\sigma$ are parameters for nuclear equation of state. $C_{\mathrm{sym}}$ 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 $C_{\mathrm{sym}}$ = 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. [10], and modified as in Ref. [11] to allow for energy conservation. The double differential probability is given by

$$\frac{\mathrm{d}^2\sigma^{\mathrm{elem}}}{\mathrm{d}E_\gamma \mathrm{d}\Omega_\gamma}=\alpha\frac{R^2}{12\pi}\frac{1}{E_\gamma}(2\beta_{\mathrm{f}}^2+3\sin^2\theta_\gamma\beta_{\mathrm{i}}^2), \quad (2)$$

here $R$ is the radius of the sphere, $\alpha$ is the fine structure constant, $\beta_{\mathrm{i}}$ and $\beta_{\mathrm{f}}$ are the initial and final velocity of the proton in the proton-neutron center of mass system, and $\theta_\gamma$ is the angle between incident proton direction and photon emitting direction. More details for the model can be found in Ref. [12].

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[13—22]. In relativistic heavy-ion collisions azimuthal asymmetry of hard photons have been recently reported in the experiments and theoretical calculations[23—26]. It shows a very useful tool to explore the properties of hot dense matter. In our previous study, see Ref. [27], we 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 were illustrated and they seemed to be anti-correlated to the corresponding free proton's flow, wherein $F$ is defined by the slope of the mean in-plane transverse momentum distribution in the reduced c.m. mid-rapidity region $(-0.5,0.5)$: $F=\left.\frac{\mathrm{d}\langle p_x\rangle}{\mathrm{d}(y)_{\mathrm{c.m.}}}\right|_{(y)_{\mathrm{c.m.}}=0}$, $v_2$ corresponds to the second Fourier coefficient in the transverse momentum distribution: $v_2=\langle\cos(2\phi)\rangle$, and direct photons in the simulations are taken as photons which are emitting before the time of the first maximum expansion of the colliding system. More details can be found in Ref. [27].

To further validate the azimuthal asymmetry of hard photons and its anti-correlation with the corresponding free proton flow, here we study the impact parameter and beam energy dependence for azimuthal asymmetry of direct photons and free protons in intermediate energy heavy-ion collisions.

## 3 Simulations and results

### 3.1 Impact parameter dependence

It is well known that anisotropic flow mainly originates from the initial asymmetric overlap volume of colliding nuclei which leads to the different pressures and anisotropic emission of the particles. Peripheral collisions have more initial asymmetry in overlap volume than central collisions, thus produce more anisotropic emission of the particles. Therefore impact parameter should be very sensitive to the anisotropic emission and its dependence can be used as a very good tool of studying the flow.

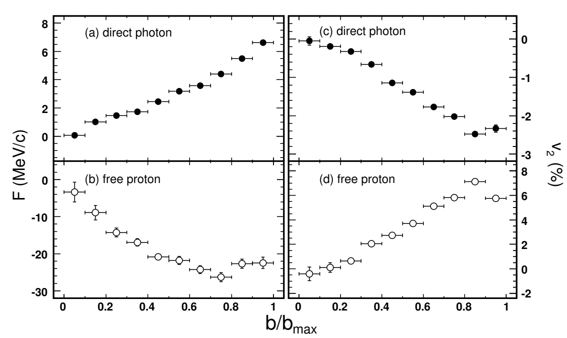


Fig. 1. (a) and (b) are the directed transverse flow parameter $F$ of direct photons and free protons, respectively, as a function of the reduced impact parameter for the reaction $^{40}$Ca + $^{40}$Ca collisions at 60 MeV/nucleon. (c) and (d) same as above but for elliptic asymmetry coefficient $v_2$.

Here we simulate the reaction $^{40}$Ca + $^{40}$Ca collisions at 60 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. Fig. 1(a) and (b) shows the directed transverse flow parameter $F$ of direct photons and free protons, respectively, as a function of the reduced impact parameter. Fig. 1(c) and (d) are the same as (a) and (b) but for elliptic asymmetry coefficient $v_2$. We can see that both $F$ and $v_2$ of direct photons and free protons have the similar tendency with the variance of impact parameter, i.e. their absolute values increase with the impact parameter except of slightly decrease in very peripheral collisions for $v_2$. We also see that for inclusive impact parameter , contrary to the negative directed transverse flow and positive elliptic flow of free protons, directed photons shows the positive $F$ and the negative $v_2$, i.e. the anisotropy is shifted by a phase $\pi/2$. It agrees with the previous conclusion that the azimuthal asymmetry of direct photons is anti-correlated with the corresponding free proton's flow.

### 3.2 Beam energy dependence

In Fig. 2 we show the directed transverse flow parameter $F$ and elliptic asymmetry coefficient $v_2$ of direct photons and free protons, respectively, as a function of beam energy for the reaction same as Fig. 1 but only semi-central events (40%—60%) and beam energy from 20 MeV/nucleon to 100 MeV/nucleon. In the beam energy range studied here, same as the impact parameter dependence, the opposite signs of $F$ and $v_2$ of direct photons and free protons also show their anti-correlation. Moreover, except the opposite sign, directed transverse flow parameter $F$ of direct photons and free protons have the very similar structures with the increase of beam energy. It shows the prospect of direct photons as a new probe of studying nuclear reaction balance energy as the nucleons. The negative direct photon elliptic asymmetry coefficient $v_2$ increases with the beam energy towards positive, which tendency also agrees with the available experimental results about hard photons in relativistic energy heavy-ion collisions.

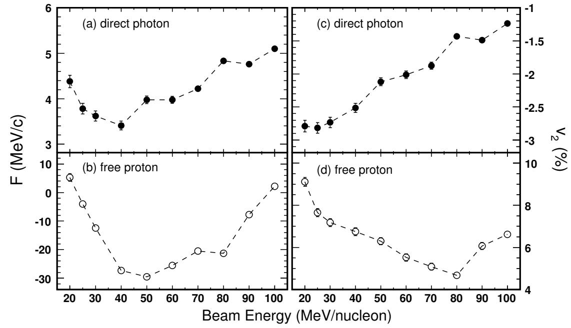


Fig. 2. (a) and (b) are the directed transverse flow parameter $F$ of direct photons and free protons, respectively, as a function of beam energy for the reaction same as Fig. 1 but only semi-central events (40%—60%). (c) and (d) same as above but for elliptic asymmetry coefficient $v_2$.

## 4 Summary

We study the impact parameter and beam energy dependence for azimuthal asymmetry of direct photons and free protons in intermediate energy heavy-ion collisions. Both of them further support the anti-correlation of anisotropic emission between direct photons and free protons. The beam energy dependence for directed transverse flow parameter $F$ and elliptic asymmetry coefficient $v_2$ of direct photons have the very similar structures to free protons'. Hence, we expect that in intermediate energy heavy-ion collisions direct photons can serve for a good probe to nuclear matter properties as the nucleons.

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