Effects of neutron-skin thickness on direct hard photon emission from the reactions induced by the neutron-rich projectile

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(Dated: January 5, 2022)

Direct hard photon emissions from incoherent proton-neutron bremsstrahlung in the collisions of neutron-rich projectile $^{50}$Ca with $^{12}$C and $^{40}$Ca targets are simulated in the framework of IQMD model, respectively. By adjusting the diffuseness parameter of neutron density in the droplet model to obtain different neutron skin thickness for $^{50}$Ca, the effects of neutron skin thickness on direct hard photon emission are investigated via several probes. The results show that more direct hard photons are produced with the increasing of the neutron skin thickness. Meanwhile, we find that yield ratio $R_{np}(\sigma_r)$ and the rapidity dependence of multiplicity and multiplicity ratio $R_{np}(N_e)$ for direct hard photons are apparently sensitive to neutron skin thickness. Furthermore, the direct hard photon differential and relative flows between central and peripheral collision are presented. We find that the differential flow is slightly more sensitive to neutron skin thickness than the relative flow. It is suggested that direct hard photon emission may be used as an experimental observable to extract the information of neutron skin thickness.

PACS numbers:

I. INTRODUCTION

The neutron skin of nuclei as an important fundamental property has attracted much attentions in traditional low energy heavy-ion physics and nuclear astrophysics [1–5]. Very recently the neutron skin effect was also recognized even in relativistic heavy-ion collision [6–9]. The neutron skin is usually defined as the difference between the root-mean-squared (rms) radii of neutrons and protons, i.e. $\delta_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$. Physically, it is closely related to nuclear equation of state, especially for the symmetry energy term [4, 10–12]. The formation of neutron skin in a nucleus depends on the balance between the inward pressure of the surface tension on excess neutrons on the edge of the nucleus and outward degeneracy pressure from excess neutrons within the core of the nucleus. Experimentally, proton rms radius can be probed to a very high accuracy with electromagnetic interaction [13]. However, it is considerably difficult to perform a measurement of the neutron (weak charge) density distributions to precision and details comparable with that of protons [14, 15].

Recent high-precision measurements of neutron skin thickness for $^{208}$Pb by PREX [16, 17] and $^{48}$Ca by CREX [18] make it possible to carry out a precise measurement of the neutron radius. But one-part-per-million parity-violating asymmetry hinders the precise measurement of the neutron radius for short-lived isotopes [19]. Therefore, more indirect experimental observable that is sensitive to neutron skin thickness is still very welcome.

Using the isospin-dependent quantum molecular dynamics (IQMD) model with the different neutron and proton density distributions in the phase-space initialization, Refs. [20, 21] proposed that the yield ratios of neutron-proton $[R(n/p)]$ can be taken as an experimental observable to extract neutron skin thickness. Then Ref. [22] indicated that the yield ratios of $^3$H-$^3$He $[R(t/He)]$ could be treated as another possible experimental observable to extract the proton skin thickness. Recently, Refs. [23, 24] have also supported that two above probes are sensitive to neutron skin thickness. Additionally, it was proposed to extract the proton rms radii $R_p$ [25] and then deduce neutron skin from charge-changing cross sections [26]. Ref. [27] also investigated the sensitivities of isoscaling behavior and mean $N/Z$ number for projectile-like fragments (PLFs) to neutron skin size and find that both them have a linear dependence on neutron skin thickness. However, compared with nucleons, light fragments and projectile-like fragments produced in the reaction, hard photons have a considerable advantage not being disturbed by the final-state interactions. Therefore, hard photons provide a clean probe of the reaction dynamics and deliver an unperturbed picture of the emitting source [28–35].

So far, many experimental [36–41] and theoretical [42–49] works have been done to understand the hard photon production mechanism in heavy-ion collision. Good reviews of hard-photon production are given by Refs. [50, 51], where energetic particles as probes of the first stages of the reaction is deeply discussed. Based on these studies, it has been pointed out that hard photon...
tons are emitted from two distinct sources, i.e. direct hard photon and thermal hard photon sources, in space and time according to experimental evidences and the Boltzmann-Uehling-Uhlenbeck model calculations [52, 53]. Direct hard photons stem from the first compression phase in the early stage of the reaction, which account for the dominant contribution. Thermal photons are produced from a thermalized source during the later stage of the reaction.

In the present work, the IQMD model takes into account the in-medium effects by introducing the in-medium nucleon-nucleon cross section in the process of two-body collisions. And a channel of incoherent proton-neutron bremsstrahlung collisions is embedded into the model. In recent calculations, we have performed a comparison with experimental data and have confirmed reliability of the method and model [54]. Moreover, considering that direct hard photon originated from the earlier stage of the reaction may keep some memories of the initial projectile. Here we shall focus on the effects of neutron skin thickness on direct hard photons emission from the reaction induced by neutron-rich projectile.

The paper is arranged as follows: In Sec. II, a brief review of the IQMD model and the formula of hard photon production probability are given. Results and discussion are described in Sec. III, where the sensitivities of several probes to neutron skin thickness are checked and discussed via direct hard photons, including yield and yield ratio, rapidity dependence of multiplicity, relative and differential flows of direct hard photons, as well as directed and elliptic flows. Finally, Sec. IV gives a summary.

II. MODEL AND FORMALISM

A. Brief review of IQMD model

The isospin-dependent quantum molecular dynamics (IQMD) model is a many-body theory which is developed from the standard QMD model by introducing isospin degrees of freedom into three components of the dynamics in heavy-ion collision at intermediate energy, namely, the mean field, two-body collisions, and Pauli blocking [20, 22–24, 27, 55–62]. In the model, each nucleon state is represented by a Gaussian wave function with width $L = 2.16 fm^2$,

$$\phi_i(r,t) = \frac{1}{(2\pi L)^{3/4}} \exp\left[ -\frac{(r - R_i)^2}{4L} + \frac{iP_i \cdot r}{\hbar} \right],$$

where $R_i$ and $P_i$ are the centers of position and momentum of the $i$-th wave packet, respectively. For a $N$-nucleon system, the total wave function $\Phi(r,t)$ that evolves with time $t$ is given by a direct product of these nucleon's wave functions,

$$\Phi(r,t) = \prod_{i=1}^{N} \phi_i(r,t).$$

In the phase space initialization of the projectile and target in the present IQMD model, the density distributions of protons and neutrons are distinguished from each other. The proton and neutron density distributions for the initial projectile and target nuclei are taken from the droplet model. By adjusting the diffuseness parameter of neutron density in the droplet model for projectile, we can get different skin size in density distributions [20, 22, 27, 63],

$$\rho_i(r) = \frac{\rho_i^0}{1 + \exp\left(\frac{r - C_i}{f_i} \right)}, i = n, p,$$

where $\rho_i^0$ is the normalization constant which can ensure that the integration of the density distribution is equal to the number of proton ($i = p$) or neutron ($i = n$); $C_i$ is half the density radius of proton or neutron density distributions; $f_i$ is introduced to adjust the diffuseness parameter $t_i$. More details can be found in Refs. [20–22, 27, 64]. In this work, $f_p = 1.0$ is used in Eq. (3) for the proton density distribution, while we take $f_n = 1.0, 1.2, 1.4, 1.6$ in Eq. (3) for neutron density distributions in order to obtain the different values of $\delta_{np}$. In Fig. 1, it plots the proton and neutron density distributions of $^{50}$Ca computed from the droplet model. The related $\delta_{np}$ values of $^{50}$Ca are also attached in the inserted figure. It can be found that with the increase of $f_n$, the neutron density distribution is more extended. Using these density distributions, the initial coordinates of nucleons in projectile and target nuclei are sampled via the Monte Carlo method. After IQMD initialization, the candidates of projectile and target nuclei are strictly selected by checking the stability of the sampled nuclei in the mean field.

Two body-collision as one of three important components in intermediate-energy heavy-ion collisions, it is well known that in-medium effects cannot be ignored in this process, especially in the Fermi-energy range.
Up to now, there are several available forms of the in-medium nucleon-nucleon cross section (in-medium NNCS) \[67–69\]. In the IQMD calculations, we take the screened cross section as the in-medium NNCS instead of free nucleon-nucleon cross section (free NNCS) parameterized from the experimental measurements \[70\]. The formula is derived from the geometric reasoning that the geometric cross section radius cannot exceed the interparticle distance \[68, 69\],

\[
\sigma_{NN}^{\text{in-medium}} = \sigma_0 \tanh(\sigma_{NN}^{\text{free}} / \sigma_0),
\]

\[
\sigma_0 = \gamma \rho^{-2/3}, \quad \gamma = 0.85.
\]

Here \(\rho\) denotes the single-particle density. It can be seen that the \(\sigma_{NN}^{\text{in-medium}}\) is strongly dependent on the density of the scattered nucleons. In Ref. \[54\], the hard photon energy spectra from our calculations are compared with the experimental data, which indicates that the calculated results employing in-medium NNCS in the IQMD model are in good accordance with experimental results.

Considering that the procedure of Pauli blocking is another important component in intermediate-energy heavy-ion collision and the Pauli blocking effects in most of QMD versions underestimate the blocking probability due to the fluctuations \[71\], we have performed some box calculations and confirmed that the Pauli blocking code in the present IQMD model are reasonable in our recent article \[54\].

**B. Hard photon production probability**

Hard photons in intermediate-energy heavy-ion collision are mainly originated from incoherent proton-neutron bremsstrahlung, i.e. \(p + n \rightarrow p + n + \gamma\). The elementary double-differential hard-photon production probability in the nucleon-nucleon center-of-mass frame employs the hard-sphere collision limit from Ref. \[72\] and is modified in Ref. \[48\] for energy conservation,

\[
\frac{d^2P}{dE_\gamma d\Omega_\gamma} = \frac{\alpha_c}{12\pi^2} E_\gamma (2\beta_0^2 - 3\sin^2 \theta_c \beta_f^2),
\]

where \(\alpha_c\) is the fine structure constant, \(E_\gamma\) is the energy of emitting photon, \(\beta_0\) and \(\beta_f\) are the initial and final velocity of the proton, and \(\theta_c\) is the angle between the momenta of the incident proton and the emitted photon.

**III. RESULTS AND DISCUSSION**

In the present work, the collisions of \(^{50}\text{Ca}\) and \(^{40}\text{Ca}\) projectiles with \(^{40}\text{Ca}\) and \(^{12}\text{C}\) targets at incident energies \((E_{\text{int}})\) from 40 to 150 MeV/nucleon are simulated under the framework of IQMD model with the in-medium NNCS in the process of two-body collision, respectively. To investigate the neutron skin effect on hard photon emission in intermediate-energy heavy-ion collision, we only focus on the central and peripheral collisions. For central collision, the collision centrality takes \(0\% - 10\%\) and central collision corresponds to \(80\% - 100\%\) centrality. Here, the centrality is defined by \(100\pi b^2 / b_{\text{max}}^2\), where \(b\) denotes impact parameter and \(b_{\text{max}}\) is the summation of the radius of projectile and target nuclei. The direct hard photons which are emitted from incoherent proton-neutron bremsstrahlung at the earlier stage of heavy-ion reaction should be more sensitive to the neutron skin thickness than thermal hard photons. That is the reason that we only check the effects of neutron skin thickness on the direct hard photon emission in this article. It needs to note that the time evolution of the dynamical process in our calculation is simulated until 100 fm/c which is the separation time \((t_s)\) between direct hard photons and thermal hard photons based on our recent work \[54, 59\].

**A. Yield and yield ratio of direct hard photons**

Figure 2 firstly plots the incident energy dependence of direct hard photon emitted from the peripheral collisions of \(^{40}\text{Ca}\) and \(^{50}\text{Ca}\) projectiles with \(^{12}\text{C}\) and \(^{40}\text{Ca}\) targets, respectively. It can be seen that there are more direct hard photons produced with the increase of \(E_{\text{int}}\) from 40 to 150 MeV/nucleon. The result is consistent with that in Ref. \[54\]. By comparing the reaction induced by \(^{40}\text{Ca}\) and \(^{50}\text{Ca}\) with \(f_n = 1.0\), it shows that more direct hard photons are emitted from the reaction with increasing neutron excess of the projectile. Moreover, we perform a comparison with the total yield of direct hard photons produced from the reactions induced by \(^{50}\text{Ca}\) with different \(f_n\), which corresponds to different value of neutron skin thickness. With the increase of neutron skin thickness, the total yield of direct hard photons will also increase at the \(E_{\text{int}}\) larger than 100 MeV/nucleon. It indicates that the larger neutron skin thickness can enhance the opportunity of incoherent proton-neutron bremsstrahlung in peripheral collisions so that more direct hard photons are produced, which is in accordance with the results in Ref. \[73\].

In order to cancel out the systematic errors to some extents, we define the yield ratios of direct hard photons from two similar reactions to probe the neutron skin thickness by

\[
R_{^{50}\text{Ca} + ^{12}\text{C}/^{40}\text{Ca} + ^{12}\text{C}}(\sigma_\gamma) = \frac{\sigma_{\gamma}(^{50}\text{Ca} + ^{12}\text{C})}{\sigma_{\gamma}(^{40}\text{Ca} + ^{12}\text{C})},
\]

\[
R_{^{50}\text{Ca} + ^{40}\text{Ca}/^{40}\text{Ca} + ^{40}\text{Ca}}(\sigma_\gamma) = \frac{\sigma_{\gamma}(^{50}\text{Ca} + ^{40}\text{Ca})}{\sigma_{\gamma}(^{40}\text{Ca} + ^{40}\text{Ca})},
\]

which is also usually used in experiments \[74\]. Note that the reactions of \(^{40}\text{Ca} + ^{12}\text{C}\) and \(^{40}\text{Ca} + ^{40}\text{Ca}\) are used as a referential reaction. Based on Eq. \(7)\) and \(8), the yield ratios of direct hard photons emitted from the two peripheral collisions as a function of incident energy and neutron skin thickness are plotted in Figure 3, respectively. Comparing with the calculated results from the re-
actions induced by the neutron-rich projectile $^{50}\text{Ca}$ with different $f_n$ in Figure 3(a) and (b), we see that the value of yield ratio keeps on a rise with the $f_n$ changing from 1.0 to 1.6 when $E_{\text{int}}$ is larger than 100 MeV/nucleon, especially for $^{50}\text{Ca} + ^{12}\text{C}$ collisions. Furthermore, the neutron skin thickness dependence of yield ratio from two similar reactions in the centrality of 80% – 100% can be observed clearly. There exists a linear correlation between yield ratio of direct hard photons from two similar reactions and neutron skin thickness when $E_{\text{int}}$ is about 120 MeV/nucleon. It indicates that yield ratio of direct hard photon is sensitive to neutron skin thickness at an incident energy of about 120 MeV/nucleon.

Similar to the yield ratio of direct hard photon from two reactions, we also check the effect of neutron skin thickness on direct hard photon production via using a probe of yield ratio of direct hard photon from the central and peripheral collisions in the same reaction by following formula

$$R_{\text{cp}}(\sigma_\gamma) = \frac{\sigma_\gamma(\text{Central coll.})}{\sigma_\gamma(\text{Peripheral coll.})} \tag{9}$$

In the above equation, the numerator is evaluated for 0% – 10% centrality and the denominator is computed for 80% – 100% centrality in our calculations. The incident energy and neutron skin thickness dependence of the $R_{\text{cp}}$ in $^{50}\text{Ca} + ^{12}\text{C}$ and $^{50}\text{Ca} + ^{40}\text{Ca}$ collisions are shown in Figure 4. It is clear to see that the value of $R_{\text{cp}}$ has a tendency to decrease with increasing $f_n$ except for that at lower incident energy because more direct hard photons are emitted from the peripheral collision induced by $^{50}\text{Ca}$ with larger neutron skin size. Meanwhile, we find that the $R_{\text{cp}}$ of direct hard photon originated from $^{50}\text{Ca} + ^{12}\text{C}$ is more sensitive to neutron skin thickness.

### B. Rapidity dependence of the direct hard photon multiplicity

Based on the discussion in Sec. III A, the energy of about 120 MeV/nucleon for incident nucleus $^{50}\text{Ca}$ is a good reaction condition to probe the neutron skin effect on direct hard photon production. So Figure 5 only shows the rapidity distributions of the multiplicity of direct hard photon in the collisions of $^{50}\text{Ca}$ projectile with $^{12}\text{C}$ and $^{40}\text{Ca}$ at an incident energy of 120 MeV/nucleon and at the centrality of 80% – 100%, respectively. It is fortunate to find that the rapidity distributions of multiplicity for direct hard photons are appreciable sensitive to the neutron skin thickness. Meanwhile, we can find
that the multiplicities of direct hard photon show an increasing trend with the increase of neutron skin thickness of the neutron-rich projectile $^{50}$Ca, especially for that at midrapidity from the participant region. The results are also confirmed that there are more direct hard photons emitted from the peripheral collisions induced by a projectile with a larger neutron skin size.

To cancel out the errors inside the reaction systems, we also employ the multiplicity ratios of direct hard photon emitted from the central and peripheral collisions in the same reaction which reads

$$R_{\text{cp}}(N_{\gamma}) = \frac{dN_{\gamma}/d(y/y_{\text{beam}})_{\text{c.m.}}(\text{Central coll.})}{dN_{\gamma}/d(y/y_{\text{beam}})_{\text{c.m.}}(\text{Peripheral coll.})}, \quad (10)$$

where the collision centrality in the numerator and denominator is the same as that in Eq. 9. Figure 6 shows the calculated results from the reaction of $^{50}$Ca+$^{12}$C and $^{50}$Ca+$^{40}$Ca. We see that the values of multiplicity ratio tend to decrease with the increasing of $f_n$ and that the ratio is also greatly sensitive to the neutron skin thickness.

C. Relative and differential flows of direct hard photon

The transverse collective flow has been used to probe the nuclear symmetry energy effects in previous work [75]. Considering that neutron skin size is closely related to the slope parameter $L$ of symmetry energy, we will also employ the transverse collective flow as an observable to check the effects of neutron skin thickness on direct hard photons produced from the reactions induced by neutron-rich projectile in this section.

Based on Eq. (6), we can estimate the hard photon production probability for one neutron-proton bremsstrahlung collision. Then the average transverse momentum of direct hard photons in the nucleus-nucleus center-of-mass frame is defined as

$$\langle p_{\gamma}^T \rangle \equiv \frac{1}{\sum P_{i}} \sum P_{i}^T \ast p_{T}^2, \quad (11)$$

where $P_{i}^T$ is the production probability of the $i-th$ hard photon with transverse momentum $p_{T}^2$. And $\sum P_{i}^T$ denotes the total production probability of direct hard photons in the reduced c.m. rapidity bin at $(y/y_{\text{beam}})_{\text{c.m.}}$. Figure 7 plots the transverse flows of direct hard photons in the collisions of $^{50}$Ca+$^{12}$C and $^{50}$Ca+$^{40}$Ca at 120 MeV/nucleon and 80% – 100% centrality as a function of the reduced c.m. rapidity, respectively. The various lines denote the $^{50}$Ca projectile with different $f_n$, which corresponds to the different neutron skin sizes. It shows that direct hard photons in $^{50}$Ca+$^{12}$C collision shows a stronger flow than that in $^{50}$Ca+$^{40}$Ca. Moreover, we fo-
Focus on the effects of neutron skin thickness on transverse momentum. As a consequence, we find that although there are different transverse momentum distributions for the reaction induced by the $^{50}\text{Ca}$ projectile with different $f_n$, unfortunately, there is no obvious correlation between the direct hard photon transverse momentum $p_\gamma^T$ and neutron skin thickness.

Furthermore, differential and relative flows for hard direct photons between central and peripheral collisions are defined by

$$
(p_\gamma^T)_{\text{Centr.}} = \frac{1}{\left(\sum P_i^T\right)_{\text{Centr.}}} \left(\sum P_i^T \right)_{\text{Centr.}} - \left(\sum P_i^T \right)_{\text{Peri.}}
$$

and

$$
(p_\gamma^T)_{\text{Peri.}} = \frac{1}{\left(\sum P_i^T\right)_{\text{Peri.}}} \left(\sum P_i^T \right)_{\text{Peri.}} - \left(\sum P_i^T \right)_{\text{Centr.}}.
$$

D. Directed and Elliptic flows of direct hard photon

In previous studies, we know the direct hard photons which are mainly emitted from incoherent proton-neutron bremsstrahlung in heavy-ion collisions have the behaviors of directed flow $v_1$ and elliptic flow $v_2$ [29, 30, 76, 77]. This section explores the effects of neutron skin thickness on the directed flow $v_1$ and elliptic flow $v_2$ of direct hard photons. Firstly, the formulas of $v_1$ and $v_2$ are read as

$$
v_1 = \langle \cos\phi \rangle = \left\langle \frac{p_x}{p_T} \right\rangle,
$$

$$
v_2 = \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle,
$$

respectively. Based on Eq. (14), Figure 9 shows the directed flow $v_1$ of direct hard photons emitted from the reactions of $^{50}\text{Ca}+^{12}\text{C}$ and $^{50}\text{Ca}+^{40}\text{Ca}$ at 120 MeV/nucleon and in 80% – 100% centrality as a function of transverse momentum $p_T$. Compared with the $v_1$ values from the reactions induced by the $^{50}\text{Ca}$ projectile with different $f_n$, the neutron skin effects on the direct hard photon $v_1$ can be neglected at lower $p_T$. Nevertheless, Figure 9 (b) demonstrates that the direct hard photon $v_1$ in $^{50}\text{Ca}+^{40}\text{Ca}$ is more sensitive to neutron skin thickness at higher $p_T$.

Figure 10 plots the elliptic flows of direct hard photon from $^{50}\text{Ca}+^{12}\text{C}$ and $^{50}\text{Ca}+^{40}\text{Ca}$ collisions at 120 MeV/nucleon as a function of transverse momentum $p_T$, respectively. Different linear correspond to the projectile $^{50}\text{Ca}$ with different neutron-skin sizes. We find that the direct hard photon $v_2$ in peripheral collisions is also insensitive to the neutron skin thickness at lower $p_T$. However, it is different from the probe of the direct hard photon $v_1$ that the neutron skin sizes in projectile $^{50}\text{Ca}$ have an apparent effect on the $v_2$ values of direct hard photon at higher $p_T$ in both $^{50}\text{Ca}+^{12}\text{C}$ and $^{50}\text{Ca}+^{40}\text{Ca}$ collisions. Unfortunately, similar to the $v_1$, there is not a certainty correlation between the $v_2$ and neutron skin thickness.
be good probes of neutron skin thickness. Therefore, the direct hard photon \( v(\gamma) \) and \( v(\alpha) \) correspond to \( \sigma_T \) of transverse momentum \((p_T)\) for the effects of neutron skin thickness on direct hard photon emissions from the reactions of \(^{50}\text{Ca}+^{12}\text{C} \) and \(^{50}\text{Ca}+^{40}\text{Ca} \) in the framework of IQMD model. By adjusting the diffuseness parameter of neutron density in the droplet model for the projectile \(^{50}\text{Ca}\) to obtain different neutron skin thickness, the sensitivities of several observable to neutron skin sizes are explored. We find that the yield ratio of direct hard photons between from central and peripheral collisions in the same reaction, i.e. \( R_{cp}(\sigma_T) \), are more sensitive to neutron skin thickness than the yield \( \sigma_T \) and yield ratio between two similar reactions. We also study on the rapidity distribution of multiplicity \( N_\gamma \) and multiplicity ratio \( R_{cp}(N_\gamma) \) of direct hard photons, and discover that both these two probes display appreciable sensitivity to neutron skin thickness. Meanwhile, we find that there are more direct hard photon produced with the increase of neutron skin thickness. Furthermore, the direct hard photon differential and relative flows between central and peripheral collisions are also presented. The calculations show that the differential flow is slightly more sensitive to neutron skin thickness than the relative flow. Additionally, we also study the transverse momentum dependence of the directed and elliptic flows of direct hard photons originated from the reaction induced by \(^{50}\text{Ca}\) with different neutron skin thickness. The result shows that it is difficult to explore the neutron skin effects of direct hard photons via both directed and elliptic flows. On the whole, direct hard photons can be treated as an experimental observable to extract the information of neutron skin thickness.

**FIG. 9:** The directed flows of direct hard photon emitted from the peripheral collisions of \(^{50}\text{Ca}+^{12}\text{C} \) (a) and \(^{50}\text{Ca}+^{40}\text{Ca} \) (b) at 120 MeV/nucleon as a function of transverse momentum \( p_T \), respectively. Different lines correspond to \(^{50}\text{Ca}\) projectiles with different \( f_n \).

**FIG. 10:** The elliptic flow \( v_2 \) of direct hard photon emitted from the peripheral collisions in the reaction of \(^{50}\text{Ca}+^{12}\text{C} \) (a) and \(^{50}\text{Ca}+^{40}\text{Ca} \) (b) at 120 MeV/nucleon as a function of transverse momentum \( p_T \), respectively. Different lines correspond to \(^{50}\text{Ca}\) projectiles with different \( f_n \).

Therefore, the direct hard photon \( v_1 \) and \( v_2 \) seem not to be good probes of neutron skin thickness.

**IV. SUMMARY**

In summary, we have carried out a systematic study for the effects of neutron skin thickness on direct hard photon emissions from the reactions of \(^{50}\text{Ca}+^{12}\text{C} \) and \(^{50}\text{Ca}+^{40}\text{Ca} \) in the framework of IQMD model. By adjusting the diffuseness parameter of neutron density in the droplet model for the projectile \(^{50}\text{Ca}\) to obtain different neutron skin thickness, the sensitivities of several observable to neutron skin sizes are explored. We find that the yield ratio of direct hard photons between from central and peripheral collisions in the same reaction, i.e. \( R_{cp}(\sigma_T) \), are more sensitive to neutron skin thickness than the yield \( \sigma_T \) and yield ratio between two similar reactions. We also study on the rapidity distribution of multiplicity \( N_\gamma \) and multiplicity ratio \( R_{cp}(N_\gamma) \) of direct hard photons, and discover that both these two probes display appreciable sensitivity to neutron skin thickness. Meanwhile, we find that there are more direct hard photon produced with the increase of neutron skin thickness. Furthermore, the direct hard photon differential and relative flows between central and peripheral collisions are also presented. The calculations show that the differential flow is slightly more sensitive to neutron skin thickness than the relative flow. Additionally, we also study the transverse momentum dependence of the directed and elliptic flows of direct hard photons originated from the reaction induced by \(^{50}\text{Ca}\) with different neutron skin thickness. The result shows that it is difficult to explore the neutron skin effects of direct hard photons via both directed and elliptic flows. On the whole, direct hard photons can be treated as an experimental observable to extract the information of neutron skin thickness.

This work is supported by the National Natural Science Foundation of China under Contracts Nos. 11890710, 11890714, 12147101, 11875066, 11925502, 11961141003, 11935001 and 12105053, the Strategic Priority Research Program of CAS under Grant No. XDB34000000, National Key R&D Program of China under Grant No. 2016YFE0100900 and 2018YFE0104600, and by Guangdong Major Project of Basic and Applied Basic Research No. 2020B0301030008.

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