Spectra and elliptic flow of thermal photons from full-overlap U+U collisions at energies available at the BNL Relativistic Heavy Ion Collider

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We calculate p_T spectra and elliptic flow for tip-tip and body-body configurations of full-overlap uranium-uranium (U + U) collisions by using a hydrodynamic model with smooth initial density distribution and compare the results with those obtained from Au + Au collisions at the BNL Relativistic Heavy Ion Collider (RHIC). Production of thermal photons is seen to be significantly larger for tip-tip collisions compared with body-body collisions of uranium nuclei in the region $p_T > 1$ GeV. The difference in the results for the two configurations of U + U collisions depends on the initial energy deposition which is yet to be constrained precisely from hadronic measurements. The thermal photon spectrum from body-body collisions is found to be close to the spectrum from most-central Au + Au collisions at RHIC. The elliptic-flow parameter calculated for body-body collisions is found to be large and comparable to the $v_2(p_T)$ for mid-central collisions of Au nuclei. On the other hand, as expected, $v_2(p_T)$ is close to zero for tip-tip collisions. The qualitative nature of the photon spectra and elliptic flow for the two different orientations of uranium nuclei is found to be independent of the initial parameters of the model calculation. We show that the photon results from fully overlapping U + U collisions are complementary to the results from Au + Au collisions at RHIC.

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I. INTRODUCTION

Anisotropic flow or in particular elliptic flow is one of the key observables used to study the properties of the Quark Gluon Plasma (QGP) produced in collisions of heavy nuclei at relativistic energies. Hydrodynamic model with smooth initial density distribution has been used successfully in recent past to study the bulk properties of matter as it simultaneously explains both the spectra and elliptic flow of charged particles [1,2]. It has been shown in many interesting recent studies that the event-by-event hydrodynamic model with fluctuating initial conditions [3–8] explains the elliptic-flow results even for most-central collisions of heavy nuclei and also the large triangular flow of hadrons at RHIC and LHC energies [9–12] both of which were unexplained earlier by hydrodynamics with smooth initial density distribution.

Photons are considered as one of the promising probes to study the properties of the quark gluon plasma formed in relativistic heavy ion collisions [13]. Recent experimental data from 200A GeV Au + Au collisions at the BNL Relativistic Heavy Ion Collider (RHIC) by PHENIX [14] and from 2.76A TeV Pb + Pb collisions at the Large Hadron Collider (LHC) by ALICE [15] have reported excess of direct photon yield over scaled proton-proton collisions. The excess yield in both cases is attributed to photon radiation from the thermalized QGP and hot hadronic matter.

Photon elliptic flow has the potential to illustrate the hot and dense initial state and its evolution more efficiently compared with hadronic v_2 [16]. Direct photon v_2 data at RHIC [17] and LHC [18] show similar qualitative nature as predicted by model calculations considering hydrodynamical evolution of the system. However, theory results under-estimate the data by a large margin [19]. This is known as the photon v_2 puzzle. Many recent studies with the viscous hydrodynamics model using event-by-event fluctuating initial conditions as well as studies considering pre-equilibrium flow have found it difficult to simultaneously explain the photon spectra and elliptic flow. Recent developments in the theory of photon production and calculation of the photon anisotropic flow parameter in relativistic heavy ion collisions can be found in Refs. [20–36].

Collisions of uranium (^{238}U) nuclei at $\sqrt{s_{\rm NN}} = 193$ GeV at RHIC have gathered a lot of attention recently. The STAR experiments at RHIC have reported interesting results on particle production as well as azimuthal flow of hadrons [37]. U + U collisions are of special interest due to the nonspherical prolate shape of the colliding nuclei [38–44] and as a result, even the most-central collisions can lead to different collision geometry and consequently different values of charged particle multiplicity and anisotropic flow parameters. Recently it has been reported that the most-central events in U + U collisions can be identified from the spectator energy deposition at the zero degree calorimeters (ZDCs). In addition, the multiplicity distribution of elliptic flow along with the ZDCs information can be used to separate different orientations of U + U collisions [37].

We know that photons are emitted throughout the lifetime of the evolving system and the thermal emission of photons is sensitive to the initial stages of the matter produced. Thus, photon production from different orientations of U + U collisions can provide valuable information about the hot and dense initial stage of the expanding system and also its evolution. In addition, it would be interesting to know how large is the photon v_2 originating from fully overlapping U + U collisions and if its comparison with the photon v_2

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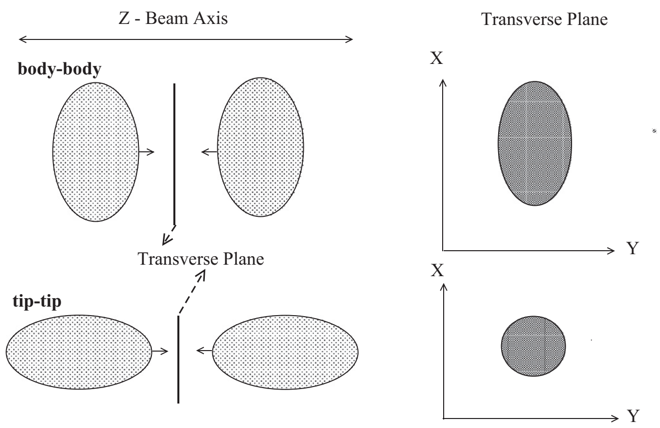

FIG. 1. Schematic of tip-tip and body-body collision of full-overlap uranium nuclei.

from noncentral Au + Au collisions can help us to understand the photon v_2 puzzle.

We calculate thermal photon spectra and differential elliptic flow at RHIC for two different orientations, *tip-tip* and *body-body*, which are the limiting cases (of particle multiplicity) of fully overlapping U + U collisions. In body-body collisions the major axes of the two incoming uranium nuclei are perpendicular to the z axis (beam axis) whereas for tip-tip collisions the major axes are parallel to the beam direction. The tip-tip collisions produce a circular overlapping zone on the transverse plane and the body-body collisions lead to an elliptical shape and a larger size of the overlapping zone (see Fig. 1). Although the number of participants in both these collisions are same, number of binary collisions is about 30% larger for the tip-tip configuration. The energy density produced is larger and consequently a higher final charged particle multiplicity is observed for tip-tip collisions than for the body-body collisions. However, the body-body collisions produce a large v_2 because of the initial geometry of the overlapping zone [37].

It has been shown in Ref. [38] that the value of the initial spatial anisotropy (ϵ_{in}) for full-overlap body-body collision is similar to the ϵ_{in} calculated for Au + Au collisions at RHIC at an impact parameter $\sim$7 fm; however, the system produced in Au + Au collisions is about half of the size of system produced in U + U collisions. Thus, the photon spectra and elliptic flow from the different orientations of U + U collisions along with the Au + Au results at RHIC would enrich our understanding of the hot and dense initial state produced in relativistic heavy ion collisions. We keep our calculations simple by using a hydrodynamical model with a smooth initial density distribution. The initial energy depositions for the tip-tip and body-body orientations are taken from Ref. [38] and the calculated thermal photon spectra and elliptic-flow parameter depend strongly on the initial conditions. An event-by-event hydrodynamic model calculation including viscous effects is expected to provide a more accurate estimation of the photon spectra and elliptic-flow parameter. However, in the present study we are more interested in showing the qualitative difference in the spectra and v_2 resulting from the different orientations of the uranium nuclei in and also the potential of thermal photons from U + U collisions to be used as probe to study the relativistic heavy ion collisions. In addition, we calculate prompt photons from body-body and tip-tip collisions of uranium nuclei and compare the direct photon spectra (obtained by adding prompt and thermal contributions) for the two configurations.

In Sec. II we briefly discus the initial parameters and the framework for the model calculation. Thermal photon spectra and elliptic-flow results are presented in Sec. III and in the next section we summarize the results.

II. FULL-OVERLAP U + U COLLISIONS AT RHIC

We use Woods–Saxon parametrization for the nuclear density distribution of deformed uranium nuclei of the form [43]

$$\rho(r,\theta) = \frac{\rho_0}{1 + \exp\frac{[r - R(\theta)]}{\xi}}, \quad (1)$$

where

$$R(\theta) = R_0\left[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)\right]. \quad (2)$$

The spherical harmonic functions and the β values introduce the deformation from spherical shape in the uranium nucleus. Here, β_2 and β_4 are 0.28 and 0.093, respectively [43]. R_0 is taken as 6.86 fm and ξ is 0.44 fm [43]. Using this parametrization in the optical Glauber model, we calculate the number of wounded nucleons (N_{part}) and binary collisions (N_{coll}) for different orientations of full-overlap U + U collisions at RHIC. The value of N_{coll} is $\sim$1870 and $\sim$1430 for tip-tip and body-body collisions, respectively, whereas N_{part} is the same for both the cases.

We modify the (2 + 1)-dimensional longitudinally boost invariant hydrodynamic code AZHYDRO [1] with smooth initial density distribution to study the evolution of the system produced in U + U collisions at RHIC. The initial formation time τ_0 is considered as 0.6 fm. The corresponding initial entropy densities (s_0) at the center of the fireball are taken as 167 fm^{-3} and 110 fm^{-3} for full-overlap tip-tip and body-body collisions, respectively, and thus the value of s_0 is about 34% higher for the tip-tip configuration [38]. For Au + Au collisions at 200A GeV, s_0 is taken as 117 fm^{-3} and it reproduces the experimentally measured charged particle multiplicity at midrapidity.

A lattice-based equation of state [45] is used and the final freeze-out temperature T_f is considered as 140 MeV. We check the sensitivity of our results to the initial parameters of the model calculation by changing the value of τ_0 and T_f from their default values. For initial density distribution we use both the wounded nucleon profile ($\alpha = 0$) as well as a two-component ($\alpha = 0.25$) model [38] (where the initial entropy is taken to be proportional to a linear combination of 25% of N_{coll} and 75% of N_{part}) to calculate the photon production from U + U collisions.

The nucleon-nucleon inelastic cross section σ_{NN} for 200 GeV collisions is 42 mb and we use the same σ_{NN} for 193 GeV collisions of uranium nuclei at RHIC. We assume that the small change in the value of σ_{NN} for change in center-of-mass energy from 200 to 193 GeV would not

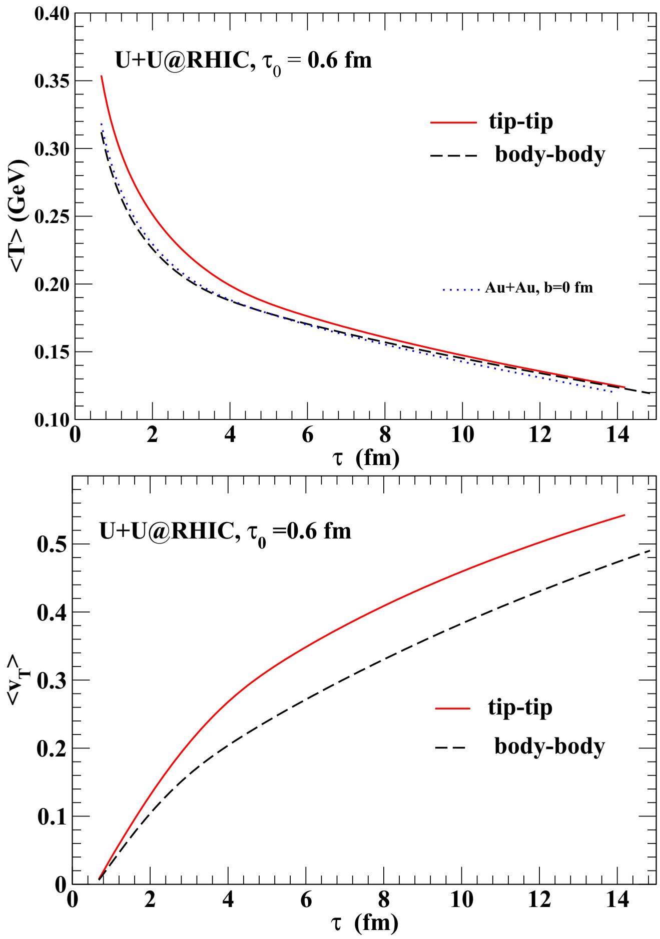

FIG. 2. Time evolution of (a) average temperature $\langle T\rangle$ and (b) average transverse flow velocity $\langle v_T\rangle$ for tip-tip and body-body full-overlap U + U collisions at RHIC.

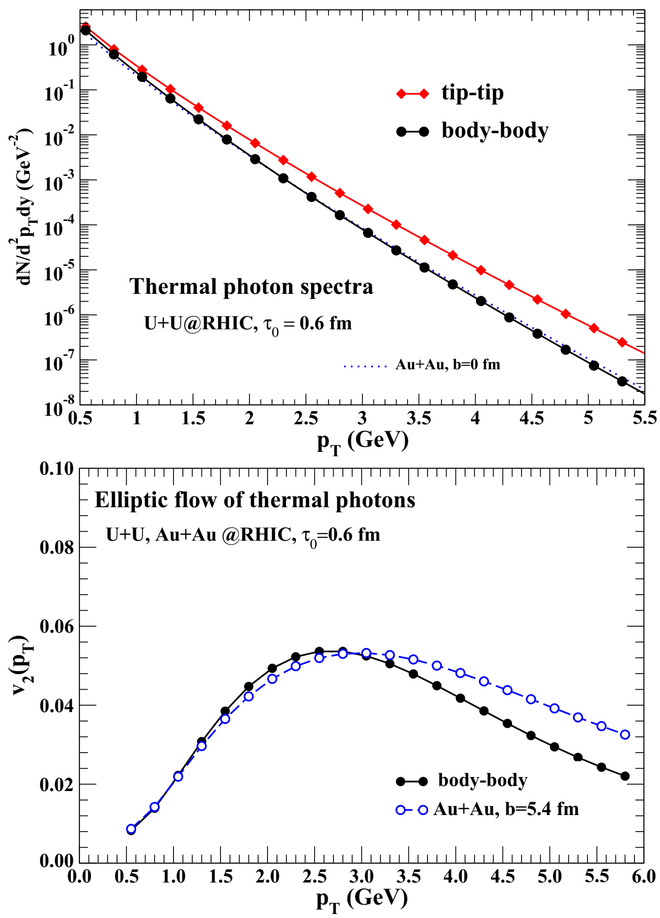

FIG. 3. Thermal photon (a) p_T spectra and (b) elliptic flow from full-overlap U + U collisions using hydrodynamic model for $\tau_0 = 0.6$ fm and $\alpha = 0.25$.

significantly affect our results. We use next-to-leading order QGP rates from Refs. [46,47] to calculate the photons spectra and elliptic flow. The photon production from the hadronic phase is calculated by using the parametrization given in Ref. [48] for different hadronic channels. The p_T spectra are calculated by integrating the emission rates over the spacetime four-volume and the elliptic-flow parameter v_2 is calculated by using the relation

$$v_2(p_T) = \langle\cos(2\phi)\rangle = \frac{\int_0^{2\pi} d\phi \cos(2\phi)\frac{dN}{p_T dp_T dy d\phi}}{\int_0^{2\pi} d\phi \frac{dN}{p_T dp_T dy d\phi}}. \quad (3)$$

III. RESULTS

The time evolution of average temperature (upper panel) and average transverse flow velocity (lower panel) for the two orientations of U + U collisions at RHIC are shown in Fig. 2. The averages are obtained by using the relation

$$\langle f\rangle = \frac{\int dx dy \epsilon(x,y) f(x,y)}{\int dx dy \epsilon(x,y)}. \quad (4)$$

The value of $\langle T\rangle$ at time τ_0 is ~350 MeV for tip-tip collisions, which is about 6% larger than for body-body collisions. The $\langle T\rangle$ for most-central Au + Au collisions is found to be close to that of body-body collisions as the initial entropy densities for these two cases are similar. We also see that the average v_T is significantly larger for tip-tip collisions throughout the system evolution and the system lifetime is slightly larger for body-body collisions.

The upper panel of Fig. 3 shows the thermal photon p_T spectra for full-overlap tip-tip and body-body collisions of uranium nuclei considering initial formation time $\tau_0 = 0.6$ fm and $\alpha = 0.25$. The p_T spectrum from central Au + Au collisions is also shown in the figure for a comparison. Thermal photon production is found to depend strongly on the orientation of the colliding uranium nuclei. The production is significantly larger for tip-tip collisions in the higher-p_T (>1 GeV) region and the photon spectrum from the body-body orientation falls more rapidly compared with the tip-tip spectrum for larger values of p_T. One can see from the figure that the production for tip-tip collisions is about a factor of 2–5 times larger than for body-body collisions in the region $2 < p_T < 4$ GeV. We have discussed that the fireball produced in tip-tip collisions is smaller in size and has larger initial energy and/or entropy density and temperature than the body-body configuration. A higher initial temperature results in more high-p_T photons from the initial stages in tip-tip collisions, which make the spectrum flatter. The production in the low p_T (<1 GeV) region for body-body as well as for tip-tip collisions is mostly from the hadronic phase. Any other orientation of full-overlap $\mathrm{U}+\mathrm{U}$ collisions would result in photon spectra lying in between the spectra from tip-tip (upper limit) and body-body (lower limit) collisions in the high-p_T region.

It is to be noted that the results presented here depend strongly on the initial energy deposition values taken from Ref. [38] for the two limiting configurations of the uranium nuclei. A more realistic estimation of the photon spectra and elliptic-flow parameter demands these initial conditions to simultaneously reproduce the experimental charged particle spectra and anisotropic flow parameter. However, this seems a little difficult at the moment due to the present status of the available experimental data. In this study we mainly focus on thermal photons as a potential probe to study $\mathrm{U}+\mathrm{U}$ collisions at RHIC and the qualitative nature of the results presented here is expected to remain unchanged for small changes in the value of initial energy deposition.

The elliptic-flow parameter $v_2(p_T)$ for body-body collisions is shown in lower panel of Fig. 3. The $v_2(p_T)$ for tip-tip collisions is zero as there is no initial spatial anisotropy present in the system (note that hydrodynamical model calculations using fluctuating initial conditions would result in a very small but nonzero photon elliptic flow even for tip-tip collisions of uranium nuclei). However, we see significantly large elliptic flow for body-body collisions. In addition, this large-flow result is found to be close to the $v_2(p_T)$ calculated from $\mathrm{Au}+\mathrm{Au}$ collisions at RHIC at an impact parameter $b=5.4$ fm. The initial spatial anisotropy of the overlapping zone is calculated by using the relation

$$\epsilon_{\rm in} = \frac{\int dxdy\ \epsilon(x,y,\tau_0)(y^2-x^2)}{\int dxdy\ \epsilon(x,y,\tau_0)(y^2+x^2)}, \tag{5}$$

where $\epsilon(x,y,\tau_0)$ is the energy density at point (x,y) on the transverse plane at time τ_0. Note that the initial spatial anisotropy of the overlapping zone for full-overlap body-body collision is about 0.26, whereas the value of $\epsilon_{\rm in}$ is about 0.19 at $b=5.4$ fm for $\mathrm{Au}+\mathrm{Au}$ collisions. The peak of $v_2(p_T)$ appears around $p_T\sim 2$ GeV and the competing contributions of photons originating from the different stages of the evolving system determine the shape of the $v_2(p_T)$ curve. Because the relative contribution from the hadronic phase compared with the QGP phase for mid-central $\mathrm{Au}+\mathrm{Au}$ collisions is much larger than for body-body collisions of uranium nuclei, we see that the results in the lower panel of Fig. 3 are similar even for a smaller $\epsilon_{\rm in}$ in the case of $\mathrm{Au}+\mathrm{Au}$ collisions.

We know that photon $v_2(p_T)$ rises towards peripheral collisions as the initial spatial anisotropy increases (as in the case for the elliptic flow of hadrons) and also due to change in the relative contributions from the quark matter and hadronic matter phases [16]. The body-body collision of uranium nuclei shows large elliptic flow even for most-central collisions and thus it would be interesting to see if v_2 for this orientation increases significantly towards peripheral collisions.

We recall that the initial formation time τ_0 plays important role in photon calculations as a smaller value of τ_0 means larger initial temperature and more production of high-p_T photons [20,49]. Thermal photon spectra and v_2 for $\tau_0=0.2$ fm are shown in Fig. 4. The value of τ_0 is reduced from 0.6 to 0.2 fm, keeping the total entropy of the system fixed. We see enhanced production of thermal photons compared with $\tau_0=0.6$ fm both for tip-tip and body-body collisions (upper panel of Fig. 4). However, the difference between the slopes of the spectra for the two orientations remain similar to the results obtained at $\tau_0=0.6$ fm. Photon v_2 for full-overlap tip-tip collisions is zero and does not depend on the initial parameters of the hydrodynamic calculation. However, for body-body collisions we see large elliptic flow (lower panel of Fig. 4) and again the result is close to the photon v_2 calculated from $\mathrm{Au}+\mathrm{Au}$ collisions at RHIC at $b=5.4$ fm and at $\tau_0=0.2$ fm. The thermal photon spectra and elliptic flow for $\tau_0=0.6$ fm and $\alpha=0$ are shown in Fig. 5. The elliptic-flow results from $\mathrm{U}+\mathrm{U}$ as well as from the $\mathrm{Au}+\mathrm{Au}$ collisions are found to be somewhat larger compared with the results obtained by considering $\alpha=0.25$. However, the qualitative nature of the spectra as well as v_2 do not show strong dependence on the value of α. We have also checked that the qualitative nature of the spectra and elliptic-flow results presented here do not change significantly when the freeze-out temperature is reduced from 140 to 120 MeV.

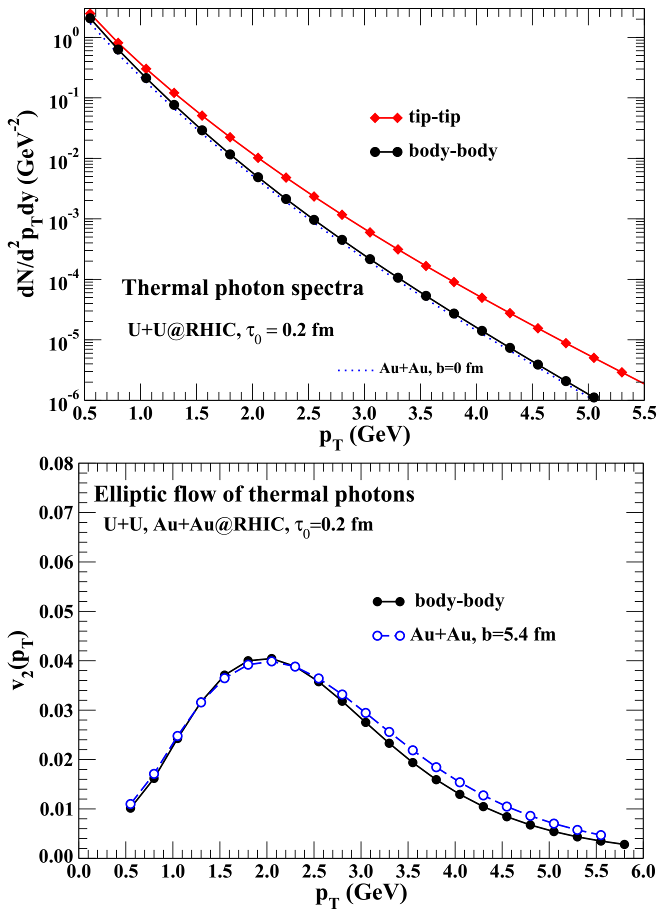

FIG. 4. Thermal photon (a) p_T spectra and (b) elliptic flow from full-overlap $\mathrm{U}+\mathrm{U}$ collisions using the hydrodynamic model for $\tau_0=0.2$ fm and $\alpha=0.25$.

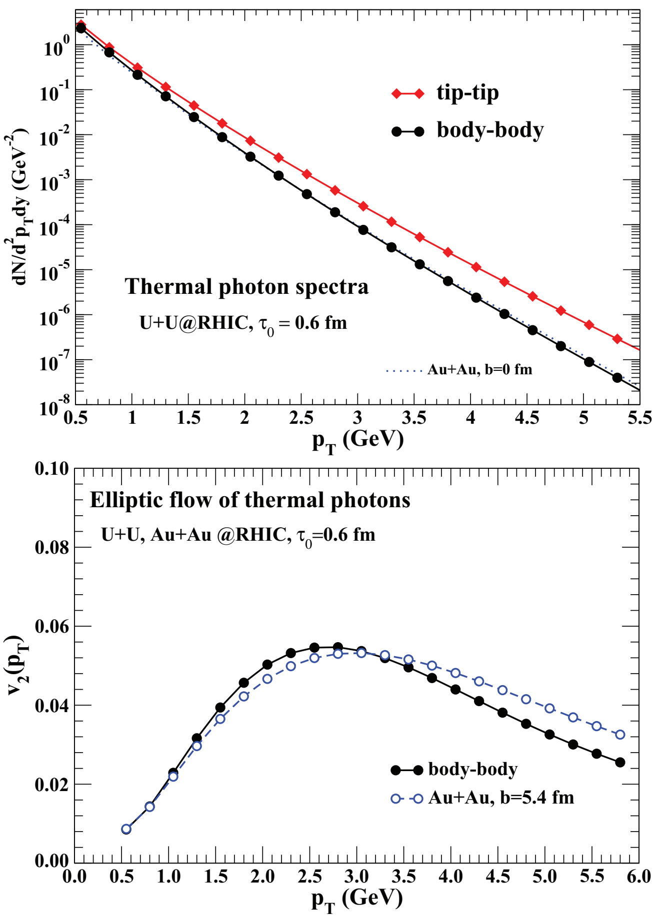

FIG. 5. Thermal photon (a) p_T spectra and (b) elliptic flow from full-overlap U + U collisions using hydrodynamic model for $\tau_0 = 0.6$ fm and $\alpha = 0$.

We know that the prompt photons produced in initial hard scatterings start to dominate the direct photon spectrum in the region $p_T > 3$–4 GeV. We estimate the prompt photons [50] by using next-to-leading order perturbative QCD (NLO pQCD) calculation and the CTEQ5M [51] structure function for the two limiting cases discussed here for full-overlap U + U collisions at 193A GeV. As the value of N_{coll} is about 30% larger for the tip-tip than for the body-body configuration, the prompt contribution is also found to be about 30% larger for the tip-tip case (see Fig. 6). One can see from the figure that the direct photon spectrum (combining prompt and thermal contributions) for tip-tip configurations is about a factor of two larger than for the body-body collisions in the range $p_T < 5$ GeV. Thus, we see that the direct photon spectra from full-overlap U + U collisions at RHIC show significant dependence on the orientation of the colliding nuclei even at larger values of p_T (~4–5 GeV), where the nonthermal contributions dominate the spectra.

Note that fluctuations in the initial density distribution might result in a small increase in v_2 in the high-p_T region for body-body collisions and also a small but nonzero v_2 even for tip-tip collisions [52]. In addition, viscosity plays a role in photon v_2 calculations by reducing v_2 at higher p_T [24].

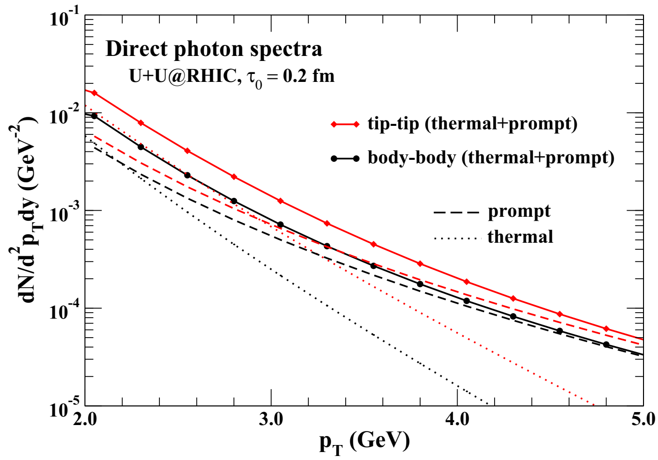

FIG. 6. Direct photon (thermal and prompt) spectra from full-overlap U + U collisions.

Thus, a complete calculation using viscous hydrodynamics with event-by-event fluctuating initial condition would be valuable and we postpone this for a future study [53]. However, the results presented in this paper are believed to be generic in nature and should remain unaltered even with the modifications discussed above.

We know that the different orientations of the most-central U + U collisions can be distinguished from the spectator energy deposition at the ZDCs together with the particle multiplicities. Thus, experimental determination of photon v_2 from different orientations of uranium nuclei should also be possible.

We see a significant enhancement in the photon production from tip-tip U + U collisions compared with central Au + Au collisions. In addition, the photon $v_2(p_T)$ from the body-body U + U collisions is found to be similar to the elliptic flow from mid-central Au + Au collisions at RHIC by using hydrodynamical model calculations. However, note that the system produced in mid-central Au + Au collisions and in body-body U + U collisions is very different in terms of initial temperature, system size, and lifetime. It is shown that the time evolution of average temperature for central Au + Au collisions and body-body U + U collisions are close to each other. Thus, the system produced in Au + Au collisions at $b = 5.4$ fm is expected to have smaller temperature than the one in body-body U + U collisions. As a result, the relative contributions of the QGP and hadronic matter phases to the total photon v_2 are very different although the flow results look similar in those two cases. Now, it is not possible to know the separate contributions of the QGP and the hadronic phases to photon elliptic flow from the experimentally obtained v_2 data. However, theory calculation has this advantage which helps us to understand that two very different systems (with different relative contributions from quark and hadronic matter phases) can have similar v_2.

Thus, experimental determination of photon spectra and elliptic flow from U + U collisions at RHIC would be valuable and comparison of the results with the photon results from Au + Au collisions at various centrality bins would provide an additional handle to study photon production in relativistic heavy ion collisions.

IV. SUMMARY

We have calculated p_T spectra and differential elliptic flow $v_2(p_T)$ of thermal photons for tip-tip and body-body orientations of full-overlap U + U collisions at RHIC by using hydrodynamic model with a smooth initial-density distribution. We see significantly larger production of thermal photons from tip-tip collisions in the region $p_T > 1$ GeV compared with the body-body collisions. The results depend on the difference in energy depositions (the values of which are yet to be constrained precisely from hadronic measurements) for the two limiting configurations of uranium nuclei. Larger initial energy densities as well as temperatures for tip-tip collisions result in more high p_T photons from the early stage of system evolution. We see relatively larger production of prompt photons from the tip-tip collisions than from the body-body collisions (because $N_{\rm coll}$ is larger for tip-tip collision) and thus, the direct photon spectra obtained by adding the prompt and thermal contributions also show significant difference between the limiting cases of full-overlap U + U collisions up to a large p_T ($\sim$5 GeV). The photon v_2 from tip-tip collisions is close to zero from hydrodynamic calculations because there is no spatial anisotropy present in the system (note that fluctuations in the initial density distribution would result in a small v_2 even for tip-tip collisions). On the other hand, we see a significantly large photon v_2 from full-overlap body-body collisions, which is comparable to the photon v_2 calculated at $b = 5.4$ fm from 200A GeV Au + Au collisions at RHIC. Comparison of photon v_2 from body-body U + U collisions and from mid-central Au + Au collisions at RHIC would be valuable to understand the photon-v_2 puzzle. We also calculate the spectra and elliptic-flow parameter from U + U and Au + Au collisions by changing the initial parameters of the hydrodynamic model calculation and see that the qualitative nature of the results remain unchanged.

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