Photons from ultrarelativistic nuclear collisions

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Using the multiple scattering model for ultrarelativistic nuclear collisions, we have calculated the cross section of photons from the decay of neutral pions that are produced in the collision between two heavy ions at energies to be available in the heavy-ion collider. We have found that photons with low energies and at forward angles do not constitute an appreciable background to the bremsstrahlung photons due to the deacceleration of the nuclei. The bremsstrahlung photon can therefore serve as a probe of the nuclear stopping power in ultrarelativistic heavy-ion collisions.

One area in the study of ultrarelativistic heavy-ion collisions is the determination of the stopping power in such collisions. This knowledge is essential for extracting the energy density reached in the collision so that one is able to determine whether the condition for creating a quark-gluon plasma is satisfied. Various models[1-5] have been developed for describing the nuclear stopping power in ultrarelativistic heavy-ion collisions. Because of the large effect of Lorentz contraction in these reactions, the momentum distribution of nucleons from the intermediate nucleon-nucleon collisions may be different from the momentum distribution from the nucleon-nucleon collision in the free space. The stopping power index α was introduced to take into account this effect.[4,5] Following the approach of Bjorken and McLerran,[6] we have recently studied the production of bremsstrahlung photon in such reactions.[7] Based on the multiple scattering model developed by Wong,[3] we have found that for collisions at ultrarelativistic energies with a fixed target the bremsstrahlung spectra at small laboratory angles are sensitive to the law of stopping when nucleons of one nucleus pass through the other nucleus. However, there is a large background of photons from the decay of neutral pions created in the reaction. In this report, we shall calculate this background using the π^0 rapidity distribution determined from the same multiple scattering model.

In the multiple scattering model, pions are created from nucleon-nucleon collisions. Due to the finite time associated with particle production and the large velocity of the nucleon, pions are assumed to be produced after the nucleus-nucleus collision is over and hence, do not undergo secondary collisions with the nucleons. For heavy-ion collision at an impact parameter b, the pion momentum distribution is simply given by the product of the average number of nucleon-nucleon inelastic collisions $n(b)$ and the pion momentum distribution from the nucleon-nucleon collision $d^2N/dp_\perp dy$, i.e.,

$$\frac{d^2N^{AB}(b)}{dp_\perp dy}=\frac{d^2N}{dp_\perp dy}n(b) . \tag{1}$$

In the above, $p_\perp$ and y are, respectively, the transverse momentum and the rapidity. The average number of nucleon-nucleon inelastic collisions can be determined from the Glauber model in terms of the nucleus-nucleus thickness function $T(b)$ and the nucleon-nucleon inelastic cross section σ_{in},

$$n(b)=\frac{ABT(b)\sigma_{\text{in}}}{\{1-[1-T(b)\sigma_{\text{in}}]^{AB}\}} , \tag{2}$$

where A and B are the atomic numbers of the two nuclei. For the energy region we are considering, we have $\sigma_{\text{in}}\approx 30$ mb. The nucleus-nucleus thickness function can be parametrized by

$$T(b)=\left[\frac{1}{2\pi\beta^2}\right]\exp(-b^2/2\beta^2) , \tag{3}$$

with $\beta^2=\beta_A^2+\beta_B^2+\beta_p^2$. In the above, β_p is the standard deviation of the nucleon-nucleon thickness function and has a value of 0.68 fm, and

$$\beta_A^2=(r_{\text{rms}})^2A^{2/3}/3 , \tag{4}$$

with r_{rms} the root-mean-squared radius parameter of nucleus A and having a value of 1.15 fm. A similar expression is for nucleus B. The neutral pion momentum distribution from the nucleon-nucleon collision $dN/dp_\perp dy$ can be parametrized by a Fermi-type distribution,[3]

$$\frac{dN}{dp_\perp dy}=\left[\frac{C}{2}\right]\left[1-\exp\left[\frac{y-y_0}{\Delta}\right]\right]^{-1} \times\left[\frac{1}{2\pi\alpha_\pi^2}\right]\exp(-p_\perp/\alpha_\pi) . \tag{5}$$

The constants in this equation can be determined from the available experimental data and have the following simple parametrizations:

$$\Delta=0.55,\quad \alpha_\pi\approx 0.38\ \text{GeV}/c , \tag{6}$$

$$C(s^{1/2})=0.48\ln(s^{1/2})+0.038 , \tag{7}$$

and

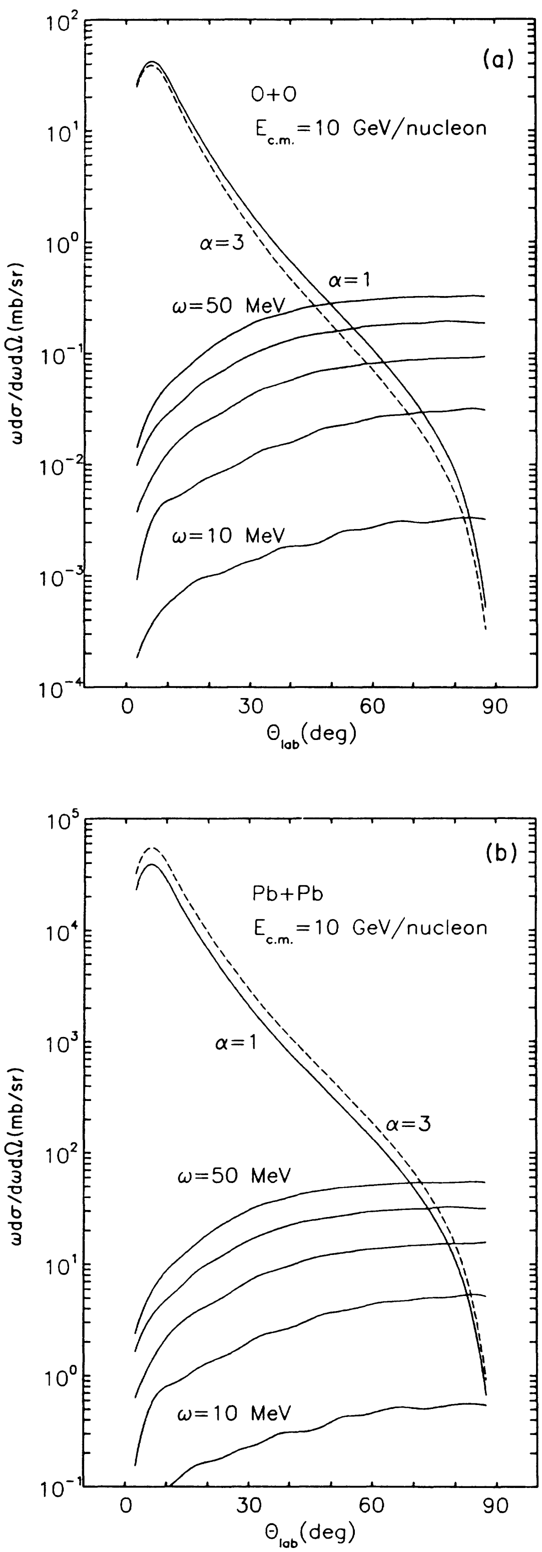

FIG. 1. (a) Photon inclusive spectra from the collision of two oxygen nuclei at a collider energy of 10 GeV/nucleon. The forward peaked spectra are from bremsstrahlung with two values of the stopping power index; solid curve for $\alpha=1$ and dashed curve for $\alpha=3$. The flatter spectra are from the decay of the neutral pions. The photon energies of the latter are 10, 20, 30, 40, and 50 MeV from the bottom to the top. (b) Same as (a) for the collision of two lead nuclei.

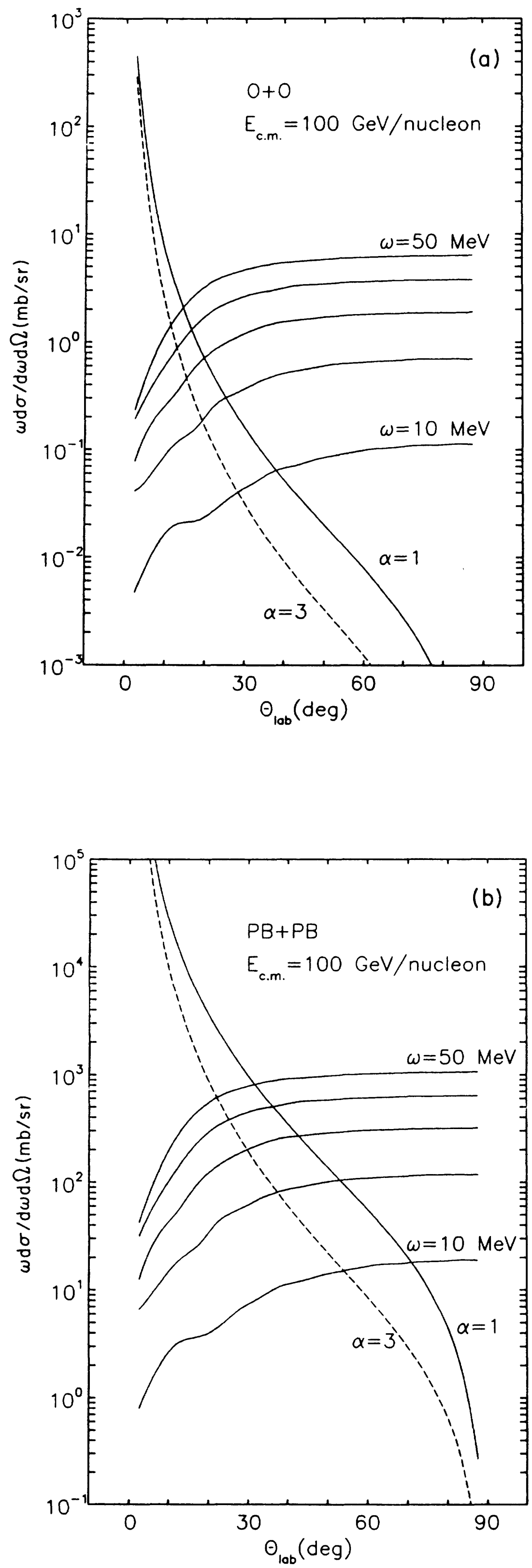

FIG. 2. (a) Same as Fig. 1(a) for collisions at 100 GeV/nucleon. (b) Same as (a) for the collision of two lead nuclei.

$$y_0(s^{1/2})=0.45\ln(s^{1/2})+1.40 \ . \tag{8}$$

In the above equations, the nucleon-nucleon center-of-mass energy is denoted by $s^{1/2}$ and is in units of GeV.

Let $dN(\mathbf{p},\mathbf{k})/d^3\mathbf{k}$ be the distribution of photons with momentum $\mathbf{k}$ from the decay of the π_0 with momentum $\mathbf{p}$, then the total photon distribution can be written as

$$\frac{dN^\gamma}{d^3\mathbf{k}}=\int d^3\mathbf{p}\frac{dN^\pi}{d^3\mathbf{p}}\frac{dN(\mathbf{p},\mathbf{k})}{d^3\mathbf{k}} \ . \tag{9}$$

An approximate evaluation of this expression has been carried out in Ref. 6 for very soft photons $k \ll m_\pi$. For high energy photons, the integral in Eq. (9) can be numerically evaluated easily as done in Ref. 8. We use instead the Monte-Carlo method to evaluate the integral in Eq. (9) so that the distribution of photons with arbitrary energies can be determined. We choose enough number of pions with their momenta distributed according to Eq. (5). Then two photons are created isotropically in the pion rest frame. The final photon distribution is obtained from transforming these photons to the laboratory frame. To calculate the cross section, we normalize the photon distribution by the actual number of neutral pions created in the collision and integrate it over the impact parameter.

For the bremsstrahlung photon from the collision, we calculate it in the soft photon approximation,[6,7] i.e.,

$$\frac{d^2\sigma}{d\omega\, d\Omega}=\frac{e^2}{16\pi^3\omega}\int d\mathbf{b}\left|\sum_i^{P,T}\int dy\left.\frac{dN}{dy}\right|_i\left[\frac{v\sin\theta}{1-v\cos\theta}-\frac{v_i\sin\theta}{1-v_i\cos\theta}\right]\right|^2 , \tag{10}$$

where the summation is over the projectile and the target. The velocity of the nucleus before the collision is denoted by v_i. The quantity $dN/dy\,|_i$ is the proton rapidity distribution of the nucleus after the collision and is determined by the same multiple scattering model as described in Ref. 3.

We have calculated the photon spectra from both the nuclear bremsstralung and the decay of the neutral pions for collisions between a number of symmetric systems at a collider energy of both 10 and 100 GeV/nucleon. Some of them are shown in Figs. 1 and 2. Only cross sections in the forward directions are shown as they are symmetric with respect to $\theta_{\text{lab}}=90°$. The forward peaked spectra are from the bremsstrahlung for two values of the stopping power index α. The solid curve is for $\alpha=1$ while the dashed curve is for $\alpha=3$. The latter corresponds to a nucleon-nucleon collision that results in a narrower rapidity distribution than that in the free space corresponding to $\alpha=1$. Those photon spectra of more or less isotropic shape at large angles are from the decay of the neutral pions. The curves from the bottom to the top correspond, respectively, to photon energies of 10, 20, 30, 40, and 50 MeV. We see that at low energies and forward angles photons from the pion decay do not lead to a significant background. The situation is particularly favorable for collisions of heavy nuclei at lower incident energies. However, the bremsstrahlung photons are less sensitive to the stopping power index α at low collision energies as the nuclei are more likely to be stopped in these collisions. For collisions at higher energies the bremsstrahlung photons depend more strongly on the stopping power index α but only those in very forward directions have cross sections that are appreciably above the background from pion decays.

In conclusion, the photon bremsstrahlung spectra from nucleus-nucleus collisions at ultrarelativistic energies are calculated using the proton spectra obtained in a multiple scattering model. The photon spectra are sensitive to the law of stopping when nucleons of one nucleus pass through the other nucleus. Using the same model we have also calculated the cross section of photons from the decay of neutral pions that are produced in the collision. We have found that for low energy photons at forward angles, they do not constitute an appreciable background. The bremsstrahlung photon therefore is a promising probe of the nuclear stopping power in ultrarelativistic heavy-ion collisions.

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