Light from Cascading Partons in Relativistic Heavy-Ion Collisions

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We calculate the production of high energy photons from Compton and annihilation processes as well as fragmentation off quarks in the parton cascade model. The multiple scattering of partons is seen to lead to a substantial production of high energy photons, which rises further when parton multiplication due to final state radiation is included. The photon yield is found to be directly proportional to the number of hard collisions and thus provides valuable information on the preequilibrium reaction dynamics.

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High-energy collisions of heavy nuclei are studied with the goal to explore the properties of matter at energy densities many times that of normal nuclear matter. There are strong theoretical reasons to believe that matter under these conditions, when thermally equilibrated, forms a quark-gluon plasma (QGP), a state of matter in which quarks and gluons are not confined to hadrons. The discovery of this state of matter and the study of its properties would constitute a major advance in our understanding of quantum chromodynamics (QCD).

The parton cascade model (PCM) [1] was proposed to provide a detailed description of the temporal evolution of nuclear collisions at high energy, from the onset of hard interactions among the partons of the colliding nuclei up to the moment of hadronization. The PCM is based on a relativistic Boltzmann equation for the time evolution of the parton density in phase space due to perturbative QCD (pQCD) interactions including scattering and radiation in the leading logarithmic approximation.

During the epoch where the partonic picture of sequential perturbative interactions among QCD quanta may be valid, important many-body effects, such as parton shadowing, color screening, and Landau-Pomeranchuk-Migdal (LPM) suppression of gluon radiation, complicate the single-particle dynamics of parton transport. Obviously, the PCM involves the application of perturbative QCD to a hitherto untested domain. This poses the question: How can one test the correctness of this approach? This is clearly not possible by studying the hadronic final state, since—if the dense matter equilibrates—all information about its dynamics before equilibrium will be lost. One may look for remnants of the preequilibrium dynamics in the form of very energetic partons, which did not lose a large fraction of their initial momentum due to interaction in the dense medium and produce jets. Even better suited to this purpose are weakly interacting probes of the preequilibrium dynamics, such as quanta that interact only electromagnetically: photons and leptons.

Photons, which are produced from Compton ($qg \rightarrow q\gamma$), annihilation ($q\bar{q} \rightarrow g\gamma$), and bremsstrahlung ($q^\star \rightarrow q\gamma$) processes (see Fig. 1), thus assume considerable importance. These are analogous to the processes governing the energy loss of energetic partons, where gluons are emitted instead of photons. Photons, however, once emitted, almost always escape the system, and their energy and momentum will remain unaffected [2] as they will only rarely interact with the surrounding medium. For this reason, they are excellent and reliable probes of the evolution of the partonic cascade in nuclear collisions. In fact, one can argue that the photons confirm the presence of parton cascading processes after the initial primary parton-parton collisions.

In this Letter, we address several questions relating to the value of photons as probes of the dense matter created in a nuclear collision: Are photons sensitive to the preequilibrium partonic reaction dynamics, i.e., parton rescattering? What effect do parton fragmentation processes have on photon production? Is there a direct connection between the photon yield and the number of hard perturbative parton-parton collisions during the reaction? In view of our specific focus, we do not consider

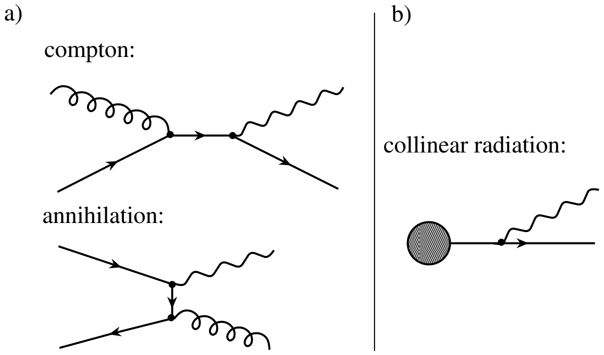

FIG. 1. Photon production processes included in our calculation.

the production of photons from a late-stage, thermal mixed phase or hadronic phase. These contributions are quite well understood [3], and can easily be added to our results.

The fundamental assumption underlying the PCM is that the state of the dense partonic system can be characterized by a set of one-body distribution functions $F_i(x^\mu, p^\alpha)$, where i denotes the flavor index ($i = g, u, \bar{u}, d, \bar{d}, \ldots$) and x^μ, p^α are coordinates in the eight-dimensional phase space. The partons are assumed to be on their mass shell, except before the first scattering. In our numerical implementation, the GRV-HO parametrization [4] is used, and the parton distribution functions are sampled at an initialization scale Q_0^2 [$\approx (p_T^{\min})^2$; see later)] to create a discrete set of particles. Partons generally propagate on-shell and along straightline trajectories between interactions. Before their first collision, partons may have a spacelike four-momentum, especially if they are assigned an "intrinsic" transverse momentum.

The time evolution of the parton distribution is governed by a relativistic Boltzmann equation:

$$p^\mu \frac{\partial}{\partial x^\mu} F_i(x, \vec{p}) = C_i[F], \tag{1}$$

where the collision term C_i is a nonlinear functional of the phase-space distribution function. The calculations discussed below include all lowest-order QCD scattering processes between massless quarks and gluons [5], as well as all ($2 \to 2$) processes involving the emission of photons ($qg \to q\gamma$, $\bar{q}g \to \bar{q}\gamma$, $q\bar{q} \to g\gamma$, $q\bar{q} \to \gamma\gamma$). A low momentum-transfer cutoff $p_T^{\min}$ is needed to regularize the infrared divergence of the perturbative parton-parton cross sections. A more detailed description of our implementation is in preparation [6].

We account for the final state radiation [7] following a hard interaction in the parton shower approach. In the leading logarithmic approximation, this picture corresponds to a sequence of nearly collinear $1 \to 2$ branchings: $a \to bc$. Here, a is called the mother parton, and b and c are called daughters. Each daughter can branch again, generating a structure with a treelike topology. We include all such branchings allowed by the strong and electromagnetic interactions. The probability for a parton to branch is given in terms of the variables Q^2 and z. Q^2 is the momentum scale of the branching and z describes the distribution of the energy of the mother parton a among the daughters b and c, such that b takes the fraction z and c the remaining fraction $1 - z$. The differential probability to branch is

$$\mathcal{P}_a = \sum_{b,c} \frac{\alpha_{abc}}{2\pi} P_{a\to bc} \frac{dQ^2}{Q^2} dz, \tag{2}$$

where the sum runs over all allowed branchings. The α_{abc} is α_{em} for branchings involving emission of a photon and α_s for the QCD branchings. The splitting kernels $P_{a\to bc}$ are given in [8]. The collinear singularities in the showers are regulated by terminating the branchings when the virtuality of the (timelike) partons drops to μ_0, which we take as 1 GeV. In principle, one could take a smaller value for the cutoff μ_0 for a quark fragmenting into a photon [9], but we have not done so as we are interested only in high energy photons here. The soft-gluon interference is included as in [7], namely, by selecting the angular ordering of the emitted gluons. An essential difference between emission of a photon and a parton in these processes is that the parton encounters further interactions and contributes to the buildup of the cascade, while the photon almost always (in our approximation, always) leaves the system along with the information about the interaction.

Some of these aspects were discussed by the authors of Ref. [10] and explored within the framework of the PCM implementation VNI [11]. Unfortunately, several components of their numerical implementation were incorrect. Our present work is based on a thoroughly revised and extensively tested implementation of the parton cascade model by the present authors, called VNI/BMS [6].

As a first step, we discuss the results obtained when the parton cascade is restricted to two-body scattering. We are considering central collisions ($b = 0$) of Au nuclei at full RHIC energy ($\sqrt{s} = 200$ GeV per nucleon pair). We have confirmed the accuracy of our code by comparing the analytical pQCD prediction for prompt photon production, due to Compton and annihilation processes, with our results, when we use an eikonal approximation in the cascade. Our results are shown in Fig. 2, where we compare the contributions from interactions involving at least one primary parton (triangles) with the result obtained with full binary cascading (diamonds). Note that

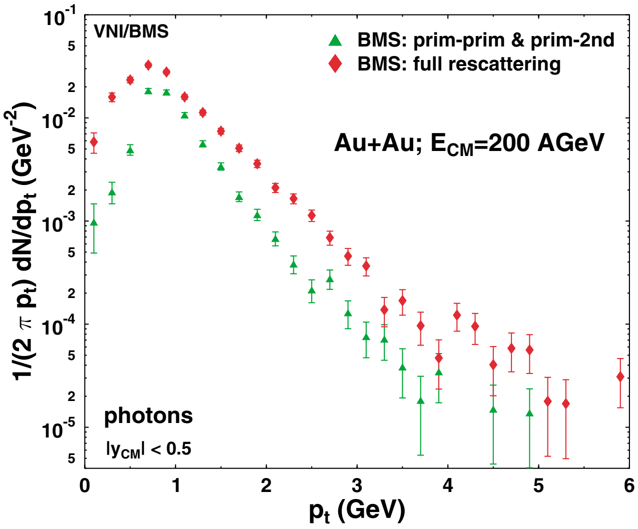

FIG. 2 (color online). Transverse momentum distribution of photons from central collision of gold nuclei at RHIC (see text for an explanation of the symbols).

contribution from primary partons does not reflect the momentum broadening (Cronin effect) due to multiple soft scattering. The figure shows that most of the photons between 2 and 4 GeV have their origin in the multiple semihard scattering of partons. This lends support to a recent prediction that there would be a substantial production of photons from the passage of high energy quarks through the QGP which may be produced in such secondary collisions [12]. We find the average squared transverse momentum of the incoming rescattered partons at the photon vertex to be $\langle p_t^2 \rangle \approx 2.1\ (\mathrm{GeV}/c)^2$, confirming previous phenomenological computations of nuclear broadening effects in prompt photon production [13].

We next allow for fragmentation processes after binary interactions as discussed above. The lower set of points in the upper frame of Fig. 3 (squares) includes only QCD induced fragmentations of partons. A comparison with Fig. 2 (diamonds) shows that this already leads to an increase in the photon emission by about a factor of 4. The reason for this surprisingly dramatic effect is that the fragmentation leads to a large multiplication of partons and thus to an enhanced photon yield due to the increase in the number of multiple scatterings. In comparison, the increase in the photon yield due to the fragmentation of photons off the scattered quarks (triangles) is small, except below 1 GeV, filling up the artificial gap caused by the cutoff p_T^{min} in the binary collisions. The strong enhancement in the low p_T region is not surprising, since radiative processes generally favor low-energy final states.

The lower frame of Fig. 3 shows the rapidity distribution of photons with $p_T > 2$ GeV for the same two cases as are discussed in the upper frame, but includes also the distribution obtained when only binary interactions are allowed (diamonds, corresponding to the uppermost curve in Fig. 2). The enhancement of photon production due to the inclusion of fragmentation processes occurs mainly around midrapidity, where a dense partonic system is created and most of the fragmentation processes contribute. We chose the cutoff $p_T > 2p_T^0$, because the photon yield below this value is expected to receive a large contribution from hadronic reactions, which do not interest us here.

The strength of the source of single photons is often discussed in terms of the ratio (γ/π^0), as most of the background to them comes from the decay of π^0. We cannot get a precise value for this unless we supplement our description with a model for the hadronization. A reasonable alternative is provided by the ratio of $(\gamma/\mathrm{partons})$ as the multiplicity of pions will be proportional to the multiplicity of partons. We find that this quantity is of the order of 0.04% when only multiple scatterings among partons is considered and rises to 0.15% when fragmentations are allowed and which considerably enhance the multiple scatterings.

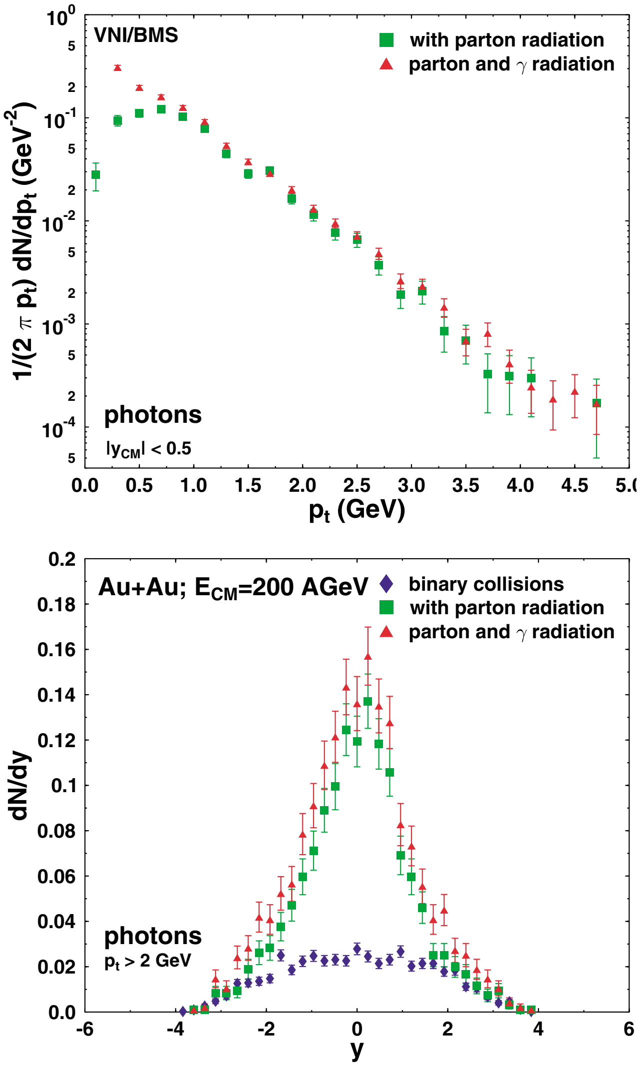

FIG. 3 (color online). Upper frame: photon transverse momentum spectra for contributions from collisions and fragmentations (triangles) and from collisions alone (squares), when parton fragmentations are included in the calculations. Results for the calculations with only the binary collisions are also given (diamonds). Lower frame: The multiplicity density of photons having $p_T > 2$ GeV.

The results shown thus far do not account for the possible LPM suppression of radiation from the scattered partons. An accurate implementation of this effect in a semiclassic treatment is difficult. To explore the possible magnitude of this effect, we consider here a treatment in which the scattered parton, having energy E_a and timelike virtuality m_a^2, is forbidden to fragment if it rescatters before the formation time of the radiated parton E_a/m_a^2 has expired. This ansatz should provide us with an upper limit of the suppression as it does not account for the relative phases of the two scatterings. We find that the emission of photons at about 2 GeV is reduced by a factor of 3.5 if the LPM suppression is treated in this manner. Most of the enhancement due to fragmentation processes

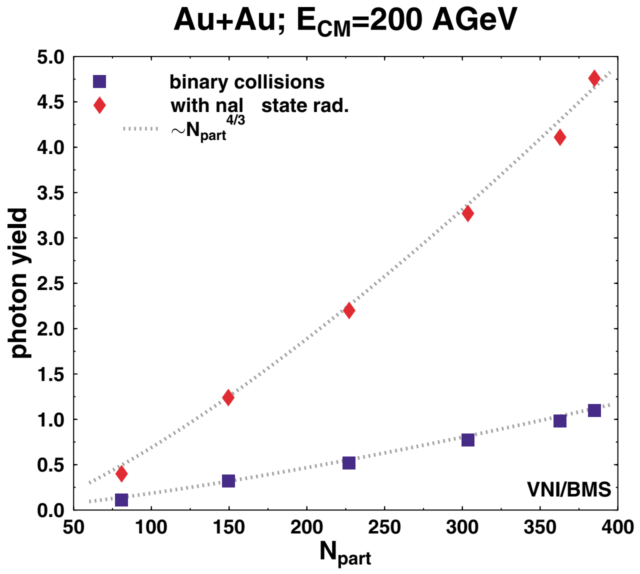

FIG. 4 (color online). Integrated photon multiplicity as a function of N_{part}. Squares denote a calculation with only binary parton-parton collisions, whereas diamonds show a calculation including fragmentation processes. The scaling with $N_{\text{part}}^{4/3}$ is indicative of the photon yield being directly proportional to the number of hard collisions.

visible in Fig. 3 disappears in this limit. Also, increasing the pQCD cutoff $(p_T^{\text{min}})^2$ to 1 GeV^2 reduces the number of binary collisions and the buildup of cascading activity. The net result is a decrease in the photon yield by a factor of about 1.5 beyond $p_T = 1$ GeV near central rapidities.

How does the photon production scale with the number of participant nucleons N_{part}? Figure 4 shows the total integrated photon yield (neglecting hadronic and thermal contributions) as a function of N_{part}. The squares denote a calculation without fragmentation processes, whereas the diamonds show the full calculation, including fragmentation. For both calculations, we observe a scaling of the photon yield with $N_{\text{part}}^{4/3}$ (dotted curves), suggestive of a scaling with the number of binary parton-parton collisions [2,14] rather than participant number. This is a valuable result, since it provides a direct connection between a measurable quantity (the photon yield) and the unobservable number of hard collisions during the time evolution of the reaction. It will be interesting to see in future studies whether the production of heavy quarks and the suppression of high-p_T hadrons reflect similar scaling properties.

In our calculation, we have used lowest-order pQCD matrix elements to study the collisions. One could in principle use a K factor to account for higher order effects. We have not done so here, as the parton shower mechanism for the final state radiations amounts to the inclusion of collinear emissions to all orders. At least for photon production in a QGP, rates are now available up to two loops [15], and to complete leading order [16]. It is not clear how these calculations can be incorporated in the PCM, unless a (local) temperature is associated with the system. Our current calculation neglects medium modifications of the matrix elements and fragmentation functions. We intend to study these effects in a forthcoming publication.

In summary, we have calculated the production of high energy photons in collision of gold nuclei at 200A GeV in the parton cascade model. Multiple scattering of partons is seen to lead to a substantial production of high energy photons, which rises further when parton multiplication due to final state radiation is included. The photon yield is found to scale as $N_{\text{part}}^{4/3}$ and is directly proportional to the number of hard parton-parton collisions in the system, providing valuable information on the preequilibrium reaction dynamics of the system. Our calculations suggest that, at the much higher energies to be reached at the Large Hadron Collider, the parton cascades developing in the nuclear collision will produce an even larger "firework" of photons.

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