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Universal parametrization of thermal photon rates in hadronic matter

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Electromagnetic (EM) radiation off strongly interacting matter created in high-energy heavy-ion collisions (HICs) encodes information on the high-temperature phases of nuclear matter. Microscopic calculations of thermal EM emission rates are usually rather involved and not readily accessible to broad applications in models of the fireball evolution which are required to compare with experimental data. An accurate and universal parametrization of the microscopic calculations is thus key to honing the theory behind the EM spectra. Here we provide such a parametrization for photon emission rates from hadronic matter, including the contributions from in-medium ρ mesons (which incorporate effects from baryons and antibaryons), as well as bremsstrahlung from $\pi\pi$ scattering. Individual parametrizations for each contribution are numerically determined through nested fitting functions for photon energies from 0.2 to 5 GeV in chemically equilibrated matter of temperatures 100–180 MeV and baryon chemical potentials 0–400 MeV. Special care is taken to extend the parametrizations to chemical off-equilibrium as encountered in HICs after chemical freeze-out. This provides a functional description of thermal photon rates within a 20% variation of the microscopically calculated values.

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I. INTRODUCTION

The understanding of hot and dense QCD matter remains a primary goal in nuclear physics. This is experimentally pursued through ultrarelativistic heavy-ion collisions (URHICs), producing a fireball of strongly interacting matter which expands and cools. Photons are an interesting probe of this fireball because they are emitted throughout its lifetime and reach the detectors without further interactions with the medium; see Refs. [1,2] for recent reviews. The experimentally measured spectra depend on both the microscopic production mechanisms and the bulk evolution of the fireball. Recent measurements of direct-photon spectra and their elliptic flow [3–7] have triggered intense activity to understand the data [8–18]. In particular, the magnitude of the elliptic flow points to large contributions from intermediate and late phases of the fireball evolution, i.e., the pseudocritical region and the hadronic phase [9].

In the present paper, we focus on thermal emission from the hot and dense hadronic medium. Early works on this problem have concentrated on hot meson matter [19–22]; a rather detailed analysis of the $\pi\rho a_1$ system (with an extension to strangeness) has been conducted in Ref. [23], where pertinent rate parametrizations in photon energy q_0 and temperature T have also been given. Based on developments in the dilepton sector [24,25], it was realized that baryonic emission sources play an important role for photon rates by carrying the in-medium ρ spectral function to the photon point [23]. The underlying many-body calculations of the ρ spectral function, which account for pion-cloud modifications (corresponding to pion-exchange reactions, including bremsstrahlung) and

resonant ρ -hadron interactions (corresponding to resonance Dalitz decays) [25–27], are rather involved and as such not readily available for a broad use in evolution models of URHICs. The main objective of the present paper is to provide compact parametrizations of these photon rates which for the first time encompass a finite baryon chemical potential μ_B as an additional variable. We also revisit the problem of hadronic bremsstrahlung, specifically for the most abundant $\pi\pi \rightarrow \pi\pi\gamma$ channel, by extending the calculations of Ref. [28] to higher energies and providing pertinent parametrizations as well.

II. THERMAL PHOTON RATE PARAMETRIZATIONS

We first consider thermal photons emitted from in-medium ρ mesons; the pertinent rates can be cast in terms of the transverse electromagnetic (EM) spectral function, ρ_{EM}^T , as [29]

$$q_0 \frac{dR_\gamma}{d^3q}(q_0; \mu_B, T) = \frac{\alpha_{\text{EM}}}{\pi} f^B(q_0; T) \rho_{\text{EM}}^T(q_0 = q; \mu_B, T), \quad (1)$$

with $f^B(q_0; T) = 1/[e^{(q_0/T)} - 1]$: Bose distribution function, and $\alpha_{\text{EM}} = 1/137$. By invoking (a generalized) vector meson dominance, the EM spectral functions can be related to the in-medium ρ propagator. The latter has been developed in Refs. [24–27] and leads to a strong broadening of the spectral peak due to interactions with baryons and antibaryons, which are critical in describing experimental dilepton spectra from URHICs [30]. Photon rates are readily extracted from the light-like limit of vanishing invariant mass, $M \rightarrow 0$, and depend on energy q_0 , temperature T , and baryon chemical potential μ_B .

In a first step of constructing a parametrization, the photon emission rates have been explicitly calculated [26] at $\mu_B = 0$ for a set of nine temperatures, $T = 100, 110, \dots, 180$ MeV, shown by the symbols in Fig. 1 [note that these rates include effects due to (equal densities of) baryons

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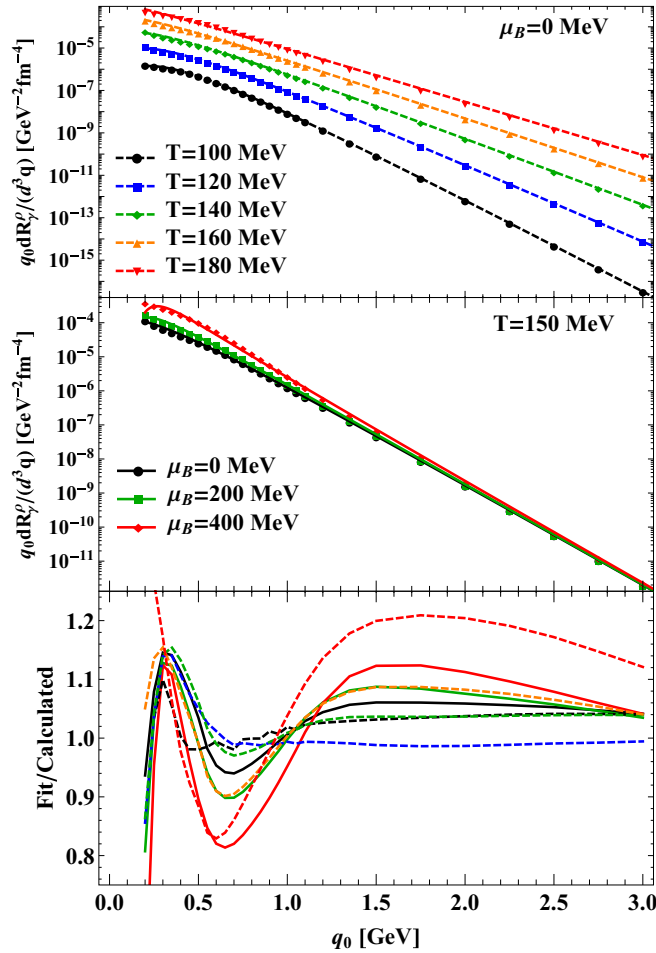


FIG. 1. (Color online) Photon emission rates (vs photon energy) calculated from in-medium ρ mesons (points) compared with their parametrization, Eq. (4) (curves), at $\mu_B = 0$ (upper panel) and $T = 150$ MeV (middle panel). (bottom panel) Ratio of parametrization over calculated rates.

and antibaryons, whose contribution, however, is strongly suppressed by the thermal weight as T decreases]. These rates are then parametrized at each temperature by the ansatz

$$q_0 \frac{dR_\gamma^\rho}{d^3q}(q_0; 0, T) = \exp \left[a(T)q_0 + b(T) + \frac{c(T)}{q_0 + 0.2} \right], \quad (2)$$

and smooth T dependencies of the parameters are found as

$$\begin{aligned} a(T) &= -31.21 + 353.61T - 1739.4T^2 + 3105T^3, \\ b(T) &= -5.513 - 42.2T + 333T^2 - 570T^3, \\ c(T) &= -6.153 + 57T - 134.61T^2 + 8.31T^3. \end{aligned} \quad (3)$$

In all parametrizations, q_0 , T , and μ_B are in units of GeV. The fit results are indicated by the symbols in the upper panel of Fig. 1, and their ratio over the calculated results is displayed in the bottom panel. For the highest temperature of $T = 180$ MeV, the deviations can reach up to 20% but are within about 10% for all other temperatures and energies up to 5 GeV [note that the blueshift due to the radial fireball

expansion in URHICs implies an appreciable shift of the rest-frame energy to the laboratory energy, e.g., by about a factor of two in Au-Au($\sqrt{s} = 200$ GeV) at RHIC energies [31]].

In a second step, the microscopic rates are calculated for three finite baryon chemical potentials, $\mu_B = 0.1, 0.2,$ and 0.4 GeV, and for each one at the nine temperatures quoted above. In chemical equilibrium, all baryons have the same chemical potential, i.e., $\mu_B \equiv \mu_N = \mu_\Delta$, etc. Based on the $\mu_B = 0$ fits above, the following factorized ansatz was made:

$$q_0 \frac{dR_\gamma^\rho}{d^3q}(q_0; \mu_B, T) = q_0 \frac{dR_\gamma^\rho}{d^3q}(q_0; 0, T) F^\rho(q_0; \mu_B, T), \quad (4)$$

with the function

$$F^\rho(q_0; \mu_B, T) = \exp \left[d(\mu_B, T) - \frac{k(\mu_B, T)}{q_0^2} - \frac{m(\mu_B, T)}{q_0} \right]. \quad (5)$$

The parameters d , k , and n are determined from fits at fixed T to determine their μ_B dependence through an expansion as

$$\begin{aligned} d(\mu_B, T) &= n(T)\mu_B + p(T)\mu_B^2 + r(T)\mu_B^3, \\ k(\mu_B, T) &= s(T)\mu_B + v(T)\mu_B^2 + w(T)\mu_B^3, \\ m(\mu_B, T) &= \alpha(T)\mu_B + \beta(T)\mu_B^2 + \eta(T)\mu_B^3. \end{aligned} \quad (6)$$

Lastly, the T dependence in the above coefficients fit via smooth functional dependencies resulting in

$$\begin{aligned} n(T) &= -0.04 + 2.3T - 12.8T^2, \\ p(T) &= 23.66 - 354T + 1175T^2, \\ r(T) &= -54.3 + 742.6T - 2350T^2, \\ s(T) &= -22.11 + 808.7T - 11604.4T^2 + 81700T^3 \\ &\quad - 282480T^4 + 384116T^5, \\ v(T) &= -1.6 - 121.7T + 1775T^2 - 5516T^3, \\ w(T) &= -9.874 + 469T - 4371.5T^2 + 11000T^3, \\ \alpha(T) &= 84.784 - 3028.6T + 42434T^2 - 291390T^3 \\ &\quad + 981000T^4 - 1295400T^5, \\ \beta(T) &= 59.64 - 726.46T + 1093.4T^2 + 4256T^3, \\ \eta(T) &= -73.9 + 458.66T + 2450T^2 - 12348T^3. \end{aligned} \quad (7)$$

A comparison between this parametrization and the explicitly calculated rates is shown in Fig. 1. We find that the parametrization reproduces the calculated rates with an accuracy better than 20%.

As a final test of the reliability of our fits, the “predictions” from the parametrization are compared to the calculated rates at $\mu_B = 0.3$ GeV, a value not used in the fitting procedure. The deviation between parametrization and calculation is found to be very similar to fitted cases. Therefore, we conclude that our parametrized photon rates lie within the 20% error margin (significantly smaller for the most part) established in the fits, for photon energies $q_0 = 0.2$ to 5 GeV, temperatures $T = 100$ to 180 MeV, and baryon chemical potentials $\mu_B = 0$ to 0.4 GeV.

Processes of type $\pi N \rightarrow \pi N \gamma$ and $NN \rightarrow NN \gamma$ are included in the ρ spectral functions used in the fits above, but meson-meson bremsstrahlung is not. Since pions are the most abundant mesons at the relevant temperatures, and their small mass renders the kinematics favorable for radiating off photons, the dominant source in the mesonic sector is expected from $\pi\pi \rightarrow \pi\pi\gamma$ processes. The pertinent rates have been calculated in Ref. [28] in an effective hadronic model for S - and P -wave $\pi\pi$ (and πK) scattering. Special care was taken in maintaining EM gauge invariance in the presence of hadronic form factors and in going beyond the often-times applied soft-photon approximation. The analysis, however, focused on rather small photon energies, below 0.5 GeV, thus limiting the applicability of the provided parametrizations. Here, we carry

these calculations to higher energies and generate suitable parametrizations.

Let us first compare the $\pi\pi$ bremsstrahlung rate to the in-medium ρ decays discussed above. At typical hadronic temperatures of $T = 150$ MeV the former exceeds the latter for $q_0 < 0.4$ GeV, but drops below it by about an order of magnitude for $q_0 \geq 1$ GeV; see Fig. 2. The bremsstrahlung rate is similarly suppressed compared to that from mesonic matter (including both the $\pi K \rho K^* a_1$ and the ωt -channel contributions) [23].¹ We note in passing that the contribution from πK bremsstrahlung amounts to about 20% of the $\pi\pi$ one [28]. We have parametrized the latter by using the ansatz

$$q_0 \frac{dR_\gamma^{\text{brems}}}{d^3q}(q_0; T) = \exp[\alpha_B(T) + \beta_B(T)q_0 + \gamma_B(T)q_0^2 + \delta_B(T)(q_0 + 0.2)^{-1}], \quad (8)$$

and found that, with

$$\begin{aligned} \alpha_B(T) &= -16.28 + 62.45T - 93.4T^2 - 7.5T^3, \\ \beta_B(T) &= -35.54 + 414.8T - 2054T^2 + 3718.8T^3, \\ \gamma_B(T) &= 0.7364 - 10.72T + 56.32T^2 - 103.5T^3, \\ \delta_B(T) &= -2.51 + 58.152T - 318.24T^2 + 610.7T^3, \end{aligned} \quad (9)$$

the calculated rates are fit within $\sim 5\%$ for $T = 100$ to 180 MeV and $q_0 = 1$ to 5 GeV (cf. middle panel of Fig. 2). Noise is statistical in nature due to the calculated rates.

III. CHEMICAL OFF EQUILIBRIUM

The above parametrizations pertain to hadronic matter in chemical equilibrium (CE), i.e., for $\mu_B = -\mu_{\bar{B}}$ without any meson chemical potentials (and therefore $\mu_{B_i} = \mu_N$ for each $B_i = N, \Delta, N^*, \dots$). However, in URHICs, hadro-chemical freeze-out occurs well before kinetic freeze-out, implying the emergence of effective chemical potentials μ_i to conserve the ratios of hadrons which are stable under strong decay, e.g., $i = \pi, K$, baryons, and antibaryons [32]. Since strong resonance formation reactions persist, one has $\mu_\rho = 2\mu_\pi$, $\mu_\Delta = \mu_N + \mu_\pi$, etc. An extension of the rate parametrizations to fully incorporate the μ_i dependencies is not practical. However, their leading effect can be rather accurately captured by fugacity factors.

For $\pi\pi$ bremsstrahlung, this amounts to an extra overall factor of z_π^2 on the right-hand side of Eq. (8), with $z_\pi = \exp(\mu_\pi/T)$. The same factor also applies to Eq. (4) (representing the ρ fugacity), but additional amendments are needed, as we will discuss now.

Let us first consider the baryonic contributions, starting from chemical freeze-out, T_{ch} , where $\mu_B^{\text{ch}} = -\mu_{\bar{B}}^{\text{ch}}$. For $T < T_{\text{ch}}$, the separate conservation of baryon and antibaryon number causes the effective antibaryon chemical potential

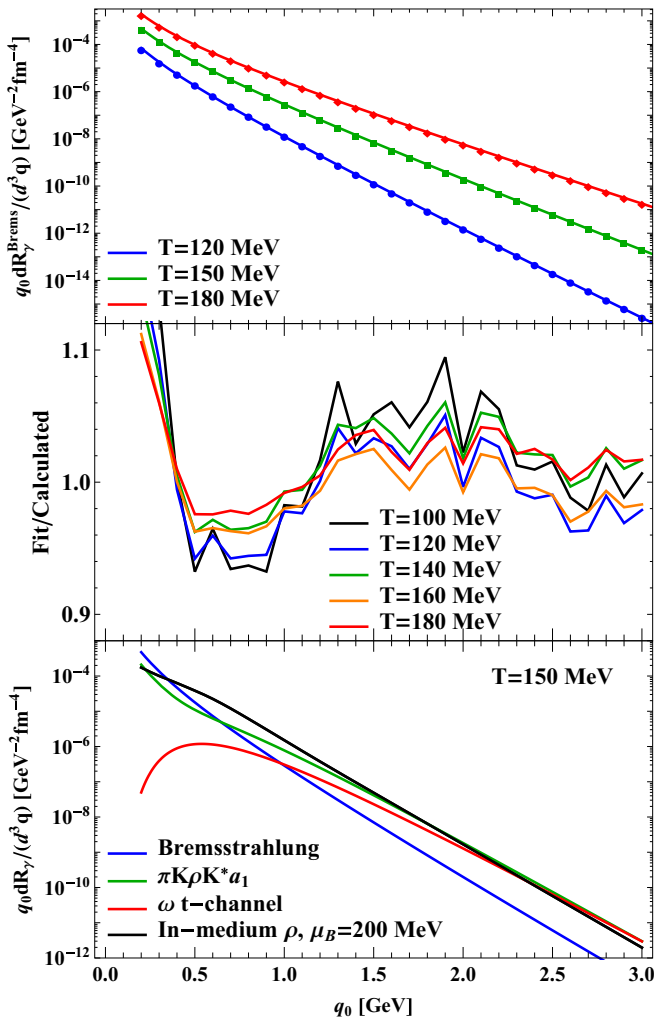


FIG. 2. (Color online) (upper panel) Calculated thermal photon rates from $\pi\pi$ bremsstrahlung (symbols) compared to their parametrization (colored lines). (middle panel) Ratio of the parametrized over calculated bremsstrahlung rates. (bottom panel) Comparison of rates at $T = 150$ MeV from bremsstrahlung (blue curve) [28], $\pi K \rho K^* a_1$ interactions (green curve) [23], $\pi\rho \rightarrow \pi\gamma$ with ωt -channel exchange (red curve) [23], and in-medium ρ decays (black curve).

¹We note that, when combining the present $\pi\pi$ bremsstrahlung rates with the ones given in the appendix of Ref. [23], the $\rho \rightarrow \pi\pi\gamma$ and $\pi\pi \rightarrow \rho\gamma$ contributions in there need to be dropped to avoid double counting.

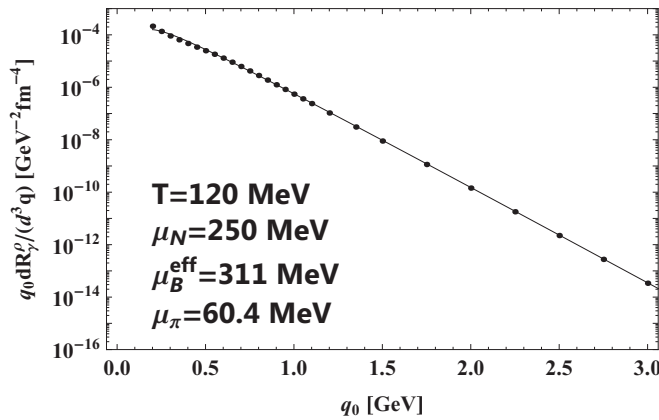


FIG. 3. Photon emission rates calculated from in-medium ρ s (points) compared to the parametrization of Eq. (4) evaluated with μ_B^{eff} from Eq. (11) and an overall fugacity of z_π^3 .

to rise with μ_B approximately as $\mu_{\bar{B}}(T) = \mu_{\bar{B}}^{\text{ch}} + [\mu_B(T) - \mu_B^{\text{ch}}] = \mu_B(T) - 2\mu_B^{\text{ch}}$ [32]. This increase in $\mu_{\bar{B}}(T)$ over the CE case must be accounted for in the baryonic contributions to the rate. Toward this end, we define the ratio r by which the chemical-off-equilibrium (COE) density of baryons plus antibaryons is enhanced over the CE value,

$$r \equiv \frac{n_{B+\bar{B}}^{\text{COE}}}{n_{B+\bar{B}}^{\text{CE}}} = \frac{n_B(\mu_B) + n_{\bar{B}}(\mu_B - 2\mu_B^{\text{ch}})}{n_B(\mu_B) + n_{\bar{B}}(-\mu_B)} = \frac{1 + e^{-2\mu_B^{\text{ch}}/T}}{1 + e^{-2\mu_B/T}}. \quad (10)$$

Here, we have utilized the Boltzmann approximation, $n_B(\mu_B) \simeq n_B(0)e^{\mu_B/T}$ (we have not yet accounted for any differences in the μ_{B_i} s caused by meson chemical potentials). The effective baryon chemical potential μ_B^{eff} to be used in the function F^ρ , Eq. (5), of the photon rate, is then given by

$$e^{\mu_B^{\text{eff}}/T} \equiv r e^{\mu_B/T} \Rightarrow \mu_B^{\text{eff}} = \mu_B + T \log(r). \quad (11)$$

However, many of the baryons are in excited states which carry larger chemical potentials than the nucleon, e.g.,

$\mu_\Delta = \mu_N + \mu_\pi$, $\mu_{N(1520)} = \mu_N + 1.45\mu_\pi$, etc. It turns out that the chemically enhanced resonance abundances can be accounted for by including an extra factor of z_π in Eq. (5), together with using $\mu_B = \mu_N$ in the above Eq. (11).

The thermal meson-induced photon emission via the ρ spectral function is mostly due to resonance formation, $P\rho \rightarrow M \rightarrow P\gamma$ [27]. With $P = \pi$ being the dominant contribution, one picks up another factor of z_π (in addition to the z_π^2 of the ρ discussed above). Thus both meson- and baryon-induced sources individually pick up an extra factor z_π , which can be pulled out of F^ρ . The total effect of the COE extension can then be concisely summarized by replacing F^ρ in Eq. (4) by

$$F^\rho \rightarrow z_\pi^3 F^\rho(q_0; \mu_B^{\text{eff}}(\mu_B = \mu_N), T), \quad (12)$$

while the $\pi\pi$ bremsstrahlung rate receives an overall factor of z_π^2 . These amendments yield rather accurate agreements, typically within less than 10% (see, e.g., Fig. 3), largely determined by the intrinsic uncertainty of the equilibrium parametrizations.

IV. CONCLUSION

We have constructed universal parametrizations for microscopic photon emission rates from in-medium ρ mesons and $\pi\pi$ bremsstrahlung over a range of photon energies, temperatures, and baryon-chemical potentials relevant to applications in URHICs. Our parametrizations reproduce the calculated rates within 20% (mostly within 10%). We have confirmed that $\pi\pi$ bremsstrahlung is appreciable for energies $q_0 < 1$ GeV, but subleading above. We have devised a prescription to extend the equilibrium parametrizations to capture the effects of chemical off equilibrium as encountered in URHICs. We believe that these parametrizations will be useful in calculations of thermal photon emission within different medium-evolution models and thus contribute to a better understanding of pertinent observables.

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