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Electromagnetic radiation in heavy ion collisions: Progress and puzzles

Charles Gale

Department of Physics, McGill University
3600 rue University, Montreal, QC, Canada H3A 2T8

Abstract

We review the current state of photon and dilepton measurements at RHIC, emphasizing that of the theoretical work seeking to interpret them. We highlight the progress made recently in the modelling of relativistic nuclear collisions, and explore the effect on electromagnetic observables. Some outstanding puzzles are presented.

Keywords: Heavy-ion collisions, Quark-gluon plasma, QCD, photons, dileptons

1. Introduction

The behaviour of strongly-interacting matter is known to be dictated by QCD, and colliding large nuclei at relativistic energies has been convincingly shown to be an efficient means of studying QCD under extreme conditions. A vibrant experimental program is currently under way at RHIC (the Relativistic Heavy Ion Collider, at Brookhaven National Laboratory), and at the LHC (the Large Hadron Collider, in CERN). In the analyses of experiments performed at those facilities, measurements of the produced hadronic particles have revealed many fascinating features of the relativistic many-body systems. Whereas energetic jets contain information on the nature of the QCD plasma at early times [1, 2], the softer hadrons have shown an impressive final-state collectivity that has become a cornerstone of the qualitative success of hydrodynamics at RHIC and LHC energies [3, 4]. Electromagnetic observables complement well the hadronic measurements. Owing to the relative smallness of the fine-structure constant, α, real and virtual photons emerge unscathed from their production site: They probe the entire space-time trajectory of the nuclear collision, from hot QCD plasma to the cooler hadronic phase. The price to pay for such a rich probe is a modest emission rate and a small signal-to-background ratio, in what concerns thermal photons, real and virtual. We review here some recent progress in the calculation of thermal photon yield and flow, and highlight some of the puzzles that have emerged in the analysis of electromagnetic radiation in relativistic heavy ion collisions.

2. Electromagnetic emission rates

Throughout the history of a single nuclear collision event, several sources of photons will come into play. The current formulation of relativistic hydrodynamics assumes that thermalization sets in after a proper time τ_0. The value of this parameter is currently not calculable with certainty: it is left as a variable. Consequently, no reliable estimates exist for pre-equilibrium photons, other than those being generated in the very first instants of the collisions, calculable with perturbative QCD (pQCD), and measured in pp collisions. These "prompt photons" constitute an irreducible background to the photons being generated through some influence of a thermal medium. This statement, however, should be clarified: pQCD photons have a jet fragmentation component which may be sensitive to quenching effects from the medium [5]. The QCD jets interacting with the medium then convert into photons [6, 7]. At $\tau > \tau_0$, the

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thermal components of the medium may also interact to generate photons. There, the appropriate respective emission rates, R, for real and virtual photons can be expressed using finite-temperature field theory [8] as

$$\omega \frac{d^3R}{d^3\mathbf{k}} = -\frac{g^{\mu\nu}}{(2\pi)^3} \frac{1}{e^{\beta\omega}-1} \,\mathrm{Im}\,\Pi^{\mathrm{R}}_{\mu\nu}(\omega, \mathbf{k}) \,,$$
$$E_+E_- \frac{d^6R}{d^3\mathbf{p}_+ d^3\mathbf{p}_-} = \frac{2e^2}{(2\pi)^6} \frac{1}{k^4} \left[p_+^\mu p_-^\nu + p_+^\nu p_-^\mu - g^{\mu\nu} p_+ \cdot p_-\right] \mathrm{Im}\,\Pi^{\mathrm{R}}_{\mu\nu}(\omega, \mathbf{k}) \frac{1}{e^{\beta\omega}-1} \quad (1)$$

In the above, lepton masses have been neglected, $\mathrm{Im}\,\Pi^{\mathrm{R}}$ is the retarded photon self-energy, ω and $\mathbf{k}$ are components of the photon four-momentum k, $E_\pm$ and $\mathbf{p}_\pm$ are components of the lepton/antilepton four-momenta, and $\beta = 1/T$. Those expressions receive correction of $O(\alpha^2)$ in the electromagnetic interaction, but are exact in the strong interaction.

The finite-temperature photon emission rates in the quark-gluon plasma (QGP) phase have been worked out to order α_s, the leading order in the strong interaction, a little more than a decade ago [9–11]. One may question the robustness of those rates against NLO corrections, especially in light of closely related investigations of the behaviour of higher-order correlation functions [12, 13]. This has been done recently, and first results have been reported [14]. It is shown there, that the phenomenological consequences of the NLO photon-emission rates are but a modest ∼20% enhancement in the region of momentum $|\mathbf{k}|/T \approx 10$. It is inappropriate here to discuss the technical intricacies of this calculation, but suffice it to say that it therefore appears that conclusions reached through previous analyses relying on LO QGP rates need not be amended. From the theoretical point of view, however, this work represents definite progress.

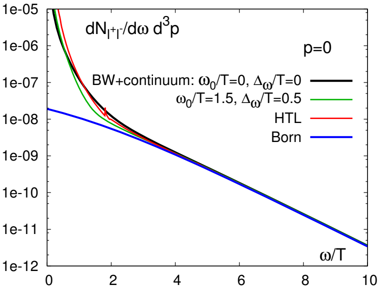

Figure 1: The rate for the production of back-to-back lepton pairs, calculated in quenched lattice QCD at $T \simeq 1.45\,T_c$, for two flavours of quarks. The top two curves of the legend represent two different ways to extract the lattice data. Also shown are calculation done with the Hard Thermal Loop resummation [15], and with keeping only the Born term. This plot is from Ref. [16].

In what concerns dileptons, another recent element of progress has been the nonperturbative evaluation of the vector current-current correlation function in lattice QCD at finite temperature. The connection with the dilepton emission rate is obtained by straightforward manipulations of Eq. (1):

$$\frac{d^4R}{d^4k} = \frac{\alpha}{12\pi^3} \frac{1}{M^2} f^{(n)\mu}_{\mu}(\omega, \mathbf{k}) \frac{1}{(e^{\beta\omega}-1)} \quad (2)$$

where $f^{(n)}$ is the "normal" [8] spectral representation of the current-current correlator, and $M^2 = (p_+ + p_-)^2$. Such extrapolations from lattice calculations however require solving an inversion problem that is mathematically ill-defined: The lattice calculates Euclidian correlation functions, $f(\tau)$, formulated in imaginary time, τ. The connection with the physical Minkowski correlation function $f(\omega)$, is

$$f(\tau)) = \int_0^\infty d\omega f(\omega) \frac{\cosh(\beta\omega/2 - \tau\omega)}{\sinh(\beta\omega/2)} \quad (3)$$

Progress in inverting this (possibly noisy) integral has been obtained in recent years using statistical approaches like the Maximum Entropy Method [17]. Some some recent work has involved using a physically-motivated ansatz for the