Thermal photons from chemically non-equilibrated QCD medium

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Introduction

- **Quark-gluon plasma (QGP):** many-body system of deconfined quarks and gluons

The QGP created in high-energy heavy ion collisions is quantified as a **relativistic fluid** with extremely small viscosity:

- Au-Au, Au-Cu (200 GeV) and U-U (193 GeV) at RHIC
- Pb-Pb (2.76 TeV) at LHC

It is a QCD phenomenon; what can an **electromagnetic probe** tell us?

Graphics by AM
Introduction

- Observables of the hot QCD matter

Electromagnetic probes:
- Jet quenching, heavy quarks:
- Hydrodynamic medium:

EM transparency
- color opaqueness
- strong coupling
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- Photon emission in heavy ion collisions (low $p_T$)

The hot medium is opaque in terms of QCD; transparent in terms of electromagnetism

Hadrons: Most of information before freeze-out is lost (*thermal* hadrons)
Photons: Retain information during the medium time evolution
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Photon emission in heavy ion collisions (low $p_T$)

- Decay photons
  - from hadronic decay
- Thermal photons (hadronic)
  - from black-body radiation
- Thermal photons (QGP)
  - from hard processes

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- Photon emission in heavy ion collisions (low $p_T$)

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Prompt photons
- from hard processes

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- **Elliptic flow $v_2$**

  ### Azimuthal momentum anisotropy

  $$v_2(p_T, y) = \frac{\int_0^{2\pi} d\phi_p \cos(2\phi_p - \Psi_2) \frac{dN}{dp_T}}{\int_0^{2\pi} d\phi_p \frac{dN}{dp_T}}$$

  Large $v_2$ imply strong-medium interaction because spatial anisotropy has to be converted

  - **Hadronic $v_2$ is well quantified by nearly ideal hydrodynamic models; strongly-coupled QGP**

  - **Photons are weakly-coupled and do not intrinsically have $v_2$**

  - **Direct photon $v_2$ can be finite because of the contribution from thermal photons which are emitted from an anisotropic medium**
Motivation

- Experiments have posed “photon $v_2$ puzzle”
  - Direct photon $v_2$ is large; no definite answer so far
    - Hydrodynamic models predict small flow harmonics because of the contribution from earlier stages with little elliptic flow
    - Viscosity? Magnetic field? Pre-equilibrium flow?
  - Direct photon $v_3$ is also LARGE

No centrality dependence

The enhancement is at least partially due to the properties of the hot medium itself

Talk by S. Mizuno (PHENIX) at QM14
Properties of bulk medium

- **Time-evolution: quark-hadron view**
  - \( \tau > 10 \text{ fm/c:} \) Hadronic gas
  - \( \tau \sim 1-10 \text{ fm/c:} \) QGP/hadronic fluid
  - \( \tau \sim 0-1 \text{ fm/c:} \) Glasma
  - \( \tau < 0 \text{ fm/c:} \) Color glass condensate

- **Color glass condensate (CGC):** Colliding nuclei are saturated gluons
- **QGP/hadronic fluid:** Equilibrated quark-gluon plasma

Chemical equilibration does not necessary coincides with thermalization (cf: AM and B. Müller, arXiv: 1403.7310)
Approach of this work

- Fewer number of quarks at the onset of QGP fluid

Equilibrated QGP (small $v_2$)

- Quark-gluon plasma
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Flow anisotropy develops (medium $v_2$)
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The model

(2+1)-dimensional ideal hydrodynamic model + rate equations

The energy-momentum conservation

$$\partial_{\mu} T^\mu_{\nu} + \partial_\nu T^\mu_{\nu} = 0$$

Quark and gluon number changing processes

$$\partial_{\mu} N^\mu_{q} = 2r_{b} n_{g} - 2r_{b} \frac{n_{eq}^{g}}{(n_{eq}^{q})^{2}} n_{q}^{2}$$

$$\partial_{\mu} N^\mu_{g} = (r_{a} - r_{b})n_{g} - r_{a} \frac{1}{n_{eq}^{q}} n_{q}^{2} + r_{b} \frac{n_{eq}^{g}}{(n_{eq}^{q})^{2}} n_{q}^{2}$$

$$+ r_{c} n_{q} - r_{c} \frac{1}{n_{eq}^{q}} n_{q} n_{g}$$

$r_{a}, r_{b}, r_{c}$: reaction rates

$n_{q}^{(eq)}, n_{g}^{(eq)}$: parton densities (in equilibrium)

Late quark chemical equilibration implies $r_{b} < r_{a}, r_{c}$

as the chemical equilibration times are $\tau_{i} \sim 1/r_{i}$
Input for numerical analyses

- **Hydrodynamic parameters (Initial conditions + fluid properties)**
  - Gluon energy distribution: Kolb, Sollfrank and Heinz, PRC 62, 054909 (2000)
  - Quark energy distribution: 0 GeV/fm$^3$
  - Initial time: 0.4 fm/c
  - Equation of state: Hadron resonance gas ($m < 2$ GeV) + Parton gas
  - Chemical reaction rates: $r_i = c_i T$ where $c_i$ ranges are
    \[ 0.2 \leq c_b \leq 2 \ (\tau_b \sim 0.5 - 5 \ fm/c) \] and
    \[ 0 \leq c_{a,c} \leq 3 \ (\tau_{a,c} \sim 0.3 - \infty \ fm/c) \]

- **Photon emission rate**

\[
E \frac{dR^\gamma}{d^3p} = \frac{1}{2} \left( 1 - \tanh \frac{T - T_c}{\Delta T} \right) E \frac{dR_{\text{hadron}}^\gamma}{d^3p} + \frac{1}{2} \left( 1 + \tanh \frac{T - T_c}{\Delta T} \right) E \frac{dR_{\text{QGP}}^\gamma}{d^3p}
\]

where $T_c = 0.17$ GeV and $\Delta T = 0.017$ GeV

- Turbide, Rapp and Gale, PRC 69, 014903
- Traxler and Thoma, PRC 53, 1348
Results

- Elliptic flow of thermal photons – $c_b$ dependence

Late quark chemical equilibration ($\tau_{\text{chem}} \sim 1/c_b T$) leads to enhancement of thermal photon $v_2$

$\tau_{\text{chem}} \sim 2 \text{ fm}/c$ is motivated in an early equilibration model (AM and B. Müller, arXiv: 1403.7310) \iff $c_b = 0.5$ for $T \sim 0.2 \text{ GeV}$
Results

- Elliptic flow of thermal photons – $c_{a,c}$ dependence

Thermal photon $v_2$ is moderately enhanced for faster gluon-involved equilibration processes

because quark production in early stages is suppressed due to quicker dampening of gluon overpopulation due to recombination
Summary and outlook

- Thermal photon $v_2$ from chemically non-equilibrated QGP is investigated
  - Late quark production leads to visible enhancement of $v_2$, contributing positively to resolution of “photon $v_2$ problem”
  - Evolution of bulk medium from CGC to QGP is a key
  - Late gluon equilibration slightly reduces $v_2$
  - Net yield of thermal photons is reduced

- Future prospects include:
  - Introduction of dynamical equation of state, more realistic initial conditions, shear and bulk viscosities
  - Estimation of the contribution from prompt photons
  - Other effects of chemical non-equilibrium, e.g., heavy quarks
Thermal + prompt photon $v_n$?

- **Optical effects in QGP medium**

  ▶ Transparent medium can have finite refractive index

  $$n^2(T, \omega) \sim 1 - \frac{\omega_p(T)^2}{\omega^2}$$

  The hot medium works as a 4D lens, bending the rays

  ➡ Geometrical anisotropy is directly mapped onto momentum distribution for both prompt and thermal photons

  ➡ How would this affect the direct photon elliptic and triangular flow?

  Possible additional phenomenology
  
  - EM opacity in QGP below $\omega < \omega_p$?
    (Experimental data indicate $\omega_p < 0.5$ GeV)
  
  - Color dispersion may be observed
Fin

- Merci de votre attention!
- Website: http://tkynt2.phys.s.u-tokyo.ac.jp/~monnai/