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?
Introduction

- Observables of the hot QCD matter

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

- EM transparency:
  Color opaqueness:
  Strong coupling:
Introduction

- Observables of the hot QCD matter

Mini-jets (of hadrons)

Photons & leptons (e.g. $\gamma$, $e^+e^-$)

Hadrons (from hot fluid)

Hadrons (from heavy quarks)

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

EM transparency
Color opaqueness
Strong coupling
Introduction

- 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 $p_T$)

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Photons:

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**Photons**: Retain information during the medium time evolution

Thermal photons (hadronic)
- from black-body radiation

Thermal photons (QGP)
- from hard processes

**Graphics by AM**
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Decay photons
- from hadronic decay

Thermal photons (hadronic)
- from black-body radiation

Prompt photons
- from hard processes

Graphics by AM

Saturated gluons

$z$

$\tau$

Hadrons

Freeze-out

Hadronic fluid

QGP fluid

Thermal photons (QGP)

Direct photons

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Introduction

Elliptic flow $v_2$

Azimuthal momentum anisotropy

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

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

  ![Graph showing $\gamma_{\text{dir}}$ vs $p_T$ for PHENIX at QM11](image)

  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**
  - $\tau > 10$ fm/c: Hadronic gas
  - $\tau \sim 1-10$ fm/c: QGP/hadronic fluid
  - $\tau \sim 0-1$ fm/c: Glasma
  - $\tau < 0$ 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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- Quark-gluon plasma

Flow anisotropy develops (medium $v_2$)
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We consider: Non-equilibrated QGP

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Contribution of later stage becomes large as thermal photons are emitted in the presence of quarks; **photon $v_2$ can be enhanced**
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The model

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

- The energy-momentum conservation
  \[ \partial_{\mu} T_{\mu}^{\nu} + \partial_{\mu} T_{\nu}^{\mu} = 0 \]

- Quark and gluon number changing processes

  \[ \partial_{\mu} N_{q}^{\mu} = 2r_{b}n_{q} - 2r_{b} \frac{n_{g}^{eq}}{n_{q}} n_{q}^{2} \]

  \[ \partial_{\mu} N_{g}^{\mu} = (r_{a} - r_{b})n_{g} - r_{a} \frac{1}{n_{q}} n_{q}^{2} + r_{b} \frac{n_{g}^{eq}}{n_{q}^{eq}} n_{q}^{2} \]

  \[ + r_{c}n_{q} - r_{c} \frac{1}{n_{q}} n_{q} n_{g} \]

- Reaction rates: \( r_{a}, r_{b}, r_{c} \)
- Parton densities (in equilibrium): \( n_{q}^{(eq)}, n_{g}^{(eq)} \)

Late quark chemical equilibration implies \( r_{b} < r_{a}, r_{c} \)
as the chemical equilibration times are \( \tau_{i} \sim \frac{1}{r_{i}} \)
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/fm³
  - 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 \( 0.2 \leq c_b \leq 2 \) (\( \tau_b \sim 0.5-5 \text{ fm/c} \)) and \( 0 \leq c_{a,c} \leq 3 \) (\( \tau_{a,c} \sim 0.3-\infty \text{ fm/c} \))

- **Photon emission rate**
  - \( E \frac{dR^\gamma}{d^3p} = \frac{1}{2} \left( 1 - \tanh \frac{T - T_c}{\Delta T} \right) E \frac{dR_{hadron}^\gamma}{d^3p} + \frac{1}{2} \left( 1 + \tanh \frac{T - T_c}{\Delta T} \right) E \frac{dR_{QGP}^\gamma}{d^3p} \)
  - Where \( T_c = 0.17 \text{ GeV} \) and \( \Delta T = 0.017 \text{ GeV} \)

  - 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
Fin

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