In-medium quasiparticle distributions and QGP photons

Akihiko Monnai (RIKEN BNL)

Yukawa Institute Molecule-type workshop “Selected topics in the physics of the Quark Gluon Plasma and Ultrarelativistic Heavy Ion Collisions”
23rd September 2015, YITP, Kyoto University, Japan
In-medium quasiparticle distributions, chemical equilibration and medium refraction for QGP photons

Akihiko Monnai (RIKEN BNL)

Yukawa Institute Molecule-type workshop “Selected topics in the physics of the Quark Gluon Plasma and Ultrarelativistic Heavy Ion Collisions”

23rd September 2015, YITP, Kyoto University, Japan
Introduction

- Heavy-ion collisions: Hadronic point of view

**Graphics by AM**

- **Hadronic transport** (> 10 fm/c)
  - Freeze-out

- **Hydrodynamic stage** (~1-10 fm/c)
  - Equilibration

- **Glasma** (~0-1 fm/c)
  - Little bang

- **Color glass condensate** (< 0 fm/c)

- **Color opaque**

  Most information before freeze-out is lost in “thermal hadrons”
Introduction

- Heavy-ion collisions: **Photonic point of view**

---

**Colliding nuclei**

- **QGP fluid**
- **Hadronic fluid**
- **Glasma** (~0-1 fm/c)
- **Hydrodynamic stage** (~1-10 fm/c)
- **Freeze-out**
- **Equilibration**
- **Little bang**

**Color opaque**

Most information before freeze-out is lost in “thermal hadrons”

**Electroweak transparent**

Photons retain information during time-evolution
Introduction

- Heavy-ion collisions: **Photonic point of view**

**Graphics by AM**

- **Decay photons**
  - from hadronic decay

- **Thermal photons (hadronic)**
  - from black-body radiation

- **Thermal photons (QGP)**
  - from hard processes

- **Prompt photons**
  - from hard processes

- **Direct photons**

**Color opaque**
Most information before freeze-out is lost in “thermal hadrons”

**Electroweak transparent**
Photons retain information during time-evolution
Introduction

- Heavy-ion observable: $p_T$ spectra
  - Direct photon $p_T$ spectra
    - Thermal photon slope $T_{RHIC} = 221 \pm 38$ MeV
      - $T_{\text{init}} = 300$-$600$ MeV implied from theoretical estimation
    - Cf: Slope parameter for LHC is $T = 304 \pm 51$ MeV
      - Wilde et al., arXiv:1210.5958
  - Comparison with Lattice QCD
    - Crossover temperature: $T_c \sim 170$ MeV
    - Heavy-ion photons are an evidence for the realization of QGP

Adare et al., PRL104 132301

Borsanyi et al., JHEP 1011 077

Crossover temperature: $T_c \sim 170$ MeV

Heavy-ion photons are an evidence for the realization of QGP
Introduction

- Heavy-ion observable: elliptic flow
  - Direct photon $v_2$ is found to be large
    - Comparable to pion $v_2$
      (Hydro models imply smaller $v_2$)
    - No definite answer so far;
      recognized as “photon puzzle”

- Direct photon $v_3$ is indicated to be large
  - Similar to pion $v_3$
  - The enhancement is at least partially due to the properties of the medium itself
Photon puzzle

- Direct photons = \textit{prompt} photons + \textit{thermal} photons

\[ E \frac{dN}{d^3p} = AB T_{AB} \times E \frac{d\sigma^{pp}}{d^3p} + \int E \frac{dR_{\text{thermal}}}{d^3p} (u^\mu, T) dx^4 + E \frac{dN_{\text{additional}}}{d^3p} \]

- Modifications in thermal photon emission?
  - Emission rate
    - Liu & Liu, PRC 89, 034906 (2014)
    - Monnai, PRC 90, 021901 (2014)
    - Hees, He & Rapp, NPA 933, 256 (2015)
    - Gale et al., PRL 114, 072301 (2015)
    - Monnai, 1504.00406
    - McLerran & Schenke, 1504.07223
  - Bulk evolution
    - Hees, Gale & Rapp, PRC 84, 054906 (2011)
    - Dion et al, PRC 84, 064901 (2011)
    - Linnyk et al., PRC 88, 034904 (2013)
    - Linnyk et al., PRC 89, 034908 (2014)
    - Heinz, Liu & Shen, 1403.8101
    - Shen et al, PRC 91, 024908 (2014)
    - Monnai, 1408.1410
    - McLerran & Schenke, NPA 933, 256 (2014)

- Modifications in prompt photon emission?

- Other sources of photons (e.g. glasma)?

- Other effects (e.g. magnetic field)?
  - Basar, Kharzeev & Skokov, PRL 109, 202303 (2012)
  - Bzdak & Skokov, PRL 110, 192301 (2013)
  - Basar, Kharzeev & Shuryak, PRC 90, 014905 (2014)

- Experimental data needs more statistics?

\textit{It could be a combination of those or something entirely different}
Photon $\nu_n$ puzzle

- In this talk we discuss
  - In-medium corrections on parton distributions

- Quark chemical equilibration

- Optical effects
Quark chemical equilibration

- Properties of bulk medium
  - Color glass condensate: Colliding two nuclei are saturated gluons
  - QGP/hadronic fluid: A plasma of equilibrated quarks and gluons

τ < 0 fm/c

τ ~ 1-10 fm/c

“Little bang”

Chemical equilibration does not necessarily coincide with thermalization (cf: AM and B. Müller, arXiv: 1403.7310)
Quark chemical equilibration

“Gluons do not shine”

Compton scattering

Pair annihilation

Flow anisotropy develops along with time evolution in hydrodynamics:

\[ Du^x = \frac{1}{e + P} \nabla^x P \]

\[ Du^y = \frac{1}{e + P} \nabla^y P \]

The contribution from later stage becomes large; photon \( v_2 \) can be enhanced
Quark chemical equilibration

- Hydrodynamic equations of motion

  - Energy-momentum conservation
    \[ \partial_\mu T_{g}^{\mu \nu} + \partial_\mu T_{q}^{\mu \nu} = 0 \]

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

  \( r_{a}, r_{b}, r_{c} \) : reaction rates
  \( n_{q}^{(eq)}, n_{g}^{(eq)} \) : equilibrium densities

  Chemical relaxation time \( \tau_{\text{chem}} \sim 1/r_{b} \)

(a) gluon splitting
(b) quark pair production
(c) gluon emission from a quark
In-medium parton distributions

- “QGP is not an ideal gas”

Equation of state

Phase-space distribution

- Non-interacting gas: Bose-Einstein or Fermi-Dirac distributions

\[ f_0 = \frac{1}{e^{\sqrt{p^2 + m^2}/T} + 1} \]

- Lattice QCD: SB limit is not reached

\[ f_q \text{ and } f_g \text{ require in-medium corrections (≠ viscosity) and they affect QGP photon emission rate} \]

*Hadrons are not affected because hadron resonance gas works
In-medium parton distributions

- Quasi-particle distribution

\[ f_{\text{eff}}^i = \frac{1}{\exp\left(\frac{\omega_i}{T}\right) \pm 1} \]

where \( \omega_i = \sqrt{p^2 + m_i^2} + W_{\text{eff}}^i \)

In-medium correction: \( W_{\text{eff}}^i(T) \)

- Thermodynamic relations

Thermodynamic consistency

\[ \frac{\partial \Phi_i}{\partial T} \bigg|_{\mu=0} = - \int \frac{g_id^3p}{(2\pi)^3} \frac{\partial \omega_i}{\partial T} f_{\text{eff}}^i \]

E.g. Biro et al., Phys. Atom. Nucl. 66, 982

Thermodynamic relations

Partition function:

\[ \ln Z_i = \pm V \int \frac{g_id^3p}{(2\pi)^3} \ln \left[ 1 \pm \exp\left( -\frac{\omega_i}{T} \right) \right] - \frac{V}{T} \Phi_i(T) \]

Energy density:

\[ e = -\frac{1}{V} \sum_i \frac{\partial \ln Z_i}{\partial \beta} = \sum_i \int \frac{g_id^3p}{(2\pi)^3} \omega_i f_{\text{eff}}^i + \Phi \]

Pressure:

\[ P = \frac{1}{V} \sum_i T \ln Z_i = \frac{1}{3} \sum_i \int \frac{g_id^3p}{(2\pi)^3} p \frac{\partial \omega_i}{\partial p} f_{\text{eff}}^i - \Phi \]
In-medium parton distributions

- Quasi-particle distribution

Effective interaction $W_{\text{eff}}^{i}(T)$ and background field contribution $\Phi_{i}(T)$ are determined by lattice QCD EoS

Note: quasi-particle picture is better than ideal gas but may not be best

- We have $n_{\text{eq}}^{g}$ and $n_{\text{eq}}^{q}$ for the rate equations
- Photon emission from hot regions are suppressed; additional enhancement of $v_{2}$
Input for the model

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

  where \( T_c = 0.17 \text{ GeV} \) and \( \Delta T = 0.017 \text{ GeV} \) with \( f_i = (n_i/n_i^{\text{eq}}) f_i^{\text{eff}} \)

  [Strickland, PLB 331, 245]

  [Turbide, Rapp and Gale, PRC 69, 014903]

- **Hydrodynamic parameters (Initial conditions + fluid properties)**
  
  - Gluon energy distribution: MC Glauber (200 GeV Au-Au at \( b = 6 \text{ fm} \))
  - Quark energy distribution: 0 GeV/fm\(^3\)
  - Initial time: 0.4 fm/c
  - Equation of state: Lattice QCD
  - 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 \( 0 \leq c_{a,c} \leq 3 \) (\( \tau_{a,c} \sim 0.3-\infty \text{ fm/c} \))
Thermal photon $v_2$

- With effective distribution

In-medium corrections to parton distribution functions additionally enhance thermal photon $v_2$

Note: Prompt photons are not included – they will reduce $v_2$
Thermal photon $\nu_2$

- With effective distribution and chemical equilibration

Late quark chemical equilibration ($\tau_{\text{chem}} \sim 1/c_b T$) leads to visible enhancement of thermal photon $\nu_2$

$\tau_{\text{chem}} \sim 2\ \text{fm}/c$ is motivated in an early equilibration model

(AM and B. Müller, arXiv: 1403.7310) \iff \quad c_b = 0.5 \text{ for } T \sim 0.2\ \text{GeV}
Thermal photon $\rho_T$ spectra

- With chemical equilibration

\[\rho_T\text{ spectrum is }\textbf{reduced} \text{ by both late quark chemical equilibration and in-medium corrections}\]

More sophisticated photon emission rate and dynamical EoS are required

(Cf. Gelis et al., JPG 30, S1031)
Discussion

- Types of equilibration in heavy-ion collisions

Conventional hydro: $\tau_{th} = \tau_{iso} = \tau_{ch}$

Chemically non-equilibrated hydro: $\tau_{th} = \tau_{iso} < \tau_{ch}$

Anisotropic hydro: $\tau_{th} = \tau_{ch} < \tau_{iso}$

Next step:

Cf: Rapidity correlation by AM and B. Schenke, 1509.04103
Summary

- Direct photons are essential in understanding the QGP

  - Flow harmonics are large: “Photon puzzle”
  - Thermal photon anisotropy is enhanced by late quark chemical equilibration
    - Early equilibration from CGC to QGP may be a key

- In-medium corrections to phase-space distributions can also enhance $\nu_2$
  - Emission rates are consistent with lattice QCD equation of state

- Photon spectra is reduced by those mechanisms and prompt photons will reduce $\nu_2$ enhancement

- We need additional mechanisms - photon emission in later stages? Or introduction of prompt photon $\nu_2$?
QGP optics

- A lens and prism
  - Transparent media can be refractive
    - Geometrical anisotropy ($\varepsilon_2, \varepsilon_3 \ldots$) is mapped onto photon flow harmonics ($v_2, v_3 \ldots$)

- I investigate optical aspects of the QGP
  - Note: no refraction still gives us experimental insight on the QGP

- Fermat’s principle

\[
\frac{d^2 x}{d\tau} = \frac{1}{2} \frac{dn^2}{dx}, \quad \frac{d^2 y}{d\tau} = \frac{1}{2} \frac{dn^2}{dy}
\]

- The path of a ray is determined by the gradient in refractive index $n$
QGP optics

- A model for the refractive index
  - Hard thermal loop estimations imply

\[ n^2(T, \omega) = 1 - \frac{\omega_p^2(T)}{\omega^2} \]

Parameterized as
\[ \omega_p^2(T) = \alpha^2 T^2 \]

Doppler effects (due to flow)
\[ \omega = \frac{\omega_0}{\gamma(1 + \beta \cos \Delta \phi)} \]

This is a model – one may find, e.g., a pseudo critical behavior

- Speed of light in the plasma
  - Phase velocity:
    \[ v_{ph} = \frac{1}{n} > 1 \]

Refraction in the medium
  - Causality is not violated

Group velocity:
\[ v_g = \frac{\partial \omega}{\partial k} = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} < 1 \]

JETP 55, 199 (1982)

PRD 84, 125027 (2011); PRD 88, 045014 (2013)
QGP optics

- A model for the refractive index
  - Naïve rough estimation in high $T$ limit
    \[ \omega_p^2 \sim m_D^2 \sim e^2 T^2 \]
    where $m_D$ is Debye mass and $e^2 = 4\pi\alpha_{EM}$
  - $a^2 \sim 10^{-1}$ when $\omega_p^2(T) = a^2 T^2$

Note: Pseudo-critical physics is missing – the range $0 < a^2 < 2$ will be explored to have an experimental insight.
Numerical analyses

- Prompt photon elliptic flow (= 0 if no refraction)

(I) Positive prompt photon $v_2$ is generated for non-absorptive region

Not large enough to explain the large direct photon $v_2$
- Thermal photons are necessary
- Pseudo-critical behavior of refractive index?

(II) Negative prompt photon $v_2$ in ultra-low momentum region

Absorptive region with $n^2 < 0$ forms a “dark core”

(III) Positive prompt photon $v_2$ near $p_T = 0$

Semi-opaque medium: easier to come out of minor axis
Numerical analyses

- Prompt photon transparency

\[ T = \left( \frac{dN_{\text{medium}}^\gamma}{2\pi p_T dp_T dy} \right) \bigg/ \left( \frac{dN_{\text{vacuum}}^\gamma}{2\pi p_T dp_T dy} \right) \]

The transparency decreases below \( \omega_p \) due to imaginary refractive index

Experimental data seem to show no sudden reduction above 0.5 GeV

- \( a < 1-2 \) is preferred; constraint on QGP plasma frequency
Summary again

- Optical effects in the QGP medium
  - Positive flow harmonics is generated
    - $p_T$ spectrum at mid-high $p_T$ is not modified
    - It is quantitatively small (as expected); refractive index near $T_c$?
  - Refractive $v_n$ can be sensitive to QGP plasma frequency
    - Ultra-low $p_T$ photon measurements may give constraint on it
and outlook

- Some theory-experiment prospects
  - Higher harmonics $v_4$ and $v_5$ of direct photons
  - Photons from small systems (d-Au, He$^3$-Au etc.)
    - Will they be similar to hadronic $v_n$? Is there a thermal medium?
  - Photons from systems at lower energies
    - Are they from the same origin? Will there be squeeze-out for photons?
The end

Thank you!