The Magneto-sono-luminescence

and photon / dilepton production in heavy ion collisions

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Outline

- Motivations and overview
- Direct photons and magnetic fields in heavy ion collisions
- Conformal anomaly and direct photon anisotropy
- Dileptons and OPE in medium
Motivations

- To see experimental signatures of processes that emerge from quantum anomalies in heavy ion collisions
- To gain better understanding of the early stage dynamics of QGP in heavy ion collisions
Some magnetic field induced processes in HIC

Magnetic field + axial anomaly:

- Chiral magnetic effect → Charge separation (Kharzeev, Zhitnitsky, Fukushima, McLerran, Warringa)
- Chiral magnetic wave → Charge dependent $v_2$
  (Burnier, Kharzeev, Liao, Yee)
- Chiral magnetic spiral → In plane current correlations
  (GB, Dunne, Kharzeev)

Photons from magnetic field:

- Photons from local parity violation (Fukushima, Mameda)
- Synchrotron radiation of quarks (Tuchin)
- AdS/CFT (Müller et. al.)
Certain materials possess pairs of Weyl-like excitations in certain points in Brillouin zone. These points can be separated by breaking $\mathcal{T}$ and $\mathcal{P}$. *proposals:* $\text{A}_2\text{Ir}_2\text{O}_7$ (Wan et. al.), heterostructure (Burkov et. al.)

Another arena for anomaly induced effects (Burkov et. al., Goswami et. al., Son, Spivak …)

Applications, even existence of CME like effects in condensed matter systems can be subtle (GB, Kharzeev, Yee; PRB **89**, 035142)
This talk:

Magnetic field + sound modes $\Rightarrow$ photon/dilpeton production

Magneto-Sono-Luminescence, noun: conversion of sound modes of QGP into real/virtual photons in the presence of magnetic field
Direct photons

- Small cross section: information on various stages of evolution
  - Prompt (high $P_T$)
    - Initial hard scatterings
    - Fragmentation
      - good agreement with pp data
  - Medium effects
    - Jets + medium
    - Thermal photons (QGP, HG) (low $p_T$)
  - Other sources?
    - Glasma (Chiu, Liao, McLerran et. al.)
    - B field (GB, Kharzeev, Skokov, Fukushima, Tuchin, ...)

\[ \text{Figure 2.17: Schematic light cone diagram of the evolution of a high energy heavy ion collision, indicating a formation phase \( \tau_0 \) (see text).} \]

\[ \text{In the simple case of extremely high } Q^2 \text{ processes the answer is that all constituents are resolved. However, at moderate } Q^2 (\text{dominating bulk hadron production}) \text{ the characteristic QCD saturation scale } Q_s(x) \text{ gains prominence, defined such that processes with } Q^2 < Q_s^2 \text{ do not exploit the initial transverse parton densities at the level of independent single constituent color field sources (see equation 2.11). For such processes the proper formation time scale, } \tau_0, \text{ is of order of the inverse saturation momentum [61], } \frac{1}{Q_s}. \]

\[ \text{At } \sqrt{s} = 200 \text{ GeV, the first profile of the time evolution, sketched in Fig. 2.17, should correspond to proper time } t = \tau_0 = 0. \]

\[ \text{At top SPS energy, } \sqrt{s} = 17.3 \text{ GeV, we can not refer to such detailed QCD considerations. A pragmatic approach suggests to take the interpenetration time, } \gamma \approx 8.5, \text{ for guidance concerning the formation time, which thus results as } \tau_0 \approx 1.5 \text{ fm/c.} \]

\[ \text{In summary of the above considerations we assume that the initial partonic color sources, as contained in the structure functions (Fig. 2.13), are spread out in longitudinal phase space after light cone proper time } t = \tau_0 \approx 0. \]

\[ \text{At top RHIC energy, no significant transverse expansion has occurred at this early stage, in a central collision of } A \approx 200 \text{ nuclei with transverse diameter of about 12 fm. The Bjorken estimate [45] of initial energy density } \epsilon \text{ (equation 2.1) refers to exactly this condition, after formation time } \tau_0. \]

\[ \text{In order to account for the finite longitudinal source size and interpenetration time, at RHIC, we finally put the average } \tau_0 \approx 0.3 \text{ fm, at } \sqrt{s} = 200 \text{ GeV, indicating the “initialization time” after which all partons that have been resolved from the structure functions are engaged in power multiplication.} \]

\[ \text{As is apparent from Fig. 2.17, this time scale is Lorentz dilated for partons with a large longitudinal momentum, or rapidity. This means that the slow}\]
Direct photons

- Small cross section: information on various stages of evolution
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PHENIX has measured the direct photon $R_{AA}$ in such collisions at $\sqrt{s_{NN}} = 200$ GeV for $p_T \leq 17$ GeV/$c$, the result is shown in Fig. 3 together with the $\pi^0 R_{AA}$. No suppression has been observed for direct photons in such collisions, but the $p_T$ range is less than in Au+Au and the uncertainties are larger at highest $p_T$. As the isospin effect scales with $x_T = 2p_T/\sqrt{s}$, looking at lower collision energies would make studies on this effect available at lower transverse momenta where the merging of $\pi^0$ decay photons on the calorimeter does not yet play a role. Therefore, direct photons in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV have been measured as well, the nuclear modification factor is shown in Fig. 4. Unfortunately, the uncertainties of the measurement are too large to draw any conclusions.

\[ \frac{d^3N}{dp_T^3} \text{ (GeV}^2\text{c}^3) \]

\[ Ed^3N/dp_T^3 \text{ at } \sqrt{s_{NN}} = \text{200 GeV} \]

At low transverse momenta ($p_T < 4.5$ GeV/$c$), PHENIX has measured the ratio $r = \gamma_{direct}/\gamma_{inclusive}$ in $p+p$ and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV via internal conversion. This ratio is consistent with pQCD predictions in $p+p$ collisions while the experimental result exceeds a binary-scaled pQCD prediction in Au+Au collisions significantly. The direct photon invariant yield can then be calculated as $dN_{direct}(p_T) = r \times dN_{inclusive}(p_T)$. Fig. 5 shows the direct photon invariant cross section and the invariant yield for $p+p$ and Au+Au collisions, respectively. For Au+Au collisions, different centrality selections are shown. The results obtained with the statistical method are added to the plot as well, showing a good agreement with the internal conversion data in the overlap region. The pQCD calculation is consistent with the $p+p$ data within uncertainties for $p_T > 2$ GeV/$c$. The same data can also be well described by a modified power law function $A_{pp} (1 + 2p_T^2/b)^{-n}$ which is represented by the dashed line in the figure. The $p+p$ curve, scaled by $T_{AA}$, the nuclear overlap function, is significantly below the Au+Au data for $p_T > 6$ GeV/$c$.
Direct photons: azimuthal anisotropy puzzle

\[
\frac{dN}{d^2p_T} = \frac{dN}{2\pi p_T dp_T} (1 + 2v_2 \cos(2\phi) + \ldots )
\]

experiment (PHENIX):

\[
\text{Au+Au } \sqrt{s_{NN}} = 200 \text{ GeV}
\]

minimum bias

• Large \(v_2\) at \(p_T < 4\) GeV/c where thermal photons dominate

• \(v_2\) consistent with 0 at high \(p_T\) where prompt photons dominate

Very surprising result: large \(v_2\) implies late emission whereas thermal radiation implies early emission

Models have difficulties in reproducing simultaneously yield and \(v_2\) of photons

Poster 282 M. Csanad

[see also talk by R. Petti]

arXiv:1105.4126

Gökçe Başar The Magneto-sono-luminescence
Magnetic field + conformal anomaly $\Rightarrow$ anisotropic photon production

\[ \mathcal{L}_{\text{eff}} = c e^2 \frac{T_\mu}{\Lambda_{QCD}^4} F_{\alpha\beta} F^{\alpha\beta} \]

“conversion of \textit{bulk sound modes} of QGP into real photons in the presence of magnetic field ”
Magnetic fields in heavy ion collisions

Strong magnetic fields are generated by the spectators

\[ B \sim m_\pi^2 \sim 10^{14}T \]

- Refrigerator magnet \( \sim 10^{-2}T \)
- MRI \( \sim 1T \)
- Levitating frog: 14T (Berry, Geim)
- Strongest continuous field: 45T (NHMFL)
- Strongest non-destructive pulsed field \( \sim 10^2T \)
- Strongest destructive pulsed field \( \sim 10^3T \)
- Neutron star \( \sim 10^6T \)
- Magnetar \( \sim 10^9T \)
Magnetic fields in heavy ion collisions

Strong magnetic fields are generated by the spectators (Kharzeev, McLerran, Warringa; Skokov et al., ...)

\[ eB \sim m_\pi^2 \sim 10^{14} T \]

- magnitude: \( eB \sim \sqrt{s} \)
- pulse width: \( t_0 \sim 1/\sqrt{s} \)

\( < eB_x > = 0 \), fluctuations:

\[ < |eB_x| >, < |eB_y| > \sim m_\pi^2 \]
The magnetic fields in medium with nonzero $\sigma$ can live longer

(Tuchin, '13)  
(Gürsoy, Kharzeev, Rajagopal, '14)
Explanation of the mechanism

\[ \mathcal{L}_{\text{eff}} = g T^\mu_\mu F_{\alpha\beta} F^{\alpha\beta} \]

\[ B \otimes \gamma \]

\[ 2 = 2 \text{Im} \left[ \gamma \right] \]

\[ q_0 \frac{d\Gamma}{d^3q} = 2 \left( \frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2} \right)^2 \frac{B_y^2 q_x^2 + B_x^2 q_y^2}{\exp(\beta q_0) - 1} \rho_\theta(q_0 = |\vec{q}|) \]

\[ B_x^2 \neq B_y^2 \Rightarrow \text{Anisotropy!} \Rightarrow \text{nonzero } v_2! \]

• anisotropy \( \neq \) flow!
• the mechanism operates at early times!
• from purely gluonic background, no need for quarks
\[ \langle T_\mu^\mu \rangle \neq 0 \iff \langle \partial_\mu S^\mu \rangle \neq 0 \iff \text{conformal anomaly} \]

**In vacuum:**

- dilatational current \(\iff\) color-singlet, scalar states (dilation)
- anomalous Ward identities, PCDC (Ellis et al., Gell-Mann et al., Migdal, Shifman,...)
- coupling to electromagnetism (Ellis et al. ’70s)

**In medium:**

- we use hydrodynamics
- associate these scalar excitations with bulk sound modes
Bulk modes in QGP

\[ \rho_\theta(q_0) : \text{spectral function of bulk modes (hydro)} \]

\[ q_0 \frac{d\Gamma}{d^3q} \propto \frac{B_y^2q_x^2 + B_x^2q_y^2}{\exp(\beta q_0) - 1} \rho_\theta(q_0 = |\vec{q}|) \]

- real photons \((q_0 = |\vec{q}|)\) are away from the sound peak
- dominant contribution: \textit{bulk viscosity} \((\zeta)\)
- \(\zeta\): response to compression/rarefaction

\[ \zeta = c_\zeta \eta (1/3 - c_s^2)^2, \quad c_\zeta: \text{carries uncertainties} \]
$v_2$: comparison with PHENIX data

FIG. 2: The azimuthal anisotropy $v_2$ of the direct photon production takes into account only the (leading at large times) contribution from spectators: we neglect the spatial gradients of magnetic field and field were evaluated in Refs. [38] and [39]. In this paper, the fluctuations of magnetic field at different values of bulk viscosity corresponding to a lower bound for the photon production. Note that this assumption of the shear viscosity factor in the range of $10^{4}$ was estimated in Refs. [3] and [21]; the fluctuations of magnetic field at characteristic thermalization time of the gluons) that can be related to the electric conductivity:

$C_{\text{em}} = \frac{1}{4} \frac{\mu}{s} \left(1 + \frac{Q}{|eB|} 1+\left(\frac{Q}{|eB|}\right)^2\right)$

where $\mu$ is the magnetic coupling constant, $s$ is the initial time (given by the characteristic decay time of the collision energy, $t_0 = 200$ GeV. In our approximation (no transverse flow), the conventional mechanism does not give any contribution to the azimuthal anisotropy. The comparison with the experimental data from PHENIX [25] indicates that conformal anomaly could account for a large fraction of the observed photon anisotropy.
Experimental signatures of MSL for photons

- Polarization of photons
- Violation of $v_4 \sim v_2^2$ scaling
- Turn off magnetic field? $\rightarrow$ central U-U collision
- Turn off flow? $\rightarrow$ non central events without hadron $v_2$
  (Bzdak, Skokov) fluctuations in initial geometry
- Impact parameter dependence
Experimental signatures of MSL for photons

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need good statistics!!
Dileptons and MSL

Sound + B field → dilepton  (GB, Kharzeev, Shuryak)

Implications for: Intermediate mass dileptons

\[ 1 \text{ GeV} < M < 3 \text{ GeV} \]
Dileptons and MSL

Sound + B field → dilepton  (GB, Kharzeev, Shuryak)

\[ \mathcal{L}_{\text{eff}} =? \]

- “Hadronic” approach (tensor meson dominance)
- Operator Product Expansion (thermal background of gluonic fields)
Dileptons and MSL

Sound + B field $\rightarrow$ dilepton \hspace{1cm} (GB, Kharzeev, Shuryak)

$\mathcal{L}_{eff} = ?$

- “Hadronic” approach (tensor meson dominance)
- Operator Product Expansion (thermal background of gluonic fields)
Sketch of the idea:

- The coupling between energy-momentum tensor and electromagnetism is captured by \( \mathcal{L}_{gg\gamma\gamma} = \Pi_{\mu\nu} A^\mu A^\nu \).
- \( \Pi_{\mu\nu} \) is calculated in background thermal gluonic fields.
- Finite temperature analog of the SVZ calculation.

The yield (schematically):

\[
\frac{dN}{d^4q} \sim \left( \int \frac{dp^0}{2\pi} \tilde{B}^2(p^0) \right) \left( \int \frac{d^3k}{(2\pi)^3} \rho(k) \right) \sim \exp \left( -2q^0 t_B - \frac{c_s |q|}{T_i} \right)
\]
Dileptons and MSL: A probe of “ultrasounds”

- The sound modes in QGP are damped,

\[
\frac{\delta T_{\mu\nu}(k, t)}{\delta T_{\mu\nu}(k, 0)} = \exp \left( -\frac{2}{3} \frac{\eta k^2 t}{s T} \right) \equiv e^{-t/t_{damp}}.
\]

only the low momentum modes survive at the time of freezout.

- MSL operates at early times before the higher momentum modes (“ultrasounds”) are damped and carries information about these modes via their spectral functions.

- The spectral data, \( \rho(k) \), of the gluonic modes are transferred into dileptons. →Diagnostic tool to analyze the out of equilibrium, high frequency fluctuations of the energy-momentum tensor et early times.
Dileptons and MSL: A probe of “ultrasounds”

The Magneto-sono-luminescence
Dileptons and MSL: importance and experimental signatures

- New diagnostics tools for hydrodynamics
- Allows one to probe modes that are damped later on

Experimental Signatures:

- Polarization \(1 + a \cos^2 \theta\), \(a = -1\)
  (partonic Drell-Yan: \(a = 1\), thermal \(q\bar{q}\): \(a=0\))
- Impact parameter dependence
The Magneto-sono-luminescence

FIG. 2: The azimuthal anisotropy $v_2$ of the direct photons is shown for minimum bias Au-Au collisions at $p_{\perp} = 100, 200 \text{ GeV}$. The comparison with the experimental data from PHENIX [25] indicates that conformal anomaly could account for a large fraction of the observed photon anisotropy.

The magnetic field in heavy ion collisions was estimated using both conventional production mechanisms and the eikonal approximation. We neglect the spatial gradients of the magnetic field and evaluate the time dependence in the eikonal approximation. In this paper, the bulk viscosity was estimated in Refs. [3] and [21]; the fluctuations of magnetic field were evaluated in Refs. [38] and [39]. In our calculations, we adopt the results of Ref. [37] with a lower bound for the photon production. Note that this estimate is in line with the lattice result of Ref. [33] for a lower bound for the photon production. The shear viscosity estimate is consistent with the lattice result of Ref. [33] for a lower bound for the photon production.

In the range of $10^{3}$ to $10^{15}$, the sounds plot near $T_c$ indicates that the magnetic field was estimated in Refs. [38] and [39]. In this paper, the bulk viscosity was estimated in Refs. [3] and [21]; the fluctuations of magnetic field were evaluated in Refs. [38] and [39]. In our calculations, we adopt the results of Ref. [37] with a lower bound for the photon production. Note that this estimate is in line with the lattice result of Ref. [33] for a lower bound for the photon production. The sounds plot near $T_c$ indicates that the magnetic field was estimated in Refs. [38] and [39].
The Magneto-sono-luminescence
Transverse momentum spectrum

- vanishes as $p_T^2$ at low $p_T$
- overcomes thermal rate above 1 GeV
- higher $p_T$: prompt photons
Conformal anomaly in QCD

\[ \Theta_\mu^\mu (p+q) \]

\[ f_\sigma g_{\sigma \gamma \gamma} = \frac{R\alpha}{6\pi} \]

identify \( \sigma \) with lightest scalar meson: \( f_0(500) \)

\[ m_\sigma = 550\text{MeV} \quad , \quad \Gamma(\sigma \rightarrow \gamma \gamma) = g_{\sigma \gamma \gamma}^2 \frac{m_\sigma^3}{4\pi} \approx 5\text{KeV} \]

\[ R \equiv \frac{\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-)} = 5 \quad \text{(PDG 2012)} \]

fix:

\[ g_{\sigma \gamma \gamma} \approx 0.02\text{GeV}^{-1} \quad f_\sigma \approx 100\text{MeV} \]
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The Magneto-sono-luminescence