PHOTONS, DILEPTONS, AND HADRONS FROM RELATIVISTIC HEAVY ION COLLISIONS AND QUARK-HADRON PHASE TRANSITION
Collaborators

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• Photons, either radiated or scattered, have remained one of the most effective probes of every kind of terrestrial or celestial matter over the ages.

• Once produced, photons leave the system without any further interaction and thus they provide information about the circumstances of their birth.
Evolution of Relativistic Heavy-ion Collision

Temperature Evolution
- Björken Hydrodynamics -

\[ T_1 \sim \left( \frac{1}{g \tau_i} \right)^{1/3} \frac{dN}{dy} \]

\[ T - T_x \sim \left( \frac{T_x}{\tau} \right)^{1/3} \]

QGP
Mixed Phase
Hadron Gas
Freeze-out

\( \tau_1 = 1 \)
\( \tau_c = 3 \)
\( \tau_h = 20 \)
\( \tau_f = 60 \text{ fm/c} \)

Total single photon production
QGP + Mixed + Hadronic Gas
# Real versus Virtual Photons

<table>
<thead>
<tr>
<th>Elementary Process:</th>
<th>Photons</th>
<th>Lepton Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling:</td>
<td>$\alpha_s , \alpha_e$</td>
<td>$\alpha_e , \alpha_e$</td>
</tr>
</tbody>
</table>

| Variable:           | Transverse momentum: $p_T$ | Transverse mass: $m_T^2 = p_T^2 + m^2$ |

| Backgrounds:        | $\pi^0 \rightarrow \gamma \gamma$ ($\sim 85\%$) | $\pi^0 \rightarrow e^+ \gamma$ ($\sim 1\%$) |
|                     | $\eta^0 \rightarrow \gamma \gamma$ ($\sim 15\%$) | $\pi^\pm, \kappa^\pm \rightarrow \mu^\pm \nu$ |
|                     | $x \rightarrow x' \gamma$ ($<2\%$) | $\eta, \eta \rightarrow l^\pm \gamma$ |

| Difficulty for A-A Collisions | Combinatorial Background in $\gamma \gamma$ to extract $\pi^0$ and $\eta^0$ | Combinatorial Background in $l^+l^-$ to extract true $l^+l^-$ |
# Single Photons from A-A Collisions

<table>
<thead>
<tr>
<th>Elementary Process:</th>
<th>Hadron Gas</th>
<th>QGP</th>
<th>N-N (prompt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[\pi \rightarrow \rho \gamma] [\pi \rightarrow \pi^0 \gamma] [\omega \rightarrow \pi^0 \gamma]...</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>Distribution:</td>
<td>Thermal ((\epsilon, T, S_{\text{HG}},\ldots)) + Radiative Decays</td>
<td>Thermal ((\epsilon, T, S_{\text{QGP}},\ldots))</td>
<td>Structure Functions</td>
</tr>
<tr>
<td>Total Yield:</td>
<td>Integration over Space-Time History</td>
<td>Superposition of N-N Collisions</td>
<td></td>
</tr>
<tr>
<td>Relevant (p_T) Range:</td>
<td>(p_T \leq 1) GeV/c</td>
<td>&quot;Thermal&quot; Photons (p_T \sim 1 - 3) GeV/c</td>
<td>&quot;Prompt&quot; Photons (p_T \geq 3) GeV/c</td>
</tr>
</tbody>
</table>
FIG. 2. (a) Simplified two-loop photon self-energy diagrams with bare vertices and propagators everywhere except for the gluon propagator since the gluon can be soft. Cutting these two-loop diagrams along the dashed lines leads to (b) bremsstrahlung and (c) annihilation with scattering off a quark, antiquark or gluon.
$\frac{dR_{e^+e^-}}{dM^2} \text{ (fm}^{-4}\text{GeV}^{-2}\text{)}$

$M$ (GeV)

$T = 150$ MeV

I. Kvasnička et al.
Formualtion

We assume that

- a thermally and chemically equilibrated QGP is formed at time $\tau_0$ and has temperature $T_0$:

$$\frac{2\pi^4}{45\zeta(3)} \frac{1}{A_T} \frac{dN}{dy} = 4aT_0^3\tau_0$$  \hspace{1cm} (1)

where $A_T$ is the transverse dimension of the colliding system, $dN/dy$ is particle rapidity-density, $a = 42.25\pi^2/90$ for a plasma of u, d, and s quarks, and gluons.

- The plasma undergoes a boost-invariant longitudinal expansion and radially symmetric transverse expan- sion, and cools.

- It gets into a mixed phase at $T = T_C$ and then into a hot hadronic matter, having all hadrons with $M \leq 2.5$ GeV, in thermal and chemical equilibrium and undergoes a freeze-out at $T = T_f$.

- The initial energy-density profile is taken as

$$\epsilon(\tau_0, r) \propto \int_{-\infty}^{\infty} \rho(\sqrt{r^2 + z^2}) \, dz$$  \hspace{1cm} (2)

corresponding to ‘wounded-nucleon distribution’.
Then we get, single-photons from:

\[
E \frac{dN_\gamma}{d^3p} = \int d^4x \left[ f_Q \left( E \frac{dN}{d^3p d^4x} \right)_{QGP} + f_H \left( E \frac{dN}{d^3p d^4x} \right)_{Had} \right],
\]

(3)
dileptons from:

\[
E \frac{dN_{\mu^+\mu^-}}{dM^2d^3p} = \int d^4x \left[ f_Q \left( E \frac{dN}{dM^2d^3p d^4x} \right)_{QGP} + f_H \left( E \frac{dN}{dM^2d^3p d^4x} \right)_{Had} \right],
\]

(4)
and hadrons from:

\[
E \frac{dN_i}{d^3p} = \int d\sigma \cdot pf(p \cdot u)
\]

(5)
where \( u^\mu \) is the four-velocity of the local rest-frame, and is obtained from numerical integration of hydrodynamic equations. \( \sigma \) describes the freeze-out surface.

And finally, Drell-Yan, for example, is estimated as:

\[
\frac{dN_{AA}}{dM^2dy} = T_{AA}(b) \frac{dN_{pp}}{dM^2dy}
\]

(6)
where \( T_{AA} \) is the nuclear thickness.
\[ \frac{dN}{dy} = 750 \]
\[ \tau_0 = \frac{1}{3}T_0 = 0.20 \text{ fm}/c \]
\[ T_0 = 335 \text{ MeV}, T_C = 180 \text{ MeV} \]

Φ WA98, Pb+Pb@SPS

Single Photons

\[ \frac{dN}{d^2k_T dy} \text{ (1/GeV}^2) \]

\[ 10^{-1} \]
\[ 10^{-2} \]
\[ 10^{-3} \]
\[ 10^{-4} \]
\[ 10^{-5} \]
\[ 10^{-6} \]

\[ k_T \text{ (GeV)} \]

Scaled pp; NLO pQCD
$\frac{dN}{dy} = 750$

$\tau_0 = 0.20$ fm/c, $T_0 = 335$ MeV

QM + HM

$T_c = 160, 180, 200$ MeV
$dN/d^2k_Tdy \ (1/\text{GeV}^2)$

$\tau_0 = 0.2, 0.4, 0.6, 1 \ \text{fm/c}$
$T_0 = 335, 265, 232, 196 \ \text{MeV}$
$T_c = 180 \ \text{MeV}$

$\diamond \ \text{Single } \gamma, \ \text{WA98}$

Upto two loops

$k_T (\text{GeV})$
Au+Au@RHIC; SSPC
Only QGP phase

- Up to 2 loops
- Up to 1 loop
- Prompt (inclusive)

Equilibrating Plasma

$dN_\gamma/d^2p_Tdy \ (1/\text{GeV}^2)$

$p_T \ (\text{GeV})$
Discussions

• Very small $\tau_0 \sim 0.2$ fm/$c$:
  
  — Parton saturation at SPS for $Pb + Pb$ collisions for $p_T^{\text{cut-off}} \sim 1$ GeV/$c$ or $\tau_0 \sim 1/p_T \sim 0.2$ fm/$c$.

• Thermal and Chemical Equilibration of Hadrons:
  
  — All particle ratios measured are described by a thermal model with a (chemical) freeze-out temperature of $\sim 180$ MeV and $\mu_b \sim 250$ MeV. Hadronic reactions *can-not* achieve this.

• Pre-equilibrium contribution:
  
  — Parton cascade model will be used to re-estimate this. Our earlier estimates are (perhaps) incorrect.
Summing up

- Significant **direct photon** excess has been observed in central $Pb+Pb$ collisions for $p_T \geq 1.5$ GeV/$c$, by the WA98 experiment.

- Excess production of **IMR dileptons** has been reported by the NA50 experiment in these collisions.

- Hadron spectra from central collisions demonstrate thermal and chemical equilibrium and **flow**.

- All these data are satisfactorily explained with a **SINGLE** set of initial conditions which suggest that a quark gluon plasma is formed in the initial state which undergoes a phase transition to a hot hadronic matter at $\approx 180$ Mev.

- As far as single photons are concerned; one loop rates fail to describe the data. In view of the fact that 3-loop rates are quite intractable at the moment, the fact that two-loop rates provide a good description is of great interest.
Caveats

• What about baryons?
  
  – They should be there, at least at SPS. And contribute to single photons. But,
  \[
  - \frac{dN_{B-B}}{dN/dy} \approx 0.10
  \]

• What about intrinsic $k_T$?
  
  – The present estimates depend on
    * quark mass- to avoid singularity
    * (should have a) $p_T$ cut-off to retain applicability of pQCD
    * it is not certain that the introduction of intrinsic $k_T$ via $f(x, Q^2) \rightarrow f(x, Q^2)g(k_T)$ is consistent with the requirement that
      \[
      [\Sigma_i E_i]^2 - [\Sigma_i p_{x_i}]^2 - [\Sigma_i p_{y_i}]^2 - [\Sigma_i p_{z_i}]^2 = M^2_{\text{nucleon}}
      \]

• It is likely that when these effects are (properly) included and a more accurate rate of photons is used we may need a lower initial temperature to explain the data.
$dN/dy = 750$
$	au_0 = 1.0 \text{ fm}/c$
$T_0 = 195 \text{ MeV}, T_c = 180 \text{ MeV}$

- QM + HM
- QM

- Single $\gamma$, WA98
- X 5

scaled pp, NLO-pQCD
Upto one loop
CONSIDERING ALL THE THINGS

- Minimalist Approach
- You can either enhance the NLO pQCD by a factor of 5
- or
- Take 2 loop rates
Phase Transition, $T_c=180$ MeV
$T_0=330$ MeV, $\tau_0=0.2$ fm/c
$S(200 AGeV)+Au$; WA80
7.4%, most central

$\frac{E^2 dN}{d^3p} (c^3/GeV^2)$

- - - - QM
- - - - QM+HM
- - - - NLO pQCD
Phase Transition, $T_c = 180$ MeV

$T_0 = 195$ MeV, $\tau_0 = 1$ fm/c

$\Sigma(200 \text{ AGeV}) + \text{Au}; \text{ WA80}$

7.4%, most central

- QM
- QM+HM
- NLO pQCD

$E dN/d^3p$ (c$^3$/GeV$^2$)

$p_T$ (GeV/c)