LBL-31473
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Physics Letters B

Equilibrium versus Non-equilibrium Photons in a Nucleus-Nucleus Collision at RHIC Energies

D.K. Srivastava, B. Sinha, M. Gyulassy, and X.-N. Wang

October 1990

U. C. Lawrence Berkeley Laboratory
Library, Berkeley

FOR REFERENCE

Not to be taken from this room

LBL-31473
Copy 1
Bldg. 50 Library.

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. Neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California and shall not be used for advertising or product endorsement purposes.

Lawrence Berkeley Laboratory is an equal opportunity employer.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-31473

Equilibrium versus Non-equilibrium Photons in a Nucleus-Nucleus Collision at RHIC Energies[1]

D. K. Srivastava and Bikash Sinha

Variable Energy Cyclotron Centre

1/AF Bidhan Nagar, Calcutta 700 064, India

M. Gyulassy

Nuclear Science Division, Lawrence Berkeley Laboratory

Berkeley, CA 94720

Xin-Nian Wang

Department of Physics, Duke University

Durham, NC 27706

Abstract

Dynamical photons produced via $qg \to q\gamma$ and $q\bar{q} \to g\gamma$ processes in an equilibrated quark gluon plasma are calculated in a hydrodynamic model for a wide range of initial conditions in ultra-relativistic heavy ion collisions. Electromagnetic decay photons are calculated via the Monte Carlo HIJING model including multiple minijet production. If rapid thermalization occurs and the decay photons can be subtracted with high efficiency, the dynamical photons in the range $p_T > 2$ GeV may serve as a useful probe of the initial conditions in the plasma.

The efficacy of dileptons and photons as a signature of quark gluon plasma (QGP) formation in ultra-relativistic heavy ion collisions has been studied by many authors[1]. Their usefulness arises from the fact that they interact only electromagnetically and final state interactions can be neglected. This enables them to probe [2] the entire volume of the dense matter. In contrast, signals associated with hadrons are strongly affected by final state interaction near the surface.

[1]This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Two aspects of photon production have to be understood better if they are to serve as a signature of QGP formation. First, we have to identify the range of initial conditions for which the yield of photons from the equilibrated quark-matter phase exceeds significantly the yield produced at later times from the expanding equilibrated hadronic matter. Second, we have to obtain an accurate estimate of the background from decay photons such as $\pi^0 \rightarrow 2\gamma$. In this work that background is estimated using the HIJING model[7] which combines the LUND model[8] for soft QCD interactions for $p_T \leq 2GeV$ with perturbative QCD [9] for larger p_T. Systematic studies[7] of high energy pp and $p\bar{p}$ data reveal clearly the importance of the minijet contribution at moderate p_T. In $A + A$ collisions at RHIC ($\sqrt{s} \sim 200$ AGeV) the main background at $p_T > p_0 \approx 2$ GeV/c is also expected to be due to a large number of minijets.

One of the aims of this study is to compare the yield of photons from an assumed equilibrated QGP to the yield of photons produced in the absence of equilibration. Multiple minijets can be thought of as simply a non-equilibrium (mostly gluonic) plasma produced via perturbative QCD (PQCD) processes early ($\tau_0 \sim \hbar/p_0$) in $A + A$ collisions. That plasma is initially out of equilibrium because PQCD produces partons with a power law rather than an exponential p_T distribution and the ratio of quarks to gluons is different from that expected assuming chemical equilibrium. If the minijet plasma evolves rapidly enough toward equilibrium, then processes such as $qg \rightarrow q\gamma$ process may "shed light" on the early conditions in an equilibrated quark-gluon plasma state. Of course, it is obvious that $qg \rightarrow q\gamma$ processes can also occur during the equilibration phase of the reaction as well. Photons are also occasionally produced after the hadronization transition via processes such as $\pi\rho \rightarrow \pi\gamma$ which may also involve only partially equilibrated configurations of hadronic matter. The final distribution of the dynamically produced photons thus involves a sum over many sources. The hope is that the contribution from the equilibrated plasma phase outshines the rest.

However, there is another copious source of photons that is unfortunately of far less interest, namely the electromagnetic decay of the final hadrons. The largest background is expected from the $\pi^0 \rightarrow 2\gamma$ decay. Decay photons must be efficiently subtracted out in order that the sought after dynamical photons are not "dimmed out"[10] in their glare. Bremmstrahlung is yet another source of photons, which however is more easily isolated[3] since those photons contribute mainly in the low $p_T < 100$ MeV/c region. In this paper, we make a conservative estimate for the yield of decay photons using HIJING in which the minijet plasma at moderate p_T remains far out of equilibrium. We expect this to overestimate the decay background. For the dynamical photons we consider on the other hand an optimistic hydrodynamic scenario in which the main source of dynamical photons is equilibrated QGP and hadronic matter. We show below that for initial temperatures $T_0 > 1.5T_C$ there may exist a p_T window in the range 2–3 GeV in which the equilibrated QGP out-shines the later equilibrated hadronic phase. In addition decay photons may be only a factor of 10 above that yield and thus their subtraction may be feasible.

For the initial thermal conditions we use the multiplicity densities and initial temperatures as estimated by Heinz *et al*[13] as upper and lower limits in a $Pb+Pb$ RHIC energies (~ 200 AGeV) as reproduced in table 1. The HIJING results for these collisions are within the range of those estimates.

The A-A multiplicity density given in table 1 is obtained by extrapolation of the p-p multiplicity density by assuming

$$\frac{dN}{dy}(\sqrt{s}/A, A-A) = A^{1+\alpha}.\frac{dN}{dy}(\sqrt{s}, p-p) \tag{1}$$

and estimating α as $0 \leq \alpha \leq 0.2$ at RHIC energies to account for collective effects such as minijets etc. The initial temperature given in table 1 is estimated using the expression[4],

$$s_0 = \frac{2\pi^4}{45\zeta(3)}\frac{1}{\pi R_A^2}\frac{1}{\tau_0}\frac{dN}{dy} = 4aT_0^3 \tag{2}$$

for the entropy density along with

$$a = \frac{\pi^2}{90}[8\times 2 + \frac{7}{8}\times 2\times 2\times 3\times 3] \tag{3}$$

for a plasma of mass-less quarks (u,d,s) and gluons.In the above τ_0 is the time-scale for local-equilibration and is taken as 1 fm/c, although simple perturbative estimates tend to give significantly longer time scales. However, nonperturbative effects in

Table 1: Multiplicity density and initial temperature† for $^{208}Pb +^{208} Pb$ system at RHIC energies.

Quantity	RHIC
$\sqrt{s}$(GeV/A)	200
α	0.0–0.2
dN/dy	670–2000
τ_0(fm/c)	1
T_0(MeV)	179–259
T_0/T_C	1.19–1.73
$\tau_0 = 1/3T_0$(fm/c)	0.22–0.13
T_0(MeV)	292–504
T_0/T_C	1.9–3.4

† Upper half adopted from Heinz et al [13]

principle could reduce the thermalization time to $\tau_0 \simeq \hbar/3T_0$. This leads to the most optimistic estimates of T_0 in table 1. Thus we see that the initial temperature may get into the range 300–500 MeV at if $\tau_0 \simeq$ 0.1-0.2 fm/c.

In our calculations, we assume that the transition temperature $T_C = 150$ MeV, the freeze-out temperature $T_F = 140MeV$, and follow the idealized QGP hydrodynamic expansion[4, 3] neglecting transverse expansion. During $\tau_0 < \tau < \tau_Q$ the system is assumed to be in a pure perturbative QGP phase, in the mixed phase during $\tau_Q < \tau < \tau_H$, and in the hadronic phase during $\tau_H < \tau < \tau_F$. Here τ_Q denotes the end of the QGP phase,τ_H the end of the hadronic phase and τ_F is the time of freeze-out as given by

$$\tau_Q = [\frac{T_0}{T_C}]^3 \tau_0, \tau_H = r\tau_Q, \tau_F = [\frac{T_C}{T_F}]^3 . \tau_H \tag{4}$$

where $r = a/a_{eff}$ is the ratio of the number of the degrees of freedom in the QGP and the hadronic phase. We take[3] for the effective number of degrees of freedom in the hadronic resonance gas $a_{eff} \simeq 6.6\pi^2/90$. With this value of the a_{eff}, the life-time of the mixed phase and the hadronic phase is almost half of the case when the hadronic gas is assumed to consist of mass-less pions only. In the mixed phase the fraction $f(\tau)$ of the total volume in the plasma phase is given by

$$f(\tau) = \frac{1}{r-1}(r\frac{\tau_Q}{\tau} - 1) \tag{5}$$

the entropy density is given by

$$s(f, T_C) = s_Q(T_C)f(\tau) + s_H(T_C)(1 - f(\tau)) \ . \tag{6}$$

While the mixed phase may not in fact exist in QCD with $N_f = 2.5$[14], the above idealized model is still useful in order to identify conditions under which dynamical photons from a perturbative QGP may dominate in particular phase space regions.

The basic processes leading to emission of dynamical photons from a QGP, are the Compton (qg$\rightarrow \gamma$ g) and the annihilation processes (q$\bar{q} \rightarrow \gamma$ g). Other processes which lead to emission of dynamical photons from the quark matter could be $q\bar{q} \rightarrow \gamma\gamma$ and bremmstrahlung. The first of these processes has been studied by many authors[1] and is known to give a much smaller contribution compared to the Compton and the annihilation interactions given above.The bremmstrahlung term is important only for $p_T \ll 1GeV$. The thermal rate for the emission of photons from the QGP phase due to these processes in a collision of two nuclei A and B integrated over the space-time history of the plasma , has been evaluated [4, 5] to give,

$$\frac{dN_{\gamma,QGP}}{d^2p_T dy}(y \approx 0) = \frac{K}{p_T^4} F(\frac{p_T}{T_C}, \frac{p_T}{T_0}) \tag{7}$$

where $F(b,a) = \int_a^b dt\, e^{-t}\, t^{2.5}$, and

$$K = \alpha\alpha_s \log(2/\alpha_s) \left\{ \frac{(R_A+R_B)^2}{R_A R_B} \frac{c}{4a} \frac{dN}{dy_\pi} \right\}^2 \frac{4\sqrt{2\pi}}{\pi^4} \frac{1}{\pi R_A^2} \tag{8}$$

For evaluating the contributions from the mixed phase , we make a simplifying assumption that the rate for emission of dynamical photons from quark matter is identical to the same from hadronic matter at $T = T_c$ consistent with detailed results of Kapusta et al[11] and Chakrabarty et al[12]. The contribution from the quark-matter in the mixed phase is then

$$\frac{dN^{Mixed}_{\gamma,QM}}{d^2p_T dy}(y \approx 0) = \frac{K(r-1)}{6p_T^4}(\frac{p_T}{T_C})^{3.5} e^{-p_T/T_C} \tag{9}$$

Similarly, the contribution of the hadronic matter in the mixed phase is obtained as

$$\frac{dN^{Mixed}_{\gamma,HM}}{d^2p_T dy}(y \approx 0) = \frac{Kr(r-1)}{6p_T^4}(\frac{p_T}{T_C})^{3.5} e^{-p_T/T_C} \tag{10}$$

Finally, the contribution of the hadronic phase to dynamical photons is given by

$$\frac{dN_{\gamma,Had.Pha.}}{d^2p_T dy}(y \approx 0) = \frac{Kr^2}{p_T^4} F(\frac{p_T}{T_F}, \frac{p_T}{T_C}) \tag{11}$$

The sum of (9) and (11) is the contribution of the plasma and similarly the sum of (12) and (13) is the contribution of the hadronic matter.

The dynamical photons produced in a typical collision of $^{208}Pb +^{208} Pb$ at RHIC energies are shown in fig. 1 corresponding to the the upper and the lower limits of initial conditions estimated by Heinz et al[13] and given in table 1 .We see that for the upper limit of the initial temperature likely to be attained in favourable cases ($T_0/T_C \approx 1.7$), the cross-section for photons from quark-matter becomes larger than those from the hadronic matter beyond $p_T \approx 2GeV$. If nonperturbative effects thermalize the plasma very quickly, with $\tau_0 \sim \hbar/3T_0$, such that $T_0 \sim 3T_C$ is reached, then as shown in Fig.1 the plasma would out shine the hadronic phase considerably in the range $p_T > 2$ GeV/c. This conclusion differs from that found in ref.[10, 11] because the initial conditions considered here are much more optimistic and the length of time assumed in the mixed phase is significantly smaller.

We turn next to sources of photons due electromagnetic decay of hadrons. There is compelling phenomenological evidence for the importance of minijet production at collider energies[7]. We have therefore used the predictions of the event generator HIJING to estimate that background. The model has been shown[7] to provide a consistent explanation of energy and multiplicity dependence of charged particle rapidity and transverse momentum spectra,the KNO scaling violation of multiplicity distributions,and the two-particle correlation functions for p-p collisions. The natural extension[7] of the treatment to A-A collision in terms of the Glauber model additionally includes the effect of gluon shadowing and jet quenching as well as direct photons.

In fig.2 we shown the upper and lower limits of the rates for photons from the quark matter in a typical central collision of two gold-nuclei at RHIC energies for initial conditions given in table 1, in a QGP scenario along with the predictions of HIJING. The HIJING estimates provide the the sum of all the photons, (upper histograms) and the ideal situation when all the photons originating from the decay $\pi^0 \rightarrow 2\gamma$ are excluded (lower histograms). The background could be decreased further if the photons from the decay of η mesons are also identified.

One can get an idea of uncertainties due to final state interactions in the HIJING from the upper and the lower limits of the above two histograms, which in fact show a cross-over around $p_T \simeq 1GeV$. The final state interaction in the HIJING is simulated by providing an energy loss, dE/dx=1 GeV/fm, for the jets while traversing the excited nuclear matter. This essentially diminishes the cross-sections for higher p_T and increases it for lower p_T (and hence the cross-over with the predictions for dE/dx=0 seen here).

We see that within the uncertainties inherent these models the yield of dynamical photons from the quark-matter in the p_T region above 2 GeV/c is small relative to the the yield of decay photons unless the initial temperature is very high. Note that the p_T distribution of the decay photons in this range is seen to vary more like a power law characteristic of PQCD processes. To help disentangle the dynamical photons from the background it may be useful to study events with large fluctuations from the average since the dynamical photon yield depends on $\sim (dN/dy)^2$ while decay photons vary more slowly.

In summary, we have calculated the yield of dynamical photons from central collisions of ultra-relativistic nuclei at RHIC energies in a hydrodynamic model of QGP expansion and compared it the yield from electromagnetic decays in a model dominated by minijet production. We find that if $T_0 > 2T_C$ the dynamical photons from the equilibrated quark matter dominate over the dynamical photons from the equilibrated hadronic matter for $p_T > 2GeV$. However, in this region the background of decay photons is at least an order of magnitude higher. However, as that background originates mainly from hard/semi hard QCD processes, it should be possible to evaluate it much accurately once more information is available from the charged hadron spectra[7]. A systematic study of the charged hadron spectrum should be able to reduce the theoretical uncertainties in the minijet yield due to gluon shadowing and the dE/dx in dense matter[7]. If the abundant decay photons can be reliably subtracted, then the dynamical photons having $p_T > 2$ GeV may indeed prove to be a useful thermometer[15] of the initial conditions in the quark gluon plasma.

We are grateful to Jan-e Alam,S. Chakrabarty, H. Gutbrod,S. Raha, H. Satz and Y. P. Viyogi for many helpful discussions. One of us (DKS) would like to thank the hospitality of Nuclear Science Division, Lawrence Berkeley Laboratory, where part of this work was performed.

References

[1] Sibaji Raha and Bikash Sinha , Int.J.Mod.Phys.A6(1991) 517, and references there-in.

[2] L.D.McLerran and T.Toimela , Phys.Rev.D31(1985)545.

[3] D.K.Srivastava and Bikash Sinha , submitted to J.Phys.G.(1991).

[4] R.C.Hwa and K.Kajantie , Phys.Rev.D32(1985)1109.

[5] M.Neubert , Z.Phys.C42(1989)231 , see also P.V.Ruuskanen , Proceedings- Large Hadron Collider Workshop,Aachen,1990, CERN-90-10.

[6] J.D.Bjorken , Phys.Rev.D27(1983)140.

[7] X.N.Wang and M.Gyulassy, LBL preprints LBL-31036 and LBL-31159 (1991), PRD in press.

[8] B.Andersson,G.Gustafson and B. Nilsson-Almqvist,Nucl. Phys. B281(1987)387.

[9] T.Sjostrand and M.van Zijl,Phys.Rev.D36(1987)2019.

[10] V. Ruuskanen, Proc. Quark Matter 91, to be published.

[11] J.Kapusta,P.Lichard and D. Seibert ,University of Minnesota preprint (1991)

[12] S.Chakrabarty,J.Alam,D.K.Srivastava,Bikash Sinha and Sibaji Raha, to be published,also contribution to QM'91.

[13] U.Heinz,P.Koch and B.Friman,Proceedings Large Hadron Collider Workshop,Aachen (1990),CERN-90-10,vol.II,p.1079.

[14] F.R.Brown, et al, Phys.Rev.Lett.65(1990)2491.

[15] E.V. Shuryak, Sov. J. Nucl. Phys. 28, (1978) 408; M. Gyulassy, Nucl. Phys. A418 (1984) 59c.

Figure Captions

Figure 1: Invariant distribution of dynamical photons at mid-rapidity from quark matter and hadronic matter for different initial temperatures for T_C=150 MeV.The results for 1.7 T_C and 3.4 T_C correspond to the same multiplicity density but τ_0=1 fm/c and $1/3T_0$= 0.13 fm/c respectively. The contribution of the hadronic matter for those two cases is identical.

Figure 2: Dynamical photon yields from the quark matter (solid lines in fig.1) for different initial conditions compared to decay photons as estimated in the HIJING model.The dark shaded region corresponds to the yield of decay photons *excluding* the $\pi^0 \rightarrow 2\gamma$ decay. The upper and lower histograms (at higher p_T) for each case correspond to dE/dx=0 and 1 GeV/fm, respectively, used for simulating final state interactions in HIJING.

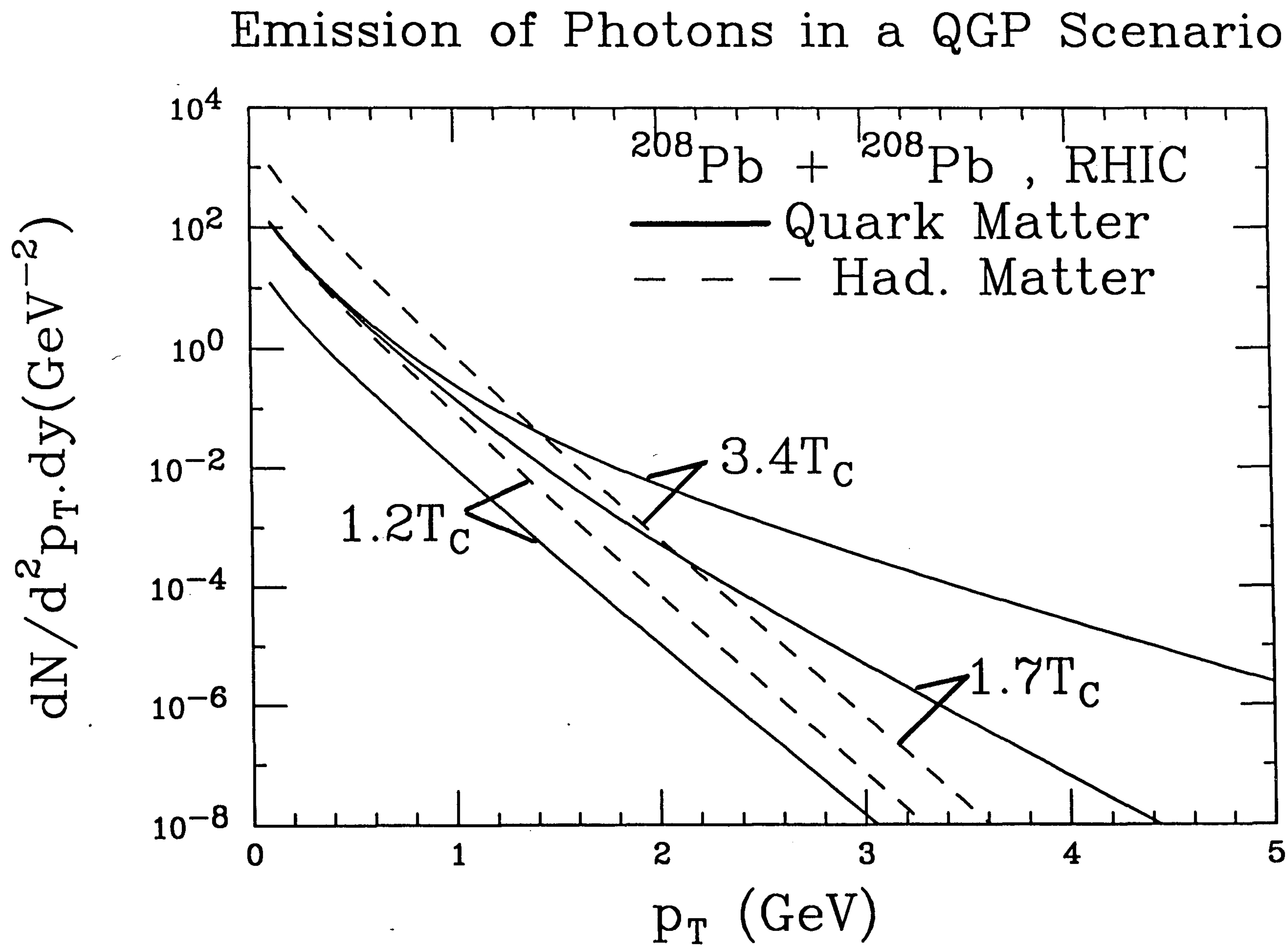
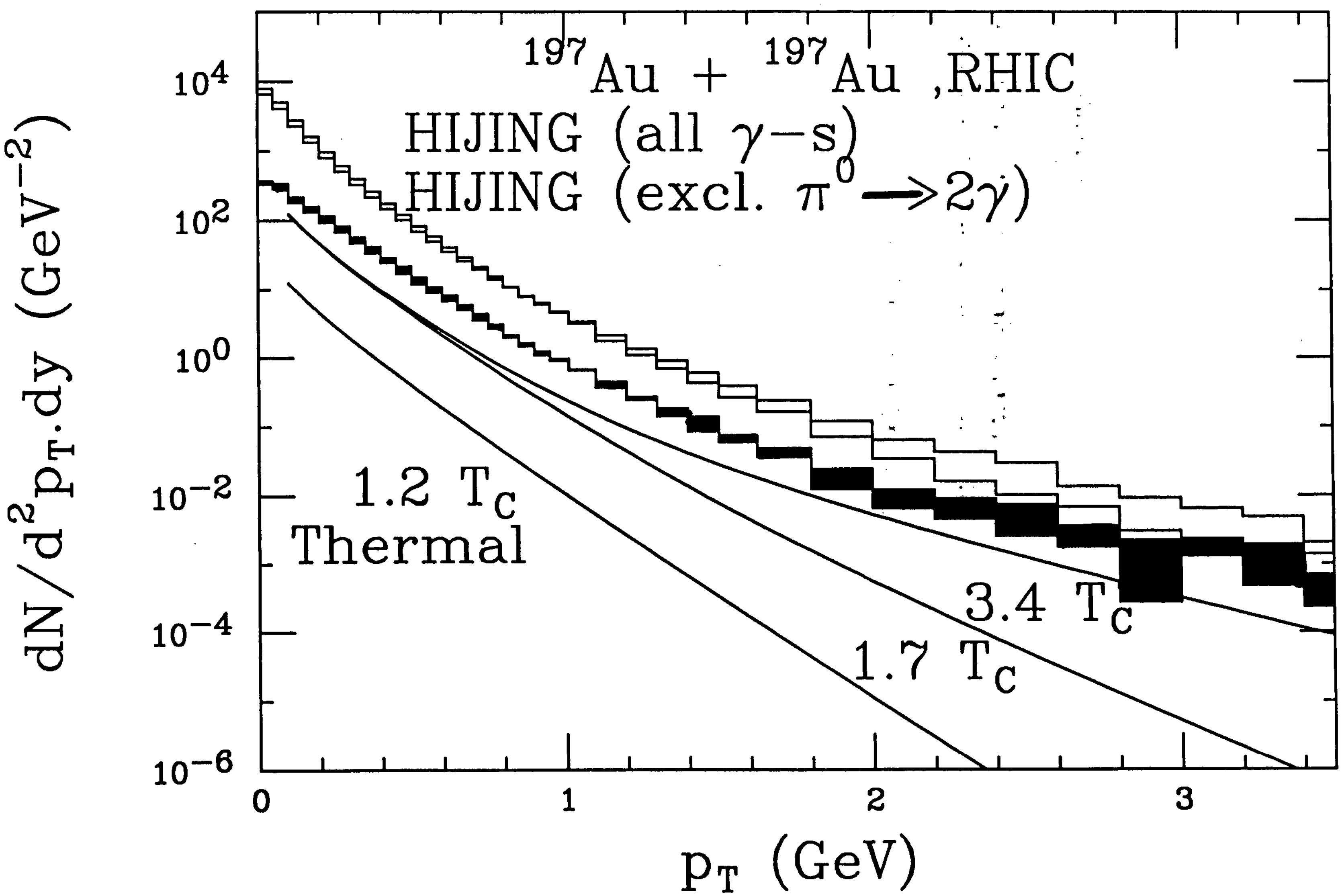

Emission of Photons in a QGP Scenario
^{208}Pb + ^{208}Pb , RHIC
Quark Matter
Had. Matter
3.4T$_c$
1.2T$_c$
1.7T$_c$
$dN/d^2p_T.dy(GeV^{-2})$
p_T (GeV)
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0
1
2
3
4
5

Figure 1



^{197}Au + ^{197}Au ,RHIC
HIJING (all γ−s)
HIJING (excl. $\pi^0 \rightarrow 2\gamma$)
1.2 T_C
Thermal
3.4 T_C
1.7 T_C
$dN/d^2p_T.dy$ (GeV^{-2})
p_T (GeV)
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0
1
2
3

Figure 2

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720