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Electromagnetic Signatures of QGP (Photons): Experimental Status

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1 Introduction

Historically, photons and lepton-pairs were amongst the first suggested probes to search for evidence of Quark Gluon Plasma formation in ultra-relativistic heavy-ion collisions. Because real and virtual photons have a mean free path much greater than the size of the nuclear system, they will escape the reaction zone once produced. As a result they carry information about the conditions at the time and location of their production. Presuming that the system attains thermal equilibrium, the spectrum of radiated real or virtual photons will reflect the temperature and local charge density. The observed photon spectrum will contain contributions from the entire thermal and spatial evolution of the system. In particular, it is expected that while the total thermal photon yield will reflect the volume and lifetime of the system, the photon yield at high p_T will be dominated by contributions from the initial high temperature phase.

In the case of QGP formation, the conventional picture is that the system quickly thermalizes in the QGP phase at initial temperature T_i. It expands and cools rapidly until the critical temperature T_C is reached. The system remains at the transition temperature in a mixed phase while it undergoes the phase conversion from the QGP phase to the hadronic phase. The length of time spent at the transition temperature is dependent upon the relative number of degrees of freedom available to the system in the two phases. Upon completion of the phase conversion the hadronic matter then cools until the freeze-out temperature T_F is attained at which point interactions cease to occur. In the non-QGP scenario, the system of hadronic matter simply expands and cools rapidly from T_i until reaching the freeze-out temperature. The thermal photon p_T spectrum is expected to contain components which reflect the various temperatures in the evolution of the system. In particular, the high p_T region should be dominated by the initial temperature of the system, while a long-lived mixed phase might give rise to a p_T spectrum which is dominated by the time spent at T_C.

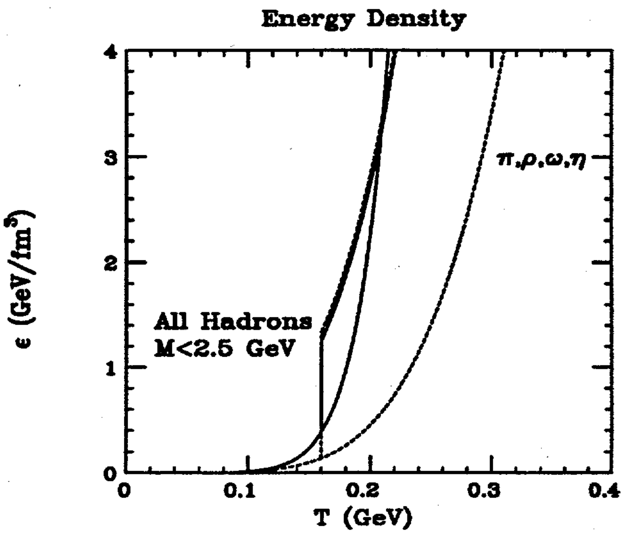

Figure 1: Energy density as a function of temperature from Ref. [1]. The dashed lines correspond to a gas containing only π, ρ, ω, and η mesons (with and without QGP phase transition). The full lines include all hadronic resonances with masses below 2.5 GeV/c^2.

The classic method to study a phase transition is to measure the heat capacity of the system as a function of the temperature. The phase transition becomes evident by a discontinuity in the heat capacity as the number of degrees of freedom available to the system makes a discontinuous change. For the hadronic system, for a given energy deposition in the system, the initial temperature is expected to vary inversely with the number of degrees of freedom available to the system (as $g^{-1/3}$), and since the hadronic phase is naively expected to have fewer available degrees of freedom, it is expected that higher initial temperatures will be attained in the case that a QGP is not formed. This expectation is demonstrated in Fig. 1 taken from Ref. [1] in which the initial energy density for the hadronic matter, rather than the heat capacity, is plotted against the initial temperature. The behavior of this "caloric curve" depends on the equation of state of nuclear matter. Calculations are shown for four different equations of state. The dotted curves indicate the case in which the hadronic matter has only a few degrees of freedom consisting of the π, ρ, ω, and η mesons, while the solid curves indicate the case in which the hadronic matter includes all known resonances up to mass 2.5 GeV/c^2. The two curves with a discontinuity in the energy density indicate the behaviour expected for equations of state which include a QGP phase transition at $T_C = 160$ MeV. Experimentally, one would like to measure the initial temperature of the system as a function of the initial energy density to map out such a caloric curve and thereby deduce the actual equation of state. The initial temperature

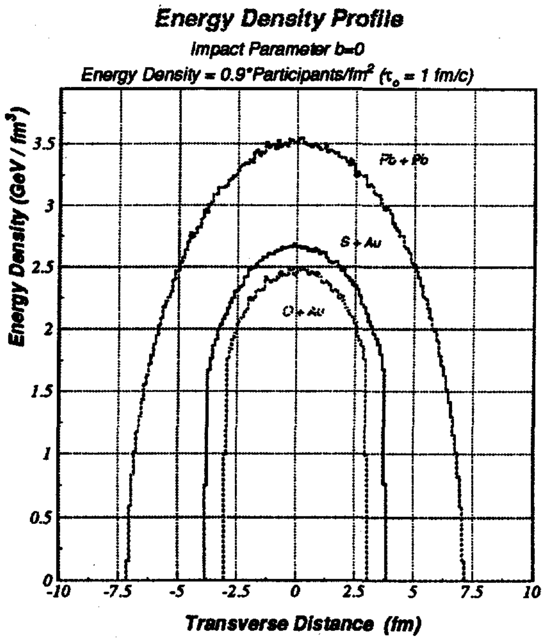

Figure 2: A comparison of the b=0 radial energy density profiles in O + Au, S + Au, and Pb + Pb collisions at the SPS.

can most directly be determined from the spectrum of radiated photons. The amount of energy which has been deposited in the system, and hence the energy density, may be extracted from the amount of transverse energy observed.

2 Results for S + Au

An estimate of the attained energy density may be obtained using the prescription given by Bjørken

$$\epsilon_{BJ} = \frac{dE_T/d\eta|_{max}}{\pi R_o^2 \tau_o} \tag{1}$$

where $dE_T/d\eta|_{max}$ is the transverse energy density at mid-rapidity, πR_o^2 is the transverse size of the system, and τ_o is the initial thermalization time, typically assumed to be 1 fm/c. Using the observed fact that $dE_T/d\eta|_{max}$ scales with the number of participant nucleons [2, 3] at SPS energies together with the calculated number of participant nucleons as a function of transverse location (purely geometry) one can generalize the above expression to calculate the energy density profile. The results are shown in Fig. 2 for zero impact parameter.

As a consequence of the radial variation of the energy density seen in Fig. 2 together with the simplified assumption of the Bjørken estimate and the uncertainty of the initial thermalization time, it is not possible to precisely state the energy densities which are attained. Nevertheless, one may infer that energy densities in the central core increase significantly as the projectile mass increases and that volume averaged energy densities of about $\epsilon_{BJ} \approx 2$ are likely attained for SPS energies These energy densities are well above the critical energy density if the critical temperature is as low as 160 MeV, as currently believed (see Fig. 1).

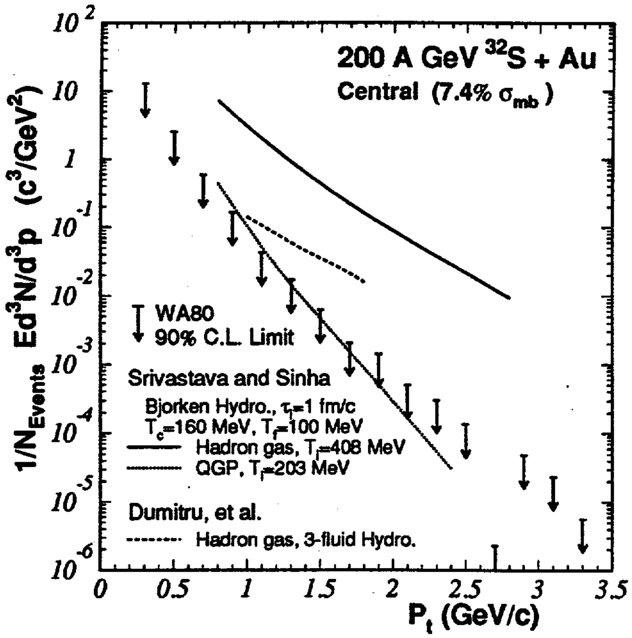

Figure 3: Upper limits at the 90% confidence level on the invariant excess photon yield per event for the 7.4% $\sigma_{\rm mb}$ most central collisions of 200·A GeV ^{32}S+Au taken from Ref. [5]. The solid curve is the calculated thermal photon production expected from a hot hadron gas taken from Ref. [6]. The dashed curve is the result of a similar hadron gas calculation taken from Ref. [7]. The dotted curve is the calculated thermal photon production expected in the case of a QGP formation also taken from Ref. [6].

To date, there has been no observation of thermal photon radiation in ultra-relativistic heavy-ion collisions. The WA80 experiment set an upper limit on the direct photon to π° ratio of $\gamma/\pi^\circ < 15\%$ at each p_T in the transverse momentum region of $0.5 < p_T < 2.4$ GeV/c for O + Au reactions at 200 A GeV [4]. As shown in Fig. 3, for 200 A GeV S + Au reactions WA80 has set an upper limit on the thermal photon yield at each p_T point over the range $0.3 < p_T < 3.3$ GeV/c [5]. The CERES experiment has given an upper limit on the direct photon excess integrated over the interval $0.4 < p_T < 2.0$ GeV/c of 14% relative to the expected decay photon background yield [8]. While no thermal photon signal has been observed, the WA80 results have nevertheless generated a great deal of theoretical interest [9] since as shown in Fig. 3 the upper limit on the thermal photon yield at high p_T puts severe constraints on the possible initial temperature of the system. A high temperature component even with a negligible integrated total yield would become evident as a photon excess at high p_T. On the basis of these WA80 results it has been concluded that, rather independent of assumptions on the equation of state, the initial temperature of the system must be less than about 250 MeV [10]. Or alternatively, it may be concluded that, given the large energy density implied and the low apparent initial temperature, the system must have access to a large number of degrees of freedom. This is consistent with a scenario of QGP formation, but would also be consistent with a hadron gas scenario in which the hadron gas consisted of the full spectrum of resonances up to high mass. The results rule out a pure hadron gas consisting of only the lowest mass π, ρ, ω, and η mesons [9] as seen by Fig. 1.

3 Preliminary Pb + Pb Results

One of the main goals of the WA98 experiment at CERN is a high precision search for direct thermal photons in 158 A GeV Pb + Pb collisions. This is accomplished using the 10,080 element leadglass detector array (LEDA) which measures the energy and emission angles of individual photons in the rapidity region $2.3 < y < 3.0$. The excess direct photon yield is determined by subtraction of the photon yield from resonance radiative decays, primarily of the π°'s and η's. The π° and η yields are measured simultaneously with the same event selection via their two-photon decay branch using the photons measured in LEDA. In total approximately 40 million Pb+Pb events were accumulated during the 1995 and 1996 WA98 run periods.

The preliminary WA98 inclusive photon transverse momentum distributions are shown in Fig. 4 for central and peripheral event selections, as well as an intermediate centrality selection. The event selection is made based on the transverse energy measured in the MIRAC calorimeter [11]. The transverse momentum spectra are seen to extend beyond 3 GeV/c with about 5% of the WA98 data sample analyzed. The inclusive photon transverse momentum distribution calculated with the VENUS 4.12 event generator [12] shows a somewhat flatter p_T slope. This same tendency is observed in the comparison of the preliminary WA98 π° transverse momentum spectra with VENUS as discussed elsewhere [13].

The extraction of the final direct photon result will require analysis of the full WA98 data sample and a careful systematic error analysis in order to obtain the maximum sensitivity to a possible direct photon excess. In the meantime it is interesting to obtain an early estimate as to whether there might be an (unexpected) large excess.

An upper limit on the integrated direct photon signal can be obtained by studying the ratio of electromagnetic to total transverse energy. Such a calorimetric measurement was one of the earliest proposed means to observe the QGP signature of enhanced photon radiation, initially estimated to be enhanced by as much as 30% [14]. The expectation is that if a significant amount of energy were

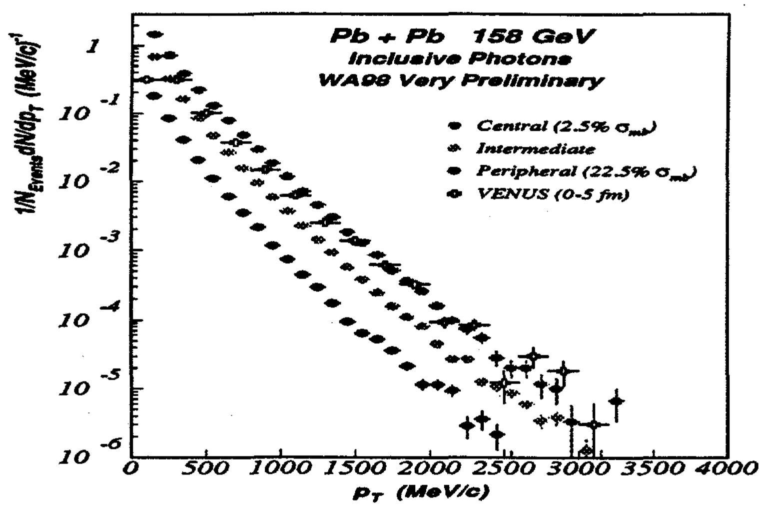

Figure 4: The preliminary WA98 inclusive transverse momentum distributions for peripheral, intermediate, and central event classes. The results are compared to the VENUS 4.12 event generator for a centrality selection corresponding to approximately the 13% most central collisions. The data are not corrected for efficiency.

radiated in the form of direct photons, the observed electromagnetic transverse energy, which dominantly measures the transverse energy of π°'s and η's which undergo radiative decays, would increase relative to the total transverse energy measured. In WA98 this measurement can be made using the MIRAC calorimeter. The MIRAC is a sampling calorimeter which consists of 180 towers. Each tower is 20x20 cm^2 in area with a Pb/Scintillator electromagnetic (EM) section of 15.6 radiation lengths followed by an Fe/Scintillator hadronic (HAD) section of 6.1 absorption lengths. Each section is readout on the left and right sides with wavelength shifting panels attached to photomuliplier [11]. In WA98 the MIRAC was arranged symmetrically about the beam axis to give nearly complete azimuthal coverage over the pseudo-rapidity interval $3.5 < \eta < 5.5$.

The centrality dependence of the ratio of electromagnetic to total transverse energy is shown in Fig. 5. The centrality is measured by the energy observed in the Zero Degree Calorimeter (ZDC). A fit to the ratio as a function of centrality gives an increase of only $0.14 \pm 0.26\%$ from peripheral ($E_{ZDC} = 30$ TeV) to central ($E_{ZDC} = 5$ TeV) collisions. There are relatively few sources of error in this measurement. Both electromagnetic and total energy are measured at the same time in the same detector, meaning there are no relative acceptance effects. Furthermore, the MIRAC covers nearly the full forward acceptance so there is little sensitivity to a change in the baryon rapidity density with centrality, which

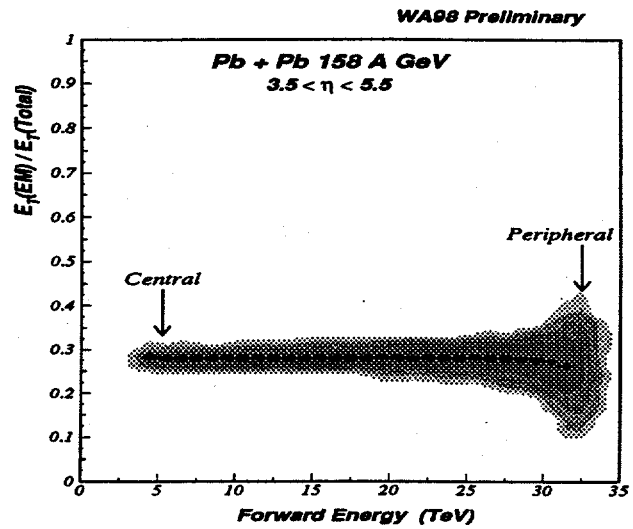

Figure 5: The ratio of electromagnetic to total transverse energy as a function of centrality, as determined by the energy measured in the WA98 zero degree calorimeter.

might affect the local ratio of electromagnetic and hadronic transverse energy. The main source of systematic uncertainty arises from the fact that the measured electromagnetic energy must be corrected for hadrons which shower early and deposit a fraction of their energy in the electromagnetic section. This correction is less than 30%, but has a slight hadron energy dependence, and so depends on centrality to the extent that the average particle energies vary with centrality.

In total it is estimated that the systematic error on the centrality dependence of the electromagnetic to total transverse energy ratio is less than 5%. Since no centrality dependence is observed this leads one to conclude that the increase in the electromagnetic transverse energy in central collisions relative to peripheral collisions is less than 6.5% of the total transverse energy at the 90% confidence level. Note that this measurement is sensitive to the additional electromagnetic transverse energy, that is, to the product $N_\gamma^{Excess.} < p_T^\gamma >$ and not simply the number of excess photons. One may conclude that there is no initial evidence for a large photon excess in central Pb + Pb collisions.

As discussed above, the most interesting information will come from the measurement, or upper limit on, the direct photon yield as a function of p_T. Comparing our preliminary inclusive photon spectrum of Fig. 4 with predictions of Ref. [1] with the expectation, based on previous experience, that we will reach a level of sensitivity corresponding to about 5% of the inclusive photon yield, we observe that the predicted direct photon yields are just at the level of experimental sensitivity.

4 Conclusions

The direct photon measurement can provide information about the thermal evolution of the hot dense nuclear matter produced in ultra-relativistic heavy-ion collisions. However, the measurement of the transverse momentum distribution of the thermal photons is essential to obtain detailed information, in particular, about the short-lived initial hot phase. To date there has been no confirmed observation of direct thermal photon radiation in the transverse momentum region below about 3 GeV/c. On the other hand, the upper limit on the direct photon yield in S + Au reactions at large transverse momenta determined by the WA80 experiment has been shown to imply that the initial temperature of the system must be relatively low ($\leq$ 250 MeV). Such low temperatures imply that the system has access to a large number of degrees of freedom, consistent with QGP formation or with a hadronic system consisting of the full spectrum of known resonances up to large mass, but inconsistent with a hadronic gas of only the lowest lying resonances. It is an interesting question how a hadronic gas consisting of the full spectrum of resonances could come into chemical equilibrium already during the initial phase of the interaction.

Preliminary results from WA98 for Pb + Pb reactions indicate that there is no significant integrated direct photon excess in central collisions compared to peripheral collisions. This conclusion is based on the variation of the ratio of the electromagnetic to total transverse energy with centrality, which is consistent with no increase. The analysis of the photon data obtained with the WA98 leadglass detector is underway. Comparison of the preliminary inclusive photon spectrum to recent theoretical predictions for the thermal direct photon signal indicate that it may be observable for the case of a hadron gas, but is likely below the expected level of sensitivity for the case of QGP formation.

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