Photon Physics with PHENIX

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In this Paper I discuss briefly the physics motivation for extending measurements of particle production with high granularity and particle id capabilities to neutrals in PHENIX. I then discuss the technique of direct photon measurement in the presence of copious background photons from π^o decays. We will measure relatively low p_t photons near y=0 in the lab frame. This new experimental environment of high multiplicity and low γ momenta will affect both the techniques used and the type of analysis which can be performed. The Phenix Electromagnetic calorimeter is described and its capabilities illustrated with results from simulation and beam tests of the first production array.

1. Introduction

Our primary motivation is that the photon spectrum from heavy ion collisions is a record of the temperature history of the collision. This record even extends back to the earliest instants when collision energy is transferred to the constituents of the nucleus. As the collision evolves and its temperature changes, photons are emitted according to the Stefan-Boltzman law. This implies a very strong temperature dependence of photon production:

$$dN_\gamma(\tau) \propto T^3, < E_\gamma > \propto T. \tag{1}$$

So thermal photons tend to originate early in the collision in contrast to observed hadrons whose mean free path is too short to escape from the early phase. The situation can be contrasted with photons from cosmic background radiation. In Heavy Ion collisions the photon mean free path is much greater than the source size so photons from all stages are visible. The cosmic photon background takes us only back to the era when atoms were formed and the mean free path suddenly increased.

1.1. The shape of the direct photon spectrum

The spectrum of photons from heavy ion collisions has been calculated by a number of authors as an integral over time,τ , of eqn. 1 taking into account the equations governing isoentropic expansion.

$$T_f^3 \times \tau_f = \frac{\kappa}{a_1} \times \frac{dN^\pi}{dy} = T_i^3 \times \tau_i \tag{2}$$

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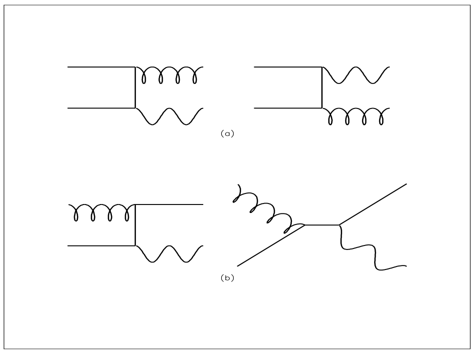

Figure 1. Annihilation and Compton which lead to direct γ production.

where κ is a constant, $\frac{dN^{\pi}}{dy}$-the observed pion multiplicity is related to the final entropy density and a_1 is larger([2]) by about a factor of eight for a quark gluon phase than in the hadron gas phase.

Contributions from both hadron gas phase and a quark gluon plasma phase have been calculated. In the latter case annihilation and Compton diagrams depicted in Figure 1 dominate. The final spectrum depends on

- the initial time, τ_i, at which thermal conditions are reached,
- whether a quark-gluon phase is formed and
- the existence of a long lived mixed phase.

Srivastava[2] argues that, if a large direct photon signal has been observed in the WA80 experiment at CERN, then the quark gluon phase must be absent in SPS collisions. This conclusion follows from eqn. 2 when we hold τ_i fixed at, say, 1 fm/c. The hadron phase, which has less degrees of freedom would reach T_i= 408MeV/c whereas if the system evolved from a quark gluon phase the same equations of isoentropic expansion yield T_i=203.4 MeV/c. On the other hand, it has been pointed out by Shuryak[1] that early thermalization in the so-called "hot glue scenario" would also raise the initial temperature.

At the highest photon transverse momenta (ie $p_t \geq 2$ GeV/c) the dominant source of photons will be from pre-equilibrium collisions. Hard photon production has been studied in $pp(\bar{p})$[5] and p-Nucleus collisions. In this case the diagrams are again those of Figure 1, however the initial state is determined by structure functions of the incident hadrons rather than temperature.

Finally the π^o and η^o mesons, because of their dominant electromagnetic decay modes (to $\gamma\gamma$) will result in copious photon production. While this provides an opportunity to measure the π^o production spectrum - it also becomes a serious background to the more interesting sources described above.

2. Extracting the direct photon signal

There are 2 basic techniques that can be used to extract the direct photon signal in the presence of meson decay photons, applicable under different conditions.

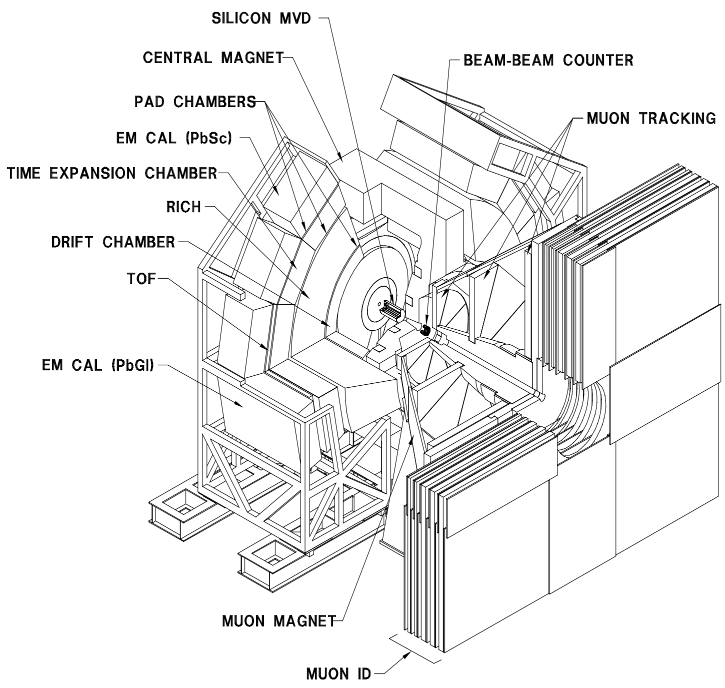

Figure 2. PHENIX detector showing a cutaway through the East Arm which contains both Pb/Glass and Pb/Scintillator Emcal octants.

2.1. high p_t, low multiplicity

To study high p_t photons in relatively low multiplicity collisions, the fraction of 'isolated' photons as a function of p_t is measured with the electromagnetic calorimeter. A nearby electromagnetic shower is assumed to be the associated π^o decay γ, even if it is partially merged with the photon candidate. The most probable decay configuration in isotropic π^o decay results in equal energy γ's and the minimum opening angle in the lab frame:

$$\theta_\gamma^{min} = 2 \times \frac{m_\pi}{p_\pi} \tag{3}$$

The angle should be small compared to the mean angle between particles in the event- a condition not satisfied in heavy ion collisions of interest at RHIC. (This technique would be used for the "RHIC Spin" program and low multiplicity ion collisions.)

The WA80 group[6] has studied the efficiency to recognize two nearby showers and finds $\epsilon \geq 50\%$ once θ_γ corresponds to at least one calorimeter cell spacing. This could give rise to a natural limit of $p_t \leq 20 - 30GeV/c$ as we'll see below. On the other hand some groups (see eg. [7]) have also used a statistical technique to measure $\frac{\gamma}{\pi^o}$ recognizing that two nearby γ's have a larger conversion probability in material in front of the calorimeter. In this way, the direct γ measurement could be extended to arbitrarily high p_t.

2.2. low p_t, high multiplicity

To see that this is our case, consider the expected hit multiplicity for central Au-Au collisions in the Phenix central detector, which covers $|d\eta| \leq 0.35$ and 50% of 2π in azimuth:

$$\frac{dN^{\pm,\gamma}}{d\eta} \times d\eta \times \frac{d\phi}{2\pi} \simeq 1,500. \times 0.7 \times 0.5 = 525 \tag{4}$$

The mean angular separation between hits can be derived from this and is greater than θ_γ^{min} only when $p^t_{\pi^o} \geq 2GeV/c$. Since thermal direct photons are likely only to be measurable for $p_t \leq 2GeV/c$, the meson can't be measured with isolation cuts but instead is extracted from the 2γ mass spectrum.

To achieve a reasonable occupancy, the calorimeter is segmented into 25,000 cells. Since the Moliere radius of the calorimeter is $R_M = 3.4$cms, the calorimeter is placed at a distance of 5m from the beam and covers $64m^2$.

Fits will be made to the level of the π^o mass peak out of all randomly chosen 2γ combinations. After subtracting the smooth combinatorial background under the π^o peak, correcting for photon reconstruction efficiency, acceptance,etc., the π^o decay γ spectrum will be calculated and subtracted from the total inclusive γ spectrum.

How well can this daughter γ spectrum be determined? This obviously bounds the thermal direct photon spectrum which can be measured in our experiment. The dominant systematic errors arise from:

1. photon reconstruction efficiency
2. extraction of the meson decay mass peaks

Previous attempts- notably WA80- have concluded that $\delta(\frac{\gamma}{\pi^o}) \sim 0.05$ is reachable [9].

Another p_t dependent limit to this uncertainty is the ratio of the fit to $\frac{peak}{total}$ in the 2γ mass plot. We consider that a meaningful measurement can't be made unless this ratio is larger than a few percent. Since both energy(and hence mass) resolution and photon multiplicity decrease with p_t, there will be a minimum measurable p_t bin -estimated to be 1.0 GeV/c with the PHENIX baseline detector.

2.3. Experimental consequences

We have seen that one of the main limitations resulting from the environment at $y_{lab} = 0$ in Heavy Ion Collisions is that spectroscopy with π^o decay photons is often overwhelmed by combinatorial background. Typically the ($\pi^o \rightarrow \gamma\gamma$) peak signal-to-noise will be less than 1:1. This dilution of π^o's will make it difficult to do π^o spectroscopy. Similarly, searches for fluctuations in rapidity space of the fraction of π^o relative to $\pi^\pm$(ie for disoriented chiral condensates [10]) must take into account the smearing of the π^o momentum vector in the decay to photons which are actually measured.

Typically, a source (such as the DCC 'bubble') decaying isotropically will appear as a cluster of secondaries with $\sigma_\eta \sim 0.7$ recognizable as an enhancement in $\frac{dN^{\pi^o}}{dydp_t}$ above the underlying event. Because of π^o decay kinematics, this fluctuation would be smeared by an additional $10 - 20\%$ in rapidity, resulting in a small dilution of the signal.

3. The Phenix Detector

A cutaway view of the PHENIX detector is shown in Figure 2, with the 2 Pb/Glass calorimeter sectors in the foreground. Taken together with the remaining 6 sectors of

Pb/Scintillator sampling calorimeters, these EM calorimeter sectors have the same coverage as the PHENIX central magnetic spectrometer($\delta\eta = 0.7$ and $\delta\phi = 50\% \times 2\pi$). The inner detectors (silicon MVD) provide full charged particle tracking over $|\eta| \leq 2.5$, without magnetic analysis. The properties of the EM calorimeter relevant to the photon measurement are summarized in table 1.

The Pb/Glass calorimeter is currently being used in the WA98 experiement at CERN and will be installed in PHENIX during the first half of 1998. We expect that, because of the experience gained with this calorimeter in a fixed target environment, we will be ready to make measurements early on in PHENIX. The main difference between PHENIX and WA98 (fixed target) environments is that the lab momentum of low p_t photons is not boosted in the collider experiment. Thus measurements will be extended to lower energy for PHENIX.

Table 1
Characteristics of the baseline EMcal sectors and of the proposed BaF_2 array.

	PbSc	**PbGl**	**BaF_2**
η cov.	$\Delta\eta = 0.7$	$\Delta\eta = 0.7$	$\Delta\eta = 0.1$
ϕ cov.	$90° + 45°$	$45°$	$90°$
Mod. (cm^2)	5.5×5.5	4.0×4.0	3.5×3.5
$\delta\phi, \eta$/mod	0.011	.008	.007
$\sigma_E/\sqrt{E(GeV)}$	$.078/\sqrt{E} \oplus .015$	$.058/\sqrt{E} \oplus .01$	$.019/\sqrt{E} \oplus .008$
σ_x (mm)	$10./\sqrt{E}$	$5./\sqrt{E} \oplus 1.0$	$4.7/\sqrt{E} \oplus 0.5$
MIP peak(MeV)	227	480	220
σ_t (ps)	$70 \oplus 70/\sqrt{E}$	$75 \oplus 143/\sqrt{E}$	80 ps
γ/π w. Δt	700 MeV/c	580 MeV/c	750 MeV/c

The remaining area is covered by a Pb/Scintillator calorimeter with 'shish-kebab' type waveshifter fiber readout geometry. The PHENIX EM calorimeter group recently completed the R & D phase in the development of this calorimeter[11] and in January 1995, the first production array of 144 channels arrived at BNL.

Figure 3 some odf the first π^o data recorded with this new detector. This online mass distribution from the current test run confirms the cosmic ray calibration of the calorimeter. The fitted π^0 mass peak without offline corrections is within 2 MeV of the databook value.

From Table I it can be seen that development of the Pb/Scintillator calorimeter emphasized low energy capabilities appropriate to the RHIC environment. In particular:

- good energy resolution at low energies due to fine sampling and high light yield
- $\sim$ 100 psec time resolution which can be used to discriminate between γ and hadron hits to $p_t \sim 700MeV/c$

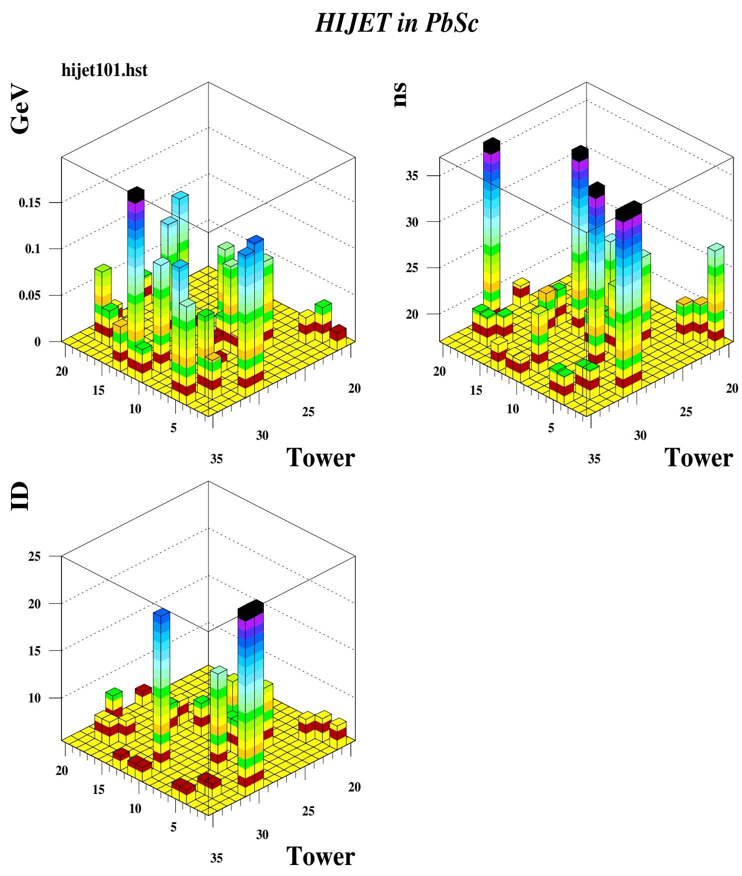

Figure 3. Three views of a typical HIJET event as seen by the calorimeter which illustrate the particle id capabilities of the Pb/scintillator calorimeter.

- a low response to minimum ionizing particles which suppresses the signal from misidentified charged hadrons.

In most respects, the same physics measurements can be carried out with both calorimeter subsystems. This will provide a useful cross-check on the direct γ signal since the two systems differ in granularity, energy resolution and particle i.d. capabilities. As part of its long term plan, PHENIX has proposed to replace subunits of each Pb/scintillator sector with high resolution BaF2 arrays [8]. This would provide the ultimate electromagnetic energy resolution and hence signal-to-noise ratio for extracting the π^o decay background contribution to the γ spectrum. Typically the same signal-to-noise as in the baseline detector will be achieved at 0.5 GeV/c lower in p_t. The scale of the array summarized in Table I will allow us to measure the η^o spectrum down to at least 1.4 GeV/c. Even with a small fraction of this coverage, we could measure the inclusive γ spectrum thereby elimination essentially all contributions of resolution smearing.

The actual installation of the BaF2 array is completely determined by funding. It is expected that at least a fraction of the full array will be installed on Day-1.

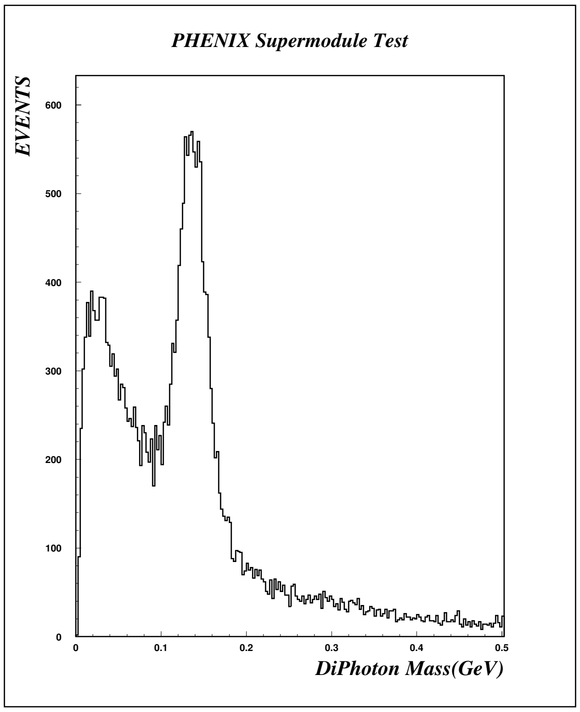

Figure 4. Mass distribution of two photon events measured with the first production Supermodule in the 1995 test beam run at the AGS. A 7 GeV π^- beam was incident on a lucite target and the event trigger was chosen to enhance charge exchange reactions.

4. Particle Identification

The particle i.d. capability of the Pb/Scintillator array and its usefulness for the direct photon anlysis are illustrated in Figure 3. This figure shows three views of calorimeter cell hits from the same HIJET event. The view labelled with the parent type (ID) shows the primary produced particle's i.d. from the Monte Carlo generator. This index is lowest for π^o's and is highest for the $\bar{n}$ in this event. The other 2 views are the ones observed in PHENIX- energy deposition and time of arrival. In this event the four γ clusters from π^o decay (foreground in display) are readily identified by their early time of arrival which is about 17 nsec at the calorimeter wall (r=5.1 m).

The case of the $\bar{n}$ is an interesting one. The expected level of production ($\frac{\bar{n}}{\pi^o} \simeq 0.05$) will lead to an apparent $\frac{\gamma}{\pi^o}$ signal above 0.5 at p_t=1 GeV/c, because of the larger energy deposit of stopping $\bar{n}$'s. This background is reduced to a negligible level [8] with a time cut of $(t - t_{predicted}) \leq 1.5nsec$. Incidentally, this easily identified background could be used to extend the measurement of antibaryon production to lower momenta than is possible with $\bar{p}$'s.

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