Neutral transverse momentum spectra in 60 and 200 $A \cdot GeV$ $^{16}$O + nucleus and proton + nucleus reactions

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WA 80 Collaboration


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Abstract. Transverse momentum ($p_T$) distributions of inclusive photons and neutral pions at midrapidity are measured with a lead glass calorimeter in 60 and 200 $A \cdot GeV$ $^{16}$O + nucleus and proton + nucleus reactions. Inclusive photon distributions are compared for central and peripheral reactions. The degree of centrality is determined either from the charged particle multiplicity or from the remaining projectile energy in the forward direction. Deviations from a nucleus + nucleus interaction model based upon linear extrapolation from p+p reactions are observed in central $^{16}$O + Au data. The variation of the average transverse momentum is investigated as function of centrality. The target-mass and energy dependence of $\pi^0 p_T$ distributions are presented. For $^{16}$O + Au a change of slope in these distributions is observed at $p_T \approx 0.8$ GeV/c compatible with hydrodynamic expansion models.

1 Introduction

Oxygen beams of 60 and 200 $A \cdot GeV$, available now in the CERN-SPS, allow a systematic study of nucleus-nucleus reactions at ultrarelativistic energies in order to investigate nuclear matter under extreme conditions of density and excitation energy. According to QCD lattice calculations [1] a first or second order transition to the deconfined phase of quarks and gluons, the quark-gluon-plasma (QGP), may occur in a finite volume of hadronic matter at energy densities larger than the energy density inside the nucleon [2]. First experimental results from $^{16}$O + nucleus reactions [3, 4] show that, in the most central events, energy densities above 2 GeV/fm$^3$ are reached. Up to now, cosmic ray data have been the only source of information [5] and the observed rise of their transverse momenta with energy density has been interpreted as due to QGP effects [6]. Since the signature of the QGP is not well established, p + nu-
ucleus data have been taken for comparison to the nucleus-nucleus data at the same incident energy per nucleon in order to observe in the heavy ion induced reactions any deviation in the distribution of transverse momenta.

2 Experiment

The WA 80 experiment at the CERN-SPS is designed to measure the distribution of charged particles in a large fraction of phase space, to analyse the forward and transverse energy distributions and to investigate the target fragmentation region. In addition, photons and neutral pions are identified near midrapidity in a high resolution lead glass calorimeter. This allows a detailed analysis of their transverse momenta ($p_T$) based on centrality selections which are determined either by measurements of the remaining projectile energy in the forward direction or the charged particle multiplicity. The experimental setup is described in detail in [7]. The results presented in this paper were derived from the following detector components: the electromagnetic lead glass calorimeter (SAPHIR), the uranium scintillator sampling calorimeter at zero degree (ZDC), and the streamer tube multiplicity arrays which cover the pseudorapidity region $1.2 < \eta < 4.2$.

The ZDC characterizes the centrality of each collision by measuring the remaining energy of projectile spectators for lab. angles $\leq 0.3^\circ$. A strong correlation between charged particle multiplicity and energy in ZDC is observed [8], so that both quantities may be used to distinguish between peripheral and central reactions.

SAPHIR measures the inclusive photon and $\pi^0$ distributions at midrapidity. Details of the construction and performance are given in Table 1. Values for energy resolution and shower development at various angles of incidence were obtained from measurements at the DESY electron test beam (0.6 to 6 GeV) with a prototype detector. The complete SAPHIR setup has been tested and calibrated with electron and hadron beams (4 to 20 GeV) at the CERN-SPS. The center of the front surface of the detector is located at 342 cm from the target and at an angle of 20° with respect to the beam direction. This gives an approximate pseudorapidity coverage of $1.5 \leq \eta \leq 2.1$ and a solid angle of 0.13 steradian. Short term gain stability is continuously monitored with a nitrogen laser system. The long term gain stability is monitored with two independent NaI(Tl) crystals doped with Am. Light fibres conduct the laser light to the front surface of each lead glass element. The laser light intensity can be varied with filters to obtain the response of the photomultipliers over the full dynamic range and to evaluate the linearity corrections ($<5\%$ max. deviation). The charged particle detection is achieved by two layers of plastic streamer tubes in front of the lead glass resulting in a 98% detection probability for charged particles. In order to enhance the statistics in the tail of the momentum distributions, SAPHIR is included in the trigger so that events with high energy photons are always recorded.

The streamer tube material contributes 4% to the photon conversion probability. The target vacuum chamber, a thin (500 µm) spherical aluminum chamber, contributes an additional 0.4%. Care was taken to keep all extraneous material out of the reaction zone, and background levels during target-out operation were found negligible. In addition, thin targets were used to minimize contributions from secondary interactions. The target thicknesses were 186 mg/cm² of C and 250 mg/cm² of Au, corresponding to an average photon conversion probability of 0.2% and 1.6% for C and Au, respectively.

3 Photon distributions

Inclusive spectra of photons, which dominantly originate from $\pi^0$ decay, have been extracted from the raw data under the following selection criteria:

1. No hit of a charged particle is observed by the multiplicity detectors in the vicinity of a photon candidate.

2. The transverse shower development is compatible with that of an electromagnetic (EM) model-shower of the same energy and at the same point of incidence.

The EM model-showers were derived from Monte Carlo simulations, and compare reasonably well with test beam data. Since there are too few modules involved in the shower development at photon energies below 0.5 GeV, this method of EM-shower selection breaks down leading to systematic errors which are included in the error bars shown in the photon spectra. For $p + Au$ and $^{16}O + Au$ reactions a maximum number of 19 and 45 hits per event, respectively, were

<table>
<thead>
<tr>
<th>Table 1. SAPHIR construction items and performance</th>
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<tr>
<td>Material: 1278 lead glass modules SF 5</td>
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<tr>
<td>Module cross section: 35-35 mm²</td>
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<tr>
<td>Module length: 460 mm = 18 radiation lengths</td>
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<tr>
<td>(98% containment for 30 GeV photons)</td>
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<tr>
<td>Total (rectangular) area: 98.171.5 cm²</td>
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<tr>
<td>Spatial resolution: $\sigma_{x} \leq 5$ mm (dependent on angle of incidence)</td>
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<tr>
<td>Energy resolution: $\sigma_{E} = E \cdot (6/\sqrt{E}) \cdot (E/GeV + 0.4)%$</td>
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<tr>
<td>Gain stability: $(0.5 \pm 0.6)%$</td>
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<tr>
<td>Dynamic range: 50 MeV to 25 GeV</td>
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<tr>
<td>Minimum ionizing signal: 540 MeV photon equivalent</td>
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</table>
Photon showers and minimum ionizing particles in SAPHIR

Fig. 1. Energy distribution (linear scale) in the lead glass detector SAPHIR in a single event selected by the high $p_T$ photon trigger from 200 $A$-GeV $^{16}$O+$^{198}$Au reactions. Different types of energy clusters (hits) are identified by the hatching of the lego-plot towers. The photon shower in the upper left corner contains an energy of 4 GeV corresponding to a transverse momentum of 1 GeV/c.

Fig. 2. Inclusive photon $p_T$ distributions selected for central reactions with 10% of the minimum bias cross section. For comparison with exponential parametrizations (solid lines) the histogram shows the FRITIOF model results for $^{16}$O+$^{198}$Au at 200 $A$-GeV.

Table 2. Slope parameters $T_{\text{eff}}$ in MeV/c from an exponential fitting procedure ($dN/dp_T \sim \exp(-p_T/T_{\text{eff}})$) for $p_T > 0.4$ GeV/c applied to the data shown in Fig. 2. Errors are statistical errors only as obtained from the fit procedure.

<table>
<thead>
<tr>
<th>Energy per nucleon</th>
<th>$p$+$^{16}$O</th>
<th>$^{16}$O+$^{198}$Au</th>
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<tr>
<td>60 GeV</td>
<td>198 ± 3</td>
<td>181 ± 2</td>
</tr>
<tr>
<td>200 GeV</td>
<td>215 ± 4</td>
<td>234 ± 2</td>
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Fig. 3. Ratios of inclusive photon cross sections for high and low charged particle multiplicity events in $^{16}$O+$^{198}$Au and $p$+$^{198}$Au reactions. The selections contain about 30% of the most central and the most peripheral reactions, respectively.

In order to investigate the $p_T$ distributions in more detail with respect to their centrality dependence, ratios of cross sections for high and low charged particle multiplicity events are plotted as function of the transverse momentum in Fig. 3. These ratios increase by a factor of 2 for the $^{16}$O+$^{198}$Au data between $p_T$.
= 0.5 GeV/c and 1.5 GeV/c and stay almost constant for the p + Au data at both energies. Thus large transverse momenta are produced more efficiently in violent $^{16}$O + Au reactions as compared to the proton induced reactions. The FRITIOF model, containing the basic kinematical constraints, does not exhibit any different slope of $p_T$ distributions for central or peripheral reactions and is in this respect consistent only with the p + Au data.

In the following we have analysed the $p_T$ region above 0.4 GeV/c of the inclusive photon spectra as a function of target mass and event centrality, characterized by the energy deposited in the zero degree calorimeter, by two different methods:

a) fitting an exponential to the $dN/dp_T$ distributions,

b) calculating the average $p_T$ from the truncated $p_T$ distributions [10] by integrating the experimental data:

$$\langle p_T \rangle_{r,c} = \int C \frac{dN}{dp_T} dp_T \int C \frac{dN}{dp_T} dp_T,$$

using $C = 400$ MeV/c. Both methods give equivalent results. Those from method b) are shown in Fig. 4. Here, a decrease in $\langle p_T \rangle_{r,400}$ of 15% is observed for $200\ A\cdot GeV\ ^{16}\ O + Au$ as function of increasing energy in the ZDC. The variation is less pronounced and lower values are observed for the lower incident energy and only little variation of $\langle p_T \rangle_{r,400}$ is observed for p + Au reactions. Since for proton projectiles the ZDC energy is more strongly influenced by leading particles and therefore no longer a good measure of centrality, the multiplicity dependence of the average transverse momenta was investigated in addition.

This analysis also yields only little variation for the p + Au data. The FRITIOF model predicts almost no variation with centrality or target mass, however, it tends to be closer to the experiment for peripheral oxygen induced reactions and for proton induced reactions. Since the low $p_T$ part of the spectrum tends to influence the results, the absolute numbers of $\langle p_T \rangle_{r,c}$ are, of course, dependent on the choice of the cutoff value $C$. We find a shift in the absolute $\langle p_T \rangle_{r,c}$ scale of $-4\% (+4\%)$ when $C$ is changed by $-80\ MeV (+120\ MeV)$ leaving the observed centrality dependence unchanged. Thus, the deviation from FRITIOF is obvious, although it has to be noted, that in this model hard scattering [11] is not yet included for nucleus + nucleus reactions, which may account for part of the observed effect [12].

4 $\pi^0$ Distributions

The momentum distributions of inclusive photons analysed in the previous section allow studies of the centrality dependence for different reaction systems with good statistical accuracy. From the various sources ($\pi^0$ and $\eta$ mesons, baryon resonances) contributing photons to the observed distributions, the $\pi^0$ are clearly dominating and expected to influence the results. However, the reaction kinematics and possible changes in the effective CM system make it difficult to extract absolute numbers of average transverse momenta for $\pi^0$ from inclusive photons. Therefore cross sections for $\pi^0$ production and their $p_T$ distributions have been obtained by analysing the invariant mass spectra of $\gamma\gamma$ pairs in small intervals of $p_T$. The detector acceptance for $\pi^0$ is defined as the probability of having both decay photons measured and resolved from those $\pi^0$ emitted into the SAPHIR solid angle. Photon conversion probabilities are included in the acceptance curves shown in Fig. 5 for the decay of $\pi^0$ and $\eta$ mesons. A lower software threshold of $E_\gamma = 500\ MeV$ was applied to the photons contributing to the $\pi^0$ yield. Error bars shown in $\pi^0$ momentum distributions include the contributions from acceptance correction uncertainties in addition to the statistical errors. The $\pi^0$ mass resolution $\sigma(M)/M$ is 5–8% and is limited mainly by variations in position resolution for different angles of incidence due to the non-projective geometry of the detector arrangement. The combinatorial background below the invariant mass peak was fitted by a third order polynomial and after subtraction leads to a gaussian $\pi^0$ mass peak. Examples for invariant mass spectra obtained in $^{16}$O reactions with C and Au targets are given in Fig. 6 in different regions of $p_T$. The combinatorial background is a more serious problem in the $^{16}$O
The acceptance (definition see text) of the SAPHIR lead glass detector for $\pi^0$ and $\eta$ mesons as function of their transverse momentum for different lower thresholds of the accepted photon energy.

Fig. 5. Invariant mass spectra of $\gamma\gamma$ pairs for $^{16}$O+C and $^{16}$O +Au at 200 A GeV in different regions of transverse momentum $p_T$: a) $0.4 \leq p_T \leq 0.8$ GeV/c, b) $0.8 \leq p_T \leq 1.2$ GeV/c, c) $1.2 \leq p_T \leq 1.6$ GeV/c. Only photons with $E_\gamma > 500$ MeV are considered.

Fig. 6a-c. Invariant mass spectra of $\gamma\gamma$ pairs for $^{16}$O+C and $^{16}$O +Au at 200 A GeV in different regions of translverse momentum $p_T$: a) $0.4 \leq p_T \leq 0.8$ GeV/c, b) $0.8 \leq p_T \leq 1.2$ GeV/c, c) $1.2 \leq p_T \leq 1.6$ GeV/c. Only photons with $E_\gamma > 500$ MeV are considered.

Fig. 7. Invariant cross sections for $\pi^0$ in different regions of the pseudorapidity $\eta$.

The obtained $\pi^0$ cross sections from $p+Au$ reactions are consistent with Fermilab data [13] within the error limits for $\pi^+$ and $\pi^-$ from $p+Au$ at the same incident energy and in approximately the same region of rapidity. Furthermore, $\pi^0$ distributions have been studied in different regions of pseudorapidity within the acceptance of SAPHIR ranging from 1.5 to 2.1 in $\eta$ in order to observe a possible variation in the slope of $p_T$ distributions due to a change in the effective CM system when proton and $^{16}$O induced reactions are compared (Fig. 7). Except for the region $p_T \leq 0.5$ GeV/c no significant change in slope in this interval is observed which is larger than the expected change in the effective CM system.

In Fig. 8 the $p_T$ dependence of invariant $\pi^0$ cross sections for minimum bias trigger conditions from proton and oxygen induced reactions is compared for different targets and energies. The slopes of these distributions for $p_T > 0.8$ GeV/c can be described by an exponential parametrization $(1/p_T dN/dp_T \sim \exp(-p_T/T_0))$, and slope parameters $T_0$ have been deduced from the same restricted transverse momentum range $0.8$ GeV/c $\leq p_T \leq 2$ GeV/c for all reaction systems (Table 3). The slope parameters turn out to be similar for proton and oxygen induced reactions in these minimum bias data and are only weakly dependent on target mass, but are larger by at least...
The spectra in Fig. 8 show a change in slope below $p_T \simeq 0.8$ GeV/c, which is most pronounced for the heavy system. A slope parameter $T_0 \leq 150$ MeV/c would be appropriate to describe the data for $p_T < 0.8$ GeV/c. This effect is not seen in $250$ GeV/c $p+p$ reactions [14], but is consistent with $\pi+\pi$ reactions at the ISR [10, 15, 16] and weakly indicated in the $p+Au$ data at 200 GeV. This feature is also predicted in thermodynamical models [17, 18] and in studies of the hydrodynamical expansion [19, 20] of the QGP.

5 Conclusion

In summary, it has been shown that even in the high multiplicity environment of $^{16}$O + Au reactions the identification of $\pi^0$ in the invariant mass spectrum of $\gamma\gamma$ pairs is achieved with good accuracy in a lead glass detector. Inclusive photon spectra and $p_T$ distributions for identified $\pi^0$ have been presented for 60 and 200 A-GeV $^{16}$O + nucleus and $p+$nucleus reactions.

The photon spectra show a target mass and centrality dependence in the region $p_T > 0.4$ GeV/c which is not predicted by the current FRITIOF model. The $\pi^0 p_T$ distributions show at least two components, a low $p_T$ one with an inverse slope of about 150 MeV/c and a high $p_T$ component with a flatter slope dependent slightly on target mass. These features are not compatible with a FRITIOF type linear extrapolation from $p+p$ data to heavy ion reactions. A description in terms of a thermodynamical evolution and hydrodynamical expansion of a hot hadronic system seems to be justified and could be used for quantitative comparisons. Nevertheless, hard scattering of partons needs to be included in nucleus + nucleus interaction models, in order to study if the above observations can be explained within refined non-thermal models.

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References


20% for $^{16}$O + Au at 200 A - GeV than for $p+p$ reactions [14] and for FRITIOF model predictions. This behaviour is consistent with the observations cited above which show that the linear extrapolation from $p+p$ reactions to heavy ion reactions, as contained in this model, is doubtful. The deviation from FRITIOF by a factor of 3 at $p_T = 1.5$ GeV/c may hardly be explained by multiple hard scattering since this effect produces only a 30% increase in calculations [12] of $p+p$ reactions at ISR energies.
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