Abstract. The production of neutral pions by the interaction of 200 A·GeV p and 16O projectiles with a Au target has been studied in the pseudorapidity range 1.5 < η < 2.1. Transverse momentum spectra have been measured between 0.4 GeV/c and 3.6 GeV/c and their dependence on the centrality of the collision has been investigated. The peripheral-collision spectra display a marked change of slope with a hard component starting at about 1.8 GeV/c, in contrast to central-collision data. The data are discussed in comparison to p+p and ~ + c~ data from the ISR.

1 Introduction

First results from ultrarelativistic heavy-ion experiments at the CERN SPS [1] have shown that with 200 A·GeV 16O projectiles on heavy targets, high energy densities are created, which approach the critical values for a quark gluon phase transition predicted by QCD lattice calculations [2]. One means of studying the properties of the compressed and highly excited reaction zone is the investigation of Pt spectra of produced pions and their dependence on the centrality of the reaction. To distinguish different contributing processes and to provide a reliable basis for comparisons with p+p scattering, a large Pt coverage is required. In particular, data at high Pt values, where hard processes become important and may be calculated by perturbative QCD are of great interest. The present investigation of Pt spectra has, therefore, concentrated on detailed measurements of Pt spectra up to 3.6 GeV/c and on selections of the data according to the centrality of the reaction. Results presented here cover the full data set of the 1986 16O + Au run and extend the subset of data previously published in [3].

2 Experimental setup and trigger requirements

The experiment has been performed at the CERN SPS using the WA80 setup [4] schematically shown in Fig. 1. The data were obtained by means of an electromagnetic calorimeter (SAPHIR), a uranium scintillator sampling calorimeter located at zero degree (ZDC), an iron scintillator calorimeter located at mid-rapidity (MIRAC), streamer tube multiplicity arrays (LAM, MIRAM, SAM), and the Plastic Ball located in the target fragmentation region.

The ZDC measures the forward energy distribution (η ≥ 6.0) which is dominated by projectile spectators. It has been found [5] that the ZDC energy EzDC for 16O + Au can be related to the number of participants and,
hence, is a measure of the centrality of the reaction. The
total transverse energy in the pseudorapidity range
2.4 ≤ η ≤ 5.5 is measured by MIRAC, LAM, MIRAM
and the Plastic Ball, together cover 97% of 4π sr solid
angle and provide the total number of charged particles
per event. It has been shown that the ZDC energy, the
total transverse energy, and the number of charged par-
ticles are strongly correlated [5, 6]. Any of the three quan-

tities can, therefore, be used for event characterization.

In our setup the minimum-bias trigger is defined by the
requirements that:

- less than 88% of the total projectile energy is de-
  posited in the ZDC (for 16O beams but not for p beams);
- at least one charged particle is recorded by LAM or
  MIRAM (1.2 ≤ η ≤ 4.4).

In the following, central 200 A · GeV 16O + Au events
are defined by 0% ≤ E_{ZDC}/E_{beam} ≤ 30%, correspon-
ding to 37% of the minimum-bias cross section σ_{mb} while pe-

eripheral events are defined by 40% ≤ E_{ZDC}/E_{beam} ≤ 88% (54%
of σ_{mb}). In a geometrical picture these cuts imply
that in central events all projectile nucleons participate
in the reaction whereas only a part of the projectile inter-
acts in peripheral reactions.

The lead-glass detector, SAPHIR, is located at a dis-

tance of 342 cm from the target and covers about 1/6th
of the azimuth φ in the pseudorapidity range 1.5 ≤ η ≤ 2.1
corresponding to a lab. angle 13.7° ≤ θ ≤ 25.9°. The SA-

PHIR detector consists of 1278 SF5 lead-glass blocks.
The dimensions of one block are 35 × 35 × 460 mm³

equivalent to 18 radiation lengths (X₀ = 25.5 mm). Each
block is wrapped in a double layer of 10 μm aluminium-
coated mylar foil in order to prevent optical crosstalk,
and is equipped with a 10-stage photomultiplier [7]. The
average gain stability of the module, monitored during
beam time by a laser reference system, was found to be
better than 0.5%. Each of the modules had been cali-

brated with an electron beam at the CERN SPS.

The calorimeter energy resolution was measured with
an electron beam at DESY, and is described by:

\[ \frac{σ}{E} = 0.4% + \frac{6%}{\sqrt{E/\text{GeV}}} \]  

At 10 GeV/c a position resolution of 5 mm for an
angle of incidence of 15 degrees was obtained by com-
paring the reconstructed shower position with the electron
position measured by a delay line wire chamber. The ob-

served π⁺ and η mass resolution during the operation of
the calorimeter at the CERN SPS was slightly worse
than expected from the calibration data mainly due to the
effect of overlapping showers in the high particle
multiplicity environment of heavy ion reactions. An ef-
fective energy resolution of σ/E ≈ 8.6%/\sqrt{E/\text{GeV}} and
σ_π ≈ 5.9 mm at 10 GeV/c is obtained by a fit to the exper-
imental data.

3 Data analysis

Electromagnetic showers deposit their energy into more
than one module depending on energy, angle of incidence

and hit position relative to the module boundaries. Such
a group of adjacent modules with a signal above thresh-
old will in the following be called a cluster. With the
information of the streamer tube arrays LAM and SAM
in front of SAPHIR the clusters are assigned to charged
or neutral. In addition, the clusters are compared with
the calculated response of electromagnetic showers [8]
necessary to separate possible overlapping showers with-
in one cluster. The efficiency of this procedure will be
discussed in the next section.

Transverse momentum distributions of neutral pions,
which are identified by their decay photons (π⁰ → 2γ)
are obtained by accumulating invariant mass spectra for
different bins of p_T bins: a) 0.6 GeV/c ≤ p_T ≤ 0.8 GeV/c,
b) 1.4 GeV/c ≤ p_T ≤ 1.6 GeV/c. The dashed lines indicate the π⁺
peak region used for integration.

Fig. 2a, b. Invariant mass spectra for peripheral and central 200
A · GeV 16O + Au reactions and polynomial background fits in the
p_T bins: a) 0.6 GeV/c ≤ p_T ≤ 0.8 GeV/c, b) 1.4 GeV/c ≤ p_T
≤ 1.6 GeV/c. The dashed lines indicate the π⁺ peak region used
for integration.

In Fig. 2 invariant mass spectra are displayed from cen-
tral and peripheral 200 A · GeV 16O + Au reactions in two
different bins of p_T. They show the typical behaviour of
Q, which is determined by the photon density in phase
space:

1. Q increases with increasing transverse momentum,
2. Q decreases with increasing photon multiplicity i.e.
at the same p_T interval Q is higher in peripheral than
Table 1. Number of analyzed events $N_{\text{events}}$ and reconstructed $\pi^0$.

<table>
<thead>
<tr>
<th>System</th>
<th>$N_{\text{events}}$</th>
<th>Reconstructed $\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 GeV p + Au</td>
<td>572</td>
<td>11</td>
</tr>
<tr>
<td>200 A·GeV O + Au</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum-bias (0% $\leq E_{\text{ZDC}}/E_{\text{beam}} \leq$ 88%)</td>
<td>2204</td>
<td>264</td>
</tr>
<tr>
<td>Central (0% $\leq E_{\text{ZDC}}/E_{\text{beam}} \leq$ 30%)</td>
<td>1730</td>
<td>229</td>
</tr>
<tr>
<td>Peripheral (40% $\leq E_{\text{ZDC}}/E_{\text{beam}} \leq$ 88%)</td>
<td>344</td>
<td>23</td>
</tr>
</tbody>
</table>

in central collisions. The mean number of neutral hits with an energy above 500 MeV increases from 2.1 for peripheral collisions to 5.1 for central reactions.

The final number $\Delta N_{\text{corr}}$ of $\pi^0$ emitted into SAPHIR's solid angle in a given $\Delta p_T$ is obtained by correcting the measured number $\Delta N$ with the geometrical acceptance and the $\gamma$ reconstruction efficiency described in the next section.

The invariant $\pi^0$ cross section $E d^3 \sigma/dp^3$ is calculated by the following expression:

$$\frac{\sigma_{\text{mb}}}{N_{\text{events}} \Delta \eta \Delta \phi \Delta p_T} \frac{\Delta N_{\text{corr}}}{\Delta p_T}. \quad (3)$$

Here $N_{\text{events}}$ is the number of analyzed events given in Table 1. As the absolute invariant $\pi^0$ cross sections are not discussed in the following, the uncertainty of $\sigma_{\text{mb}}$ (±10%) [10] is not taken into account in the error calculation and no attempt has been made to calculate the efficiency of the minimum-bias trigger conditions or to extrapolate the minimum-bias cross section to the total inelastic cross section. In the considered $p_T$ range the pseudorapidity interval $\Delta \eta$ is used instead of the rapidity interval which introduces a maximum relative error of only 0.5%.

The absolute energy scale and its linearity can be monitored by investigating the $\pi^0$ mass peak position as a function of the energy of one photon, the other photon energy fulfilling the constraint 0.8 GeV $\leq E_\gamma \leq$ 2 GeV (see Fig. 3). Any nonlinearity should then be visible as a shift of the $\pi^0$ peak position with varying photon energy. The $\pi^0$ peak position $\mu$ (solid circles), which is fitted by a gaussian turns out to be nearly independent of the photon energy. A maximum nonlinearity in $\Delta E/E$ of 3% can be derived from the experimental data. However, the mean peak position increases from 136.6 ± 0.2 MeV/c² for minimum-bias 200 GeV p + Au reactions to 138.4 ± 0.2 MeV/c² for minimum-bias 200 A·GeV $^{16}$O + Au reactions. The mean number of photons with an energy above 500 MeV for the two systems is 0.5 and 4.7, respectively, which leads for the 200 A·GeV $^{16}$O + Au reactions to a higher probability that two or more showers merge to one. This tends to increase the energy of the shower and yields a higher mass of the reconstructed $\pi^0$ and an asymmetric shape of the mass peak. In order to account for this effect, an modified gaussian with the following parametrization is applied:

$$f(x) = \begin{cases} A \exp\left(-0.5 \frac{x-\mu}{\sigma}\right) & \text{for } x \geq \mu \\ A \exp\left(-0.5 \frac{x^2}{\omega}\right) & \text{for } x < \mu \end{cases}$$

Here $x$ is the invariant mass, $A$ the normalization constant and $\beta$ the asymmetry parameter. For the 200 A·GeV $^{16}$O + Au events and a photon energy above 2 GeV these peak positions (open circle in Fig. 3) agree with the rest mass.

The mass shift from the system p + Au to the system $^{16}$O + Au causes a maximum relative change of the $\Delta N/\Delta p_T$ distribution of 20%. The $\pi^0 p_T$ distributions are corrected for this effect. The relative uncertainty of the corrected $\Delta N/\Delta p_T$ is estimated by Monte Carlo Simulations to be smaller than 4%.

4 Efficiency and acceptance corrections

As mentioned before, the efficiency to identify a hit as a photon is determined by the probability $e_\gamma$ to assign it as a neutral particle and the probability $\kappa$ that no overlap with unresolved nearby showers has occurred. Both quantities are found to be multiplicity dependent.

In the following we will discuss them as a function of the mean multiplicity $\mu_{\text{all}}$ of all hits, which are determined for different classes of events. In this context hit means the number of resolved particles implying that one cluster may consist of two hits whose centroids could still be distinguished.

The probability that a photon is correctly identified as a neutral particle can be determined by calculating the invariant mass for pairs of one neutral particle, called trigger particle, combined with all other particles in the same event. In order to increase the probability to recon-
Fig. 4. Probability \( \varepsilon \) (see (5)) averaged over \( p_T \) as a function of the mean multiplicity of hits \( \mu_{\text{all}} \) for different reaction systems and centralities of the reactions.

Fig. 5. Probability \( \kappa \) (see text) averaged over \( p_T \) as a function of the mean multiplicity of hits \( \mu_{\text{all}} \). The different points for one reaction system are calculated by superimposing two, three, and four events. The two lines represent the estimated systematic uncertainty of the probability.

The influence of overlapping showers not resolved by this analysis is determined by superimposing raw data events with low particle multiplicity and comparing the particle identification from the superimposed events with the identification of the low particle multiplicity events. Again no significant \( p_T \) dependence is found for the probability \( \kappa \), except for the superimposed events with the highest multiplicity, \( \mu_{\text{all}} = 21.1 \). Figure 5 displays \( \langle \kappa \rangle_{p_T} \) as a function of the mean multiplicity \( \mu_{\text{all}} \). Starting with minimum-bias 200 GeV \( p + C \), 200 GeV \( p + \text{Au} \) and peripheral 200 \( A \cdot \text{GeV} \) \({}^{16}\text{O} + \text{Au} \) events the synthetic events are created by superimposing two, three, and four of these events. The region between the two lines in Fig. 5 demonstrates the estimated systematic uncertainty of this procedure which is caused by the fact that even peripheral 200 \( A \cdot \text{GeV} \) \({}^{16}\text{O} + \text{Au} \) events do have a mean multiplicity of \( \mu_{\text{all}} = 7 \) and therefore already contain a certain number of overlapping showers which cannot be resolved.

In order to obtain the total \( \gamma \) reconstruction efficiency both probabilities, \( \varepsilon \), \( \kappa \), have to be multiplied and in the case that both quantities are independent of \( p_T \), one may use the product of \( \langle \varepsilon \rangle_{p_T} \), \( \langle \kappa \rangle_{p_T} \).

The total acceptance for assigning both decay photons as resolved neutral particles is calculated by a Monte Carlo simulation taking into account:

i) branching ratio for the decay \( \pi^0 \to 2\gamma \)

ii) \( \pi^0 \) angular distribution from the event generator FRITIOF [12],

iii) a maximum nonlinearity of \( \Delta E/E = 3\% \),

iv) an uncertainty of \( \pm 50 \text{ MeV} \) for the software energy threshold of 500 MeV due to finite energy resolution,

v) the total \( \gamma \) reconstruction efficiency,

vi) a minimum opening angle of 0.95\(^\circ\) necessary to resolve two \( \pi^0 \) decay photons.

Figure 6 shows the total acceptance for peripheral and central 200 \( A \cdot \text{GeV} \) \({}^{16}\text{O} + \text{Au} \) reactions. The magnitude of the errors, which are added quadratically, is displayed as the shaded areas in Fig. 6. The main contribution stems from the uncertainty of the total \( \gamma \) reconstruction efficiency, whereas the nonlinearity and the uncertainty of the energy threshold do have minor influence on the total error. Furthermore, it has been verified that the acceptance is insensitive to the details of the angular distribution used in this calculation. The minimum opening angle for the \( \pi^0 \) decay photons influences the acceptance at \( p_T \geq 4 \text{ GeV}/c \). This effect is responsible for the drop of the acceptance in Fig. 6a).

The reliability of the \( p_T \) dependence of the acceptance calculation has been checked by comparing distributions of the energy asymmetry \( \alpha \):

\[
\alpha = \frac{|E_1 - E_2|}{E_1 + E_2}
\]
Fig. 6. Total acceptance for measuring both decay photons from $\pi^0$ with transverse momentum $p_T$ as neutral resolved particles for a) peripheral and b) central 200 $A\cdot$GeV $^{16}\text{O}+\text{Au}$ reactions. The shaded area represents the total error (description see text).

Fig. 7. Energy asymmetry $x$ for central 200 $A\cdot$GeV $^{16}\text{O}+\text{Au}$ events for two $p_T$ bins (solid circles). For comparison the Monte Carlo results are shown (squares).

from experimental data with those from a Monte Carlo calculation. Here $E_1$, $E_2$ are the energies of the $\pi^0$ decay photons. Figure 7 shows results for central 200 $A\cdot$GeV $^{16}\text{O}+\text{Au}$ reactions. The distributions agree within the statistical errors with the Monte Carlo calculations. Hence it can be concluded from the region above $x \approx 0.5$ that the detector geometry and energy cut is well implemented in the Monte Carlo simulation and from $x$ below 0.2 that the merging of high energetic decay photons does not occur in the $p_T$ region under consideration.

5 Results and discussion

Invariant $\pi^0$ cross section for reactions of p and $^{16}\text{O}$ projectiles with a Au target at 200 $A\cdot$GeV have been obtained as a function of transverse momentum for different trigger conditons. The experimental cross-sections are given in Tables 2-5. In Fig. 8 minimum-bias data for p + Au are compared to charged pion cross sections from Ref. [13]. In the overlap region there is excellent agreement between the different data sets. An exponential which describes the pion $p_T$ distribution below $p_T$
Table 4. Invariant cross-section for central 200 A-GeV $^16$O + Au collisions

<table>
<thead>
<tr>
<th>$p_T$ range (GeV/c)</th>
<th>$E(d^3\sigma/dp^3)$ (mb c$^{-2}$ GeV$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4-0.5</td>
<td>$(3.0 \pm 0.7) \times 10^3$</td>
</tr>
<tr>
<td>0.5-0.6</td>
<td>$(1.0 \pm 0.2) \times 10^4$</td>
</tr>
<tr>
<td>0.6-0.7</td>
<td>$(5.5 \pm 0.7) \times 10^3$</td>
</tr>
<tr>
<td>0.7-0.8</td>
<td>$(3.3 \pm 0.4) \times 10^3$</td>
</tr>
<tr>
<td>0.8-0.9</td>
<td>$(2.0 \pm 0.2) \times 10^3$</td>
</tr>
<tr>
<td>0.9-1.0</td>
<td>$(1.2 \pm 0.1) \times 10^3$</td>
</tr>
<tr>
<td>1.0-1.1</td>
<td>$(7.9 \pm 0.8) \times 10^2$</td>
</tr>
<tr>
<td>1.1-1.2</td>
<td>$(4.8 \pm 0.5) \times 10^2$</td>
</tr>
<tr>
<td>1.2-1.3</td>
<td>$(3.1 \pm 0.3) \times 10^2$</td>
</tr>
<tr>
<td>1.3-1.4</td>
<td>$(1.6 \pm 0.2) \times 10^2$</td>
</tr>
<tr>
<td>1.4-1.5</td>
<td>$(1.0 \pm 0.1) \times 10^2$</td>
</tr>
<tr>
<td>1.5-1.6</td>
<td>$(6.9 \pm 0.9) \times 10^1$</td>
</tr>
<tr>
<td>1.6-1.7</td>
<td>$(5.0 \pm 0.7) \times 10^1$</td>
</tr>
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<td>$(3.8 \pm 0.5) \times 10^1$</td>
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<tr>
<td>1.8-1.9</td>
<td>$(2.5 \pm 0.3) \times 10^1$</td>
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<td>1.9-2.0</td>
<td>$(1.4 \pm 0.2) \times 10^1$</td>
</tr>
<tr>
<td>2.0-2.1</td>
<td>$(9.6 \pm 1.5) \times 10^0$</td>
</tr>
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<td>2.1-2.2</td>
<td>$(6.6 \pm 1.0) \times 10^0$</td>
</tr>
<tr>
<td>2.2-2.3</td>
<td>$(4.5 \pm 0.7) \times 10^0$</td>
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<td>2.5-2.6</td>
<td>$(1.3 \pm 0.3) \times 10^0$</td>
</tr>
<tr>
<td>2.6-2.7</td>
<td>$(6.5 \pm 0.3) \times 10^{-1}$</td>
</tr>
<tr>
<td>2.7-2.8</td>
<td>$(5.3 \pm 2.3) \times 10^{-1}$</td>
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<tr>
<td>2.8-3.0</td>
<td>$(3.6 \pm 1.3) \times 10^{-1}$</td>
</tr>
<tr>
<td>3.0-3.2</td>
<td>$(1.7 \pm 0.8) \times 10^{-1}$</td>
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<tr>
<td>3.2-3.6</td>
<td>$(4.6 \pm 2.7) \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Table 5. Invariant cross-section for peripheral 200 A-GeV $^16$O + Au collisions

<table>
<thead>
<tr>
<th>$p_T$ range (GeV/c)</th>
<th>$E(d^3\sigma/dp^3)$ (mb c$^{-2}$ GeV$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4-0.5</td>
<td>$(6.1 \pm 1.5) \times 10^3$</td>
</tr>
<tr>
<td>0.5-0.6</td>
<td>$(3.0 \pm 0.5) \times 10^3$</td>
</tr>
<tr>
<td>0.6-0.7</td>
<td>$(1.4 \pm 0.2) \times 10^3$</td>
</tr>
<tr>
<td>0.7-0.8</td>
<td>$(9.7 \pm 1.0) \times 10^2$</td>
</tr>
<tr>
<td>0.8-0.9</td>
<td>$(5.8 \pm 0.6) \times 10^2$</td>
</tr>
<tr>
<td>0.9-1.0</td>
<td>$(3.0 \pm 0.3) \times 10^2$</td>
</tr>
<tr>
<td>1.0-1.1</td>
<td>$(1.6 \pm 0.2) \times 10^2$</td>
</tr>
<tr>
<td>1.1-1.2</td>
<td>$(1.3 \pm 0.1) \times 10^2$</td>
</tr>
<tr>
<td>1.2-1.3</td>
<td>$(7.9 \pm 1.0) \times 10^1$</td>
</tr>
<tr>
<td>1.3-1.4</td>
<td>$(3.8 \pm 0.5) \times 10^1$</td>
</tr>
<tr>
<td>1.4-1.5</td>
<td>$(2.1 \pm 0.3) \times 10^1$</td>
</tr>
<tr>
<td>1.5-1.6</td>
<td>$(1.3 \pm 0.2) \times 10^1$</td>
</tr>
<tr>
<td>1.6-1.7</td>
<td>$(6.6 \pm 1.3) \times 10^0$</td>
</tr>
<tr>
<td>1.7-1.8</td>
<td>$(4.8 \pm 1.0) \times 10^0$</td>
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<td>1.8-1.9</td>
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<td>1.9-2.0</td>
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<td>2.0-2.2</td>
<td>$(1.1 \pm 0.2) \times 10^0$</td>
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<td>2.2-2.4</td>
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<td>2.4-2.6</td>
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<tr>
<td>2.6-2.8</td>
<td>$(1.0 \pm 0.2) \times 10^{-1}$</td>
</tr>
</tbody>
</table>

$\approx 1$ GeV/c for p+p events is normalized to the $\pi^0$ data at $p_T = 500$ MeV/c. The deviation between the experimental data and the exponential starting at about $p_T \approx 1.8$ GeV/c has been ascribed to hard scattering phenomena [14]. More insight into the particular mechanism of heavy-ion reactions at high energy can be gained by comparing central and peripheral $^16$O + Au collisions with lighter systems. Collective effects or the formation of new states of nuclear matter are expected primarily in very central collisions. Data of peripheral collisions may provide, on the other hand, a link to p+ nucleus and p+p reactions.

In Fig. 9 invariant $\pi^0$ cross sections are plotted for minimum-bias events and in Fig. 10 for central and peripheral 200 A-GeV $^16$O + Au events. Attempts to fit the cross sections with a function consisting out of two thermal distributions do not give reliable results, i.e. the two temperatures depend on the relative normalization of the two thermal distributions and tend to be sensitive to statistical fluctuations [11]. Following a suggestion by Hagedorn [15], the $E^3\sigma/dp^3$-spectra are parameterized by the following expression:

$$E^3\sigma/dp^3 = \begin{cases} A \exp(-m_T/T) & \text{for } p_T \leq 800.\text{MeV/c} \\ C \left(\frac{p_0}{p_T + p_0}\right)^n & \text{for } p_T \geq 800.\text{MeV/c} \end{cases}$$

where $A$, $T$, $C$, $p_0$, and $n$ are parameters and $m_T$ is the transverse mass ($m_T = \sqrt{p_T^2 + m^2}$). The first expression is an approximation to a thermal distribution; the second is an empirical formula, inspired by QCD. The requirement that in both expressions the values and the slopes match at $p_T = 0.8$ GeV/c leaves three free parameters, e.g. $A$, $T$, and $n$. The fit results are given in Table 6 and also shown in Figs. 9 and 10. Variations are found for the parameter $n$ in Table 6, indicating that the spectra show different behaviours in the $p_T$ range above 0.8 GeV/c. However, as already mentioned in [15], the parameters $p_0$ and $n$ are highly correlated and hence no obvious interpretation can be given for $n$. Neverthe-
Fig. 9. Invariant $\pi^0$ cross sections from minimum-bias collisions of $p$ (squares) and $^{16}$O (triangles) projectiles with an Au target at 200 A·GeV measured in the pseudorapidity range $1.5 \leq \eta \leq 2.1$. The lines represent fits to the data with (7) and parameters of Table 6.

Table 6. Parameters obtained from fitting (7) to the experimental data shown in Figs. 9 and 10. NDF is the abbreviation for the number of degrees of freedom.

<table>
<thead>
<tr>
<th>System</th>
<th>$A$ (mb·c·GeV$^{-2}$)</th>
<th>$T$ (MeV/c)</th>
<th>$n$</th>
<th>$\chi^2$/NDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 GeV p+Au</td>
<td>(1.3 ± 0.5) $\times$ 10$^4$</td>
<td>180 ± 16</td>
<td>37.6 ± 3.9</td>
<td>9.0/17</td>
</tr>
<tr>
<td>200 A·GeV O+Au</td>
<td>(3.6 ± 1.3) $\times$ 10$^5$</td>
<td>184 ± 14</td>
<td>25.9 ± 2.4</td>
<td>17.8/27</td>
</tr>
<tr>
<td>Minimum-bias</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peripheral</td>
<td>(6.6 ± 2.9) $\times$ 10$^4$</td>
<td>174 ± 18</td>
<td>16.8 ± 1.9</td>
<td>40.2/17</td>
</tr>
<tr>
<td>Central</td>
<td>(1.7 ± 0.8) $\times$ 10$^5$</td>
<td>194 ± 22</td>
<td>26.0 ± 3.1</td>
<td>14.3/24</td>
</tr>
</tbody>
</table>

less, for the parameter $T$ no significant change for the different data sets is observed. As $T$ also determines the mean transverse momentum this finding is consistent with results from [16], where nearly no variation of the mean transverse momentum for charged pions as a function of centrality and for different systems is found.

The difference between the $^{16}$O+Au and p+Au spectra is more clearly displayed by plotting the ratios of the spectra (Fig. 11). A similar representation has previously been used by Cronin et al. [13] to discuss the nuclear enhancement of p+nucleus compared to p+p data. In that work, a scaling of the minimum-bias cross section ratios with $A_{\text{target}}$ and a rise of $z$ with $p_T$ was observed for charged pions in the range 0.8 GeV/c $\leq p_T$. 

Fig. 10. Invariant $\pi^0$ cross sections from central (circles) and peripheral (squares) collisions of $^{16}$O projectiles with an Au target at 200 A·GeV measured in the pseudorapidity range $1.5 \leq \eta \leq 2.1$. The lines represent fits to the data with (7) and parameters of Table 6.

Fig. 11. Ratio of the $\pi^0$ spectra from central (squares) and peripheral (circles) $^{16}$O+Au collisions normalized to the $\pi^0 p_T$ spectra from minimum-bias p+Au events.

Fig. 12. Comparison of peripheral-collision $\pi^0$ spectra (circles) from the present $^{16}$O+Au experiment at $\sqrt{s_{NN}} = 19.4$ GeV with charged-pion spectra from minimum-bias p+p data (triangles) at $\sqrt{s_{NN}} = 23$ GeV [17]. (n$^-$ and n$^+$ data are averaged and plotted as a single set of data points which are scaled by a factor 100.)
Fig. 13. Ratio of the $\pi^0$ $p_T$ spectra from central (squares) and peripheral (circles) $^{16}\text{O} + \text{Au}$ collisions normalized to the $\pi^0$ spectrum from minimum-bias $p + p$ events [17].

$\leq 5 \text{ GeV/c}$. A similar enhancement, which can be attributed to different projectile masses, is seen in going from $p + \text{Au}$ to central $^{16}\text{O} + \text{Au}$ reactions, whereas the $\pi^0$ production from peripheral $^{16}\text{O} + \text{Au}$ reactions is very similar in shape to the $\pi^0$ production from $p + \text{Au}$ events. Fig. 12 shows a comparison of the peripheral-collision $\pi^0$ spectrum from $^{16}\text{O} + \text{Au}$ at 200 $A\cdot GeV$ ($|s_{NN}| \approx 19.4 \text{ GeV}$) with charged-pion spectrum from inclusive $p + p$ at $\sqrt{s_{NN}} = 23 \text{ GeV}$ [17]. There is a remarkable agreement in the spectral slope of the data up to the highest $p_T$ of the present experiment. As mentioned before, the flattening in the $p + p$ data beyond $p_T \approx 1.8 \text{ GeV/c}$ has been interpreted as the onset of hard QCD scattering, which becomes important for $p_T$ values of several GeV/c (see Fig. 8). The similarity of the pion cross sections from peripheral $^{16}\text{O} + \text{Au}$ and $p + p$ reactions and the difference between the $\pi$ spectrum from central $^{16}\text{O} + \text{Au}$ and $p + p$ events is even more pronounced by calculating ratios of the $\pi$ spectra (Fig. 13). As the charged pion spectra from $^{16}\text{O} + \text{Au}$ are binned differently than our $\pi^0$ cross sections, the $\pi^0$ data are fitted over the entire $p_T$ range with the second function from (7) and then used to obtain Fig. 13. The ratio with central $^{16}\text{O} + \text{Au}$ data increases with $p_T$ up to $p_T \approx 1.8 \text{ GeV/c}$ and becomes flat or even decreases at higher transverse momenta. The ratio is roughly constant for peripheral data. Therefore, it appears that the hard-scattering component of the elementary $p + p$ interaction survives in peripheral heavy-ion collisions, but in the present $p_T$ range it is strongly obscured by nuclear effects in central collisions. Forthcoming experiments in an extended $p_T$ range are expected to reveal whether the hard component emerges in central collisions at higher $p_T$ values.

The pattern of Fig. 13 is rather similar to results from pion measurements in $p + p$ and $\pi + \pi$ experiments at $\sqrt{s_{NN}} = 63 \text{ GeV}$ and $\sqrt{s_{NN}} = 31.2 \text{ GeV}$, respectively [14, 18, 19]. In these experiments a selection of the data was made according to their associated charged-particle multiplicities [14, 18], which corresponds to a certain energy in the ZDC in our experiment. Ratios between pion cross sections from events with high charged-particle multiplicities to those with low multiplicities show an increase by a factor of $\approx 2$ when going from $p_T \approx 0.5 \text{ GeV/c}$ to $p_T \approx 2 \text{ GeV/c}$, which is also observed in our data. The comparison between $\pi$ spectra from $\pi + \pi$ and $p + p$ events, which also means a comparison of events with different charged-particle multiplicities, shows the same behaviour below $p_T \approx 2 \text{ GeV/c}$ as mentioned before. At higher $p_T$ values a flattening similar to that of Fig. 13 is found [19].

The observed similarity suggests a common underlining mechanism in $p + p$, $\pi + \pi$ and heavy-ion collisions, which causes the characteristic behaviour in different $p_T$ regions. Especially the flattening above $p_T \approx 2 \text{ GeV/c}$ is interpreted in the framework of multiple-scattering of quarks and gluons [20]. For the $p_T$ region $< 2 \text{ GeV/c}$ several attempts have been made within hydrodynamical and thermodinamical models [21, 22] to describe the development of a hot and dense reaction zone and its connection to measured $p_T$ spectra. In [23] a hydrodynamical model with isentropic expansion of a fireball and a certain freeze-out criterion is applied to our data. The low and intermediate part of the $p_T$ spectrum is well described in this model with an initial energy density of 1.5-2 GeV/fm$^3$. However, the high $p_T$ component in the peripheral-collision data is not described, indicating again that it may be due to hard scattering processes. In thermodynamical descriptions [24, 25], where the slopes of the $p_T$ spectra are considered to be measures of the reaction temperature, different $p_T$ regions and slopes are related to the breakup of substructures or to different scattering mechanisms. In the $p_T$ region above 2 GeV/c, where hard QCD processes become increasingly important, the influence in the entrance channel may be studied by extending the comparison of $p + p$ with heavy-ion data to multiplicity selected spectra covering a large $p_T$ range.

6 Summary

Transverse momentum distributions of $\pi^0$ have been measured for 200 $A\cdot GeV$ $p$- and $^{16}\text{O}$-induced reactions in the pseudorapidity range $1.5 \leq \eta \leq 2.1$. Centrality selection has been achieved by applying different cuts in the energy of the zero degree calorimeter (ZDC). The invariant $\pi^0$ cross sections have been fitted by a formula proposed by Hagedorn. In this model a temperature of $\approx 180 \text{ MeV/c}$ is observed in the low $p_T$ region for all spectra, indicating that the mean transverse momentum is rather constant as a function of the reaction centrality and of the projectile mass. Significant differences in the shape of the $\pi^0$ $p_T$ distributions between central- and peripheral-$^{16}\text{O} + \text{Au}$ reactions have been observed. The variation is similar to the variation of charged pion $p_T$ distributions from $p + p$ and $\pi + \pi$ reactions at ISR energies. It is found that over the complete $p_T$ range, the shape of the $\pi^0$ $p_T$ distribution for peripheral events follows very closely the pion spectra from inclusive $p + p$ collisions. A striking feature of the present $^{16}\text{O} + \text{Au}$ data
is that the onset of the hard-scattering component ($p_T > 1.8$ GeV/c) is not observed in the data for central collisions.

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**References**