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Thomas Peitzmann for the WA98 collaboration

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First results from the WA98 experiment on 33 TeV ^{208}Pb ion reactions with various targets measured at the CERN SPS are presented. Data on transverse energy production and particle multiplicity are discussed. Special emphasis is laid on photon and neutral meson production.

1. Experimental Setup and Physics Goals

The WA98 experiment [1] consists of large acceptance hadron and photon spectrometers. It allows to study a variety of observables in heavy-ion reactions via inclusive distributions and also event-by-event. It is unique in its capabilities to measure photons and neutral mesons in these reactions.

The experimental setup as implemented in 1995 is shown in fig. 1¹. It includes a magnetic spectrometer for negative particles consisting of the GOLIATH magnet, six multistep avalanche chambers for tracking and a time-of-flight wall, which is discussed in detail in [2].

Figure 1. The WA98 experimental setup.

¹The Charged Particle Veto Detector was still under construction in 1995.

The plastic ball detector consists of 655 $\Delta E-E$ modules arranged in a sphere around the target, which allow to measure charged particles and identify π^+ s and light ions in the target rapidity region. Charged particle multiplicities are measured by a combination of a silicon drift detector and a silicon pad multiplicity detector (*SPMD*) located 12.5 and 30 cm away from the target, respectively. The *SPMD* is based on a double metal, AC coupled design consisting of approximately 4000 pads, arranged radially in 180 ϕ -bins and 22 equal η -bins between $\eta = 2.35$ and 3.75. Photon multiplicities are measured in the range of $2.4 \leq \eta \leq 4.4$ by a highly granular photon multiplicity detector (*PMD*) employing a lead converter and 54000 scintillator pads. Further downstream, the midrapidity calorimeter (*MIRAC*) [3] measures the transverse energy in the forward region $3.0 \leq \eta \leq 5.2$, and the zero-degree calorimeter (*ZDC*) measures the forward energy. These two provide global event characterization which determines the centrality of the collision.

Photon and neutral hadron spectroscopy is accomplished by a 10,000 module lead glass detector array (*LEDA*). Each module is made up of a $4 \times 4 \times 40$ cm³ lead glass block with photomultiplier tube readout. HV to each phototube is provided by newly developed active bases [4] controlled with a VME based system. The detector is equipped with an improved gain monitoring system based on LEDs monitored by PIN-photodiodes [5] and with a new readout system including ADCs, TDCs and trigger circuits [6].

The experiment has been successfully operated in the 1995 Pb-ion beam time at the CERN SPS. The different event triggers were defined by the transverse energy detected in *MIRAC*. For collisions of $^{208}\text{Pb}+\text{Pb}$, ca. 8 Mio. central ($\approx 10\%$ of the min. bias cross section), 8 Mio. peripheral ($\approx 20\%$) and 4 Mio. events of intermediate centrality have been taken. In addition, approximately 1 Mio. events each were measured for Nb and Ni targets.

The WA98 experiment has been designed to measure and correlate different observables in different classes of events. Its strength lies in photon detection both via the *PMD* and the spectrometer *LEDA*. We will therefore search for signatures of a phase transition in these observables, namely

- direct photon production as a measure of initial temperature and
- isospin fluctuations as a signal for disoriented chiral condensates.

From current theoretical knowledge and experimental limitations however none of the proposed QGP signals is unambiguous by themselves. It is therefore of utmost importance to study and understand other observables in the same event samples and possibly event-by-event.

The WA98 experiment has the capability to study global observables, event shape, charged particle inclusive spectra and correlation functions simultaneously with photon and neutral hadron production. In addition also peripheral $^{208}\text{Pb}+\text{Pb}$ reactions and p-induced reactions are studied with the same apparatus to provide reference measurements. In this way we hope to obtain more conclusive information about the possibility of a phase transition in these reactions. This ambitious goal is, however, not yet reached in the analysis of $^{208}\text{Pb}+\text{Pb}$ collisions, as very detailed studies of systematic errors have to be performed.

In this paper we will concentrate on first results concerning transverse energy and charged particle multiplicity measurements and inclusive photon and neutral pion pro-

Figure 2. a) Transverse energy distributions measured in MIRAC for 158 AGeV ^{208}Pb ions on different targets. b) $dE_T/d\eta$ from very central $^{208}\text{Pb}+\text{Pb}$ collisions compared to NA49 measurements.

duction. Results on charged particle spectra and correlations are discussed in [2]. The analysis presented here is based on less than 10% of the total data sample of the 1995 beam time.

2. Transverse Energy

Transverse energy distributions for reactions of ^{208}Pb projectiles with different targets are shown in figure 2. On the left hand side (a) one can see the typical distributions governed by reaction geometry. The total E_T measured in MIRAC reaches values close 600 GeV for the most central $^{208}\text{Pb}+\text{Pb}$ collisions. In figure 2b the $dE_T/d\eta$ distribution is displayed and compared to NA49 data - one can see that there is good agreement in the region of overlap. For this comparison we have applied a similar event selection based on the forward energy as NA49. The acceptance of MIRAC extends very close to midrapidity which makes it reasonable to extract values of $dE_T/d\eta|_{max}$ assuming a Gaussian shape of the distribution. These maximum values for central reactions (10% of the minimum bias cross section) for ^{208}Pb projectiles on Ni, Nb and Pb targets are displayed in figure 3 as a function of the average number of participants calculated from the forward energy. Included are dashed lines for the scaling laws obtained by WA80 for ^{16}O and ^{32}S induced reactions at 60 and 200 AGeV. It can be seen that the present data follow nicely the scaling law for 200 AGeV, i.e. a production of a transverse energy of 0.9 GeV/participant at midrapidity. In addition very central reactions (2%) of $^{208}\text{Pb}+\text{Pb}$

Figure 3. Maximum of $dE_T/d\eta$ for different reactions as a function of the number of participants. The dashed lines show scaling laws obtained by WA80 for ^{16}O and ^{32}S induced reactions.

are also shown. Interestingly, the value extracted for these is significantly higher than predicted by the above scaling.

Table 1
Björken estimates of energy density.

system	$\epsilon(\text{GeV}/\text{fm}^3)$
Pb+Ni central	2.6
Pb+Nb central	2.5
Pb+Pb central 10%	2.0
Pb+Pb very central 2%	2.5
S+Au central	≈ 2
S+Au very central	2.9

Energy densities can be calculated from $dE_T/d\eta|_{\max}$ with the help of the Björken formula. Values obtained in WA98 are summarized in table 1. Energy density estimates from WA80 for $^{32}\text{S}+\text{Au}$ reactions are included. It can be seen that the average central $^{208}\text{Pb}+\text{Pb}$ collision has a lower volume averaged energy density than reactions with lighter targets. This can be understood from the lower area density of participating nucleons because of the larger contribution of the fringe of the Pb nucleus. Still very central collisions yield a higher density comparable to that of the lighter targets. Here one should keep in mind that the core densities in these reactions should be significantly higher.

3. Photon and Neutral Pion Production

In the lead glass calorimeter LEDA photons are identified with the help of the lateral dispersion of the showers. For this analysis only showers with $E > 750$ MeV are considered - this cut ensures a good photon identification. The photon multiplicity distributions were analysed for different samples selected via their charged particle multiplicity measured in the SPMD. The distribution can be very well described by Gaussians. Figure 4 shows the mean values (a) and the widths (b) as a function of the charged multiplicity. There is a natural increase of the average photon multiplicity with the charged multiplicity. Also the width increases following approximately a square root dependence. The absolute values however are slightly higher than expected from pure Poissonian fluctuations. The origin of these fluctuations has to be investigated by comparison to reasonable Monte-Carlo calculations.

Figure 4. a) Average photon multiplicities as a function of the charged multiplicity measured with the SPMD. b) Width of the photon multiplicity distribution as a function of the charged multiplicity measured with the SPMD. The photon multiplicities are not corrected for detection efficiency.

The photon spectrometer also allows to study the momentum distribution of inclusive photons. Examples are displayed in figure 5, which shows transverse momentum spectra for central and peripheral reactions of $^{208}\text{Pb}+\text{Pb}$. A comparison with exponential fits shows clearly that these spectra cannot be described by a single exponential. A comparison of the different centralities in a model independent way can most easily be done via the ratio of the two distributions which is shown in the inset in the same figure. Evidently the spectrum for central reactions is flatter than for peripheral ones. However, the ratio starts to level off again beyond 1.5 GeV/c, indicating that a flatter component sets in for the peripheral reactions at this point. Included in figure 5 are results of a calculation using VENUS 4.12 [7] - this spectrum is normalized to the data at $p_T = 500$ MeV/c. While the VENUS simulation describes the shape of the experimental distribution reasonably well in the intermediate p_T range, there is a clear discrepancy for higher transverse momenta. One should note that the VENUS sample is of slightly higher centrality than the

experimental data, which should however only have a small effect on the shape of the spectra.

Figure 5. Photon transverse momentum distributions as measured with LEDA for central (open circles) and peripheral (open squares) $^{208}\text{Pb}+\text{Pb}$ reactions. The filled triangles show results of the event generator VENUS 4.12. The inset shows the ratio of central and peripheral data. Data are not corrected for efficiency.

The photon spectrometer has a reasonably large acceptance so that observables related to the photons can be studied event-by-event. As a first attempt in this direction we have studied the mean transverse momentum for photons with $p_T > 180 \text{ MeV}/c$. (This cut is roughly equivalent to the energy cut used above, but is more appropriate for a study involving transverse momenta.) We can then look at the distribution of these event-by-event mean- p_T values for central collisions – this is displayed in figure 6a.

Figure 6. Distribution of truncated average transverse momentum of photons measured event-by-event in central $^{208}\text{Pb}+\text{Pb}$ collisions. The left hand side shows the data, while on the right hand side a distribution obtained from a simple simulation (see text) is displayed.

The slightly asymmetric distribution has a mean value of ≈ 190 MeV/c and an RMS value of ≈ 36 MeV/c. It is interesting to compare this with a simple toy model simulation. We have generated artificial events containing photons emitted independently according to the measured multiplicity and single particle distributions, i.e. these events are made up of completely uncorrelated photons. The result of this simulation is displayed in figure 6b. It matches the experimental distribution surprisingly well. While these distributions will be studied more carefully with realistic simulations, we can note that, on the level of this analysis, the variations in the mean transverse momentum from one central reaction to the other are largely explained by statistical fluctuations.

Still the large statistics of the WA98 measurements allows to implement more drastic cuts to investigate extreme samples and look for interesting new physics. In this early stage of the analysis we can just show an example of such a study: In figure 7 inclusive photon p_T distributions for three different samples selected for their photon multiplicity N_γ are displayed. The two spectra for events with $N_\gamma = 40 - 59$ and $N_\gamma = 60 - 79$ are very similar and agree to the spectrum for the average central events. The spectrum for $N_\gamma \geq 80$ however appears to be much flatter. This can also be seen from inverse slopes obtained by exponential fits in the region $0.6 \text{ GeV/c} \leq p_T \leq 2.2 \text{ GeV/c}$. While the slope for the very high multiplicity sample is about 200 MeV/c, those for the other samples are 186-188 MeV/c.

As the extreme sample studied here is of very limited statistics (the selection corresponds to ca. 0.3% of the minimum bias cross section), a more detailed investigation of

Figure 7. Transverse momentum distributions of photons for different reactions of $^{208}\text{Pb}+\text{Pb}$ selected by their photon multiplicity in LEDA. The lines show exponentials fitted to the intermediate p_T -range.

this phenomenon must await a higher statistics analysis which is under way.

Neutral pions are measured in WA98 via their two-photon decay. The invariant mass of pairs of photons is calculated. The background in the invariant mass distributions is then constructed by an event mixing procedure and can be subtracted. From the peak contents above the background the neutral pion yield can be extracted. Figure 8a shows an example of such an invariant mass distribution.

To obtain a transverse momentum spectrum of π^0 's such distributions are analyzed for each p_T bin. Results of this procedure are displayed in figure 8b. It shows distributions for central and peripheral $^{208}\text{Pb}+\text{Pb}$ collisions together with exponential fits. The yields have been corrected using an extrapolation of the efficiency obtained in WA80 [8]. This should be a good estimate, as the crucial variable, the particle density seen by the detector, is similar. Minor changes, however, may occur once the correct efficiency will be used. Data from WA80 and a VENUS 4.12 prediction are included for comparison. Again the simulation is normalized to the data at $p_T = 500$ MeV/c – the same argument as above applies concerning the centrality.

The spectra cover a large range in transverse momenta up to almost 4 GeV/c already with this limited data sample. One can see that the spectrum for central reactions is flatter

Figure 8. a) Two-photon invariant mass distribution. b) Transverse momentum distributions of neutral pions for central (open circles) and peripheral (open squares) $^{208}\text{Pb}+\text{Pb}$ reactions. The filled triangles show results of the event generator VENUS 4.12. For comparison also data from WA80 on central $^{32}\text{S}+\text{Au}$ reactions are included (crosses).

than the one for peripherals – it is however not as flat as in the case of central $^{32}\text{S}+\text{Au}$ collisions. The distributions deviate from an exponential shape both in the low and high p_T region. The VENUS distribution shows an excess at higher p_T , similar to the inclusive photon spectra. From exponential fits to the region $0.2\text{GeV}/c \leq p_T \leq 3.2\text{GeV}/c$ one obtains inverse slopes for central and peripheral reactions of 204 MeV/c and 173 MeV/c, respectively.

From the decay kinematics the neutral pion detection has a limited acceptance at low transverse momenta – this makes the measurement very difficult in the low p_T region. Nevertheless we make an attempt to estimate the integrated neutral pion yield by extrapolating the spectral shape down to $p_T = 0$. For this purpose a pure exponential in p_T is not adequate – here we use a Bessel function to describe the distributions:

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto m_T \cdot K_1 \left(\frac{m_T}{T} \right).$$

This function describes the spectrum for central reactions below $p_T = 1.5\text{GeV}/c$ reasonably well with a slope parameter of $T = 155\text{MeV}$. This function has been fitted to p_T

Figure 9. a) Neutral pion rapidity distributions (open circles) obtained by extrapolation of the measured p_T -spectra to low p_T . VENUS 4.12 predictions are included. b) Examples of the low p_T extrapolation with a Bessel function (top: $y = 2.65$, bottom: $y = 2.75$).

spectra for different bins in rapidity – examples of such fits are displayed in figure 9b. The integrated yields are then shown in figure 9a. For comparison VENUS 4.12 results are included. The rapidity density of neutral pions from this estimate is $\approx 165 \pm 20$. The VENUS prediction is slightly higher, which can however be attributed to the different centrality selection discussed above.

To perform a more quantitative comparison we have therefore followed a different approach. We use the charged particle multiplicity measured with the SPMD in the same event sample. In figure 10a the SPMD measurement is shown compared to the VENUS calculation for charged particles. In this case the event selection of the experimental data has been matched more closely to the simulation (i.e. 7.5% central). One can see that the magnitude of the charged particle density at midrapidity is well described by VENUS. However, the shape of the distributions is significantly different. The experimental data are compatible with a completely flat distribution while the VENUS results show indications of a Gaussian-like shape.

The neutral pion rapidity density can then be directly compared to the charged particle pseudorapidity density measured by the SPMD for the 10% central sample. This has been done in figure 10b: The charged particle density ($\approx 15\%$ lower than in a) is displayed together with twice the number of π^0 s. The slightly higher density of charged particles ($\approx 400 \pm 20$) is in line with the additional contribution of charged particles other than pions. If we assume a similar behaviour of charged and neutral pions, we are left with $\approx 70 \pm 28$ surplus charged particles which is consistent with ≈ 35 protons

Figure 10. a) Pseudorapidity distributions for charged particles measured with the SPMD compared to VENUS 4.12 for the 7.5% most central reactions of $^{208}\text{Pb}+\text{Pb}$. b) Pseudorapidity distributions for charged particles measured with the SPMD compared to twice the rapidity density of neutral pions (see fig. 9) for the 10% most central reactions of $^{208}\text{Pb}+\text{Pb}$.

[9] and $\langle K^+ + K^- \rangle / \langle \pi^+ + \pi^- \rangle \approx 10\%$. So the total charged particle yield could be explained using charged pion spectra identical to the π^0 , where no low p_T enhancement was taken into account.

Direct photons will be extracted by a similar procedure as performed in the recently published analysis by WA80 [8]. The background of hadron decay photons is calculated from measured π^0 and η distributions. Artificial showers from simulated photons and hadrons (created with the GEANT simulation package [10]) will be added to real heavy-ion events. From the reconstruction of these showers the detection efficiencies and the contamination for realistic particle densities can be obtained. Currently our detector simulation is being adapted for this task.

Compared to WA80 we hope to improve our accuracy by higher statistics of the measurement, which should especially allow to calculate more precisely the η -contribution to the hadron decay photons, and by an improved knowledge of the detector properties. For this purpose extensive studies including e.g. the tracking of Cherenkov photons in the leadglass are in progress.

4. Summary

- Transverse energies produced in 158 A GeV ^{208}Pb induced collisions exhibit a similar

scaling as $200 \text{ A GeV } ^{16}\text{O}$ and ^{32}S induced reactions. Volume averaged energy densities reach values of $\epsilon = 2.5 \text{ GeV/fm}^3$.

- Photon multiplicity distributions for $^{208}\text{Pb}+\text{Pb}$ indicate slightly larger fluctuations than expected from Poisson statistics.
- Inclusive photon and neutral pion p_T spectra are flatter for central than for peripheral reactions. Inverse slopes are similar to $^{32}\text{S}+\text{Au}$. VENUS 4.12 tends to overpredict the yield in the high p_T region.
- The variations of the event-by-event mean- p_T are largely governed by statistical fluctuations.
- Events of extremely high photon multiplicity in LEDA show indications of a flatter inclusive photon spectrum than average central events.
- The neutral pion production is consistent with the charged particle yield without a drastic low p_T enhancement beyond a Bessel function with $T = 155 \text{ MeV}$.

The general performance of the experiment and especially the photon spectrometer has proven to be very good. This should allow a high accuracy direct photon measurement.

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