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The preliminary results of anisotropic transverse flow will be reported in 158 A GeV Pb + Pb collisions. The centrality dependence of the directed flow has been measured at the target rapidity region. The directed flow of the pions is opposite to that of the protons, where the magnitude of the directed flow of protons seem to be significantly smaller than observed at AGS energies and than RQMD. While, maximum directed flow is observed in more peripheral events. Near mid-rapidity region, the elliptic flow of $\pi^{\pm}$ mesons is studied. The shape of the two-pion correlation function is investigated as a function of the two-particle emission angle relative to the target proton flow. Our preliminary results show an indication of a dependence of the two-pion correlation function on the direction of emission relative to the target flow direction for semi-central collisions.

1. Introduction

In the case of a QCD phase transition from ordinary nuclear matter to quark gluon plasma, it is expected that the equation of state (EOS) should exhibit a softening due to the increase number of degrees of freedom [1–6]. According to the recent theoretical discussion, it is expected that the information about the EOS can be extracted from the study of the collective flow. Especially, studies of flow effects in terms of the azimuthal anisotropy of particle production have been discussed as an unique tool for extracting the information about pressure created at the early stage of the collisions.

At AGS and SPS energies, the observation of directed and elliptic transverse flow has recently been reported [7–12], demonstrating its presence even at higher beam energies than the BEVALAC/SIS energy region [13–15].

In this article, we will report the recent results of the identified hadrons spectra measured by the CERN-WA98 experiment in 158AGeV Pb+Pb collisions, focusing on three topics. First of all, the systematic study of the directed flow for identified protons and π^{+}s will be reported at target rapidity region. Secondly, the dependence of elliptic transverse emission on the particle species near mid-rapidity region will be shown. Thirdly, the study on the shape of the two-pion correlation functions at mid-rapidity will be reported as a function of the azimuthal flow angle in the Plastic Ball. This study allows one to extract the information on the evolution of the hot and dense hadronic matter in the relativistic heavy-ion collisions [18] and possibly contains additional information of flow, which can not be accessed only by the single particle spectra.

2. Analysis and Results

The data presented here were taken with a subset of the full WA98 experiment detector system using the 158 A·GeV ^{208}Pb beams of the CERN-SPS on a ^{208}Pb target of 213 μm thickness. In the WA98 setup the incident Pb beam is defined by a gas Cherenkov start counter with a timing resolution of 30 ps and a veto counter with a 3 mm diameter hole [19]. The centrality of the collision is determined by the total transverse energy, E_T, measured with the mid-rapidity calorimeter (MIRAC) which covers the pseudo-rapidity range of $3.5 < \eta < 5.5$.

One of the key detectors for the present analysis is the Plastic Ball which covers the pseudo-rapidity range of $-1.7 < \eta < 0.5$ with full azimuthal coverage. It identifies pions, protons, deuterons, and tritons with kinetic energies of 50 to 250 MeV by $\Delta E - E$ measurement [20].

The measurement of identified particles near mid-rapidity is performed using two tracking spectrometer arms with a large (1.6 m) aperture dipole magnet (GOLIATH). The particle

identification is based on a measurement of momentum and time-of-flight. Detailed information of the experiment can be found elsewhere [12,16].

2.1. Reaction-Plane Determination

The reaction plane is determined from the azimuthal direction of the total transverse momentum vector of fragments (p, d, and t) detected by the Plastic Ball detector. The azimuthal angle of the reaction plane, Φ_0 is thus determined as

$$\Phi_0 = \tan^{-1}\left(\frac{\sum_{i=1}^{N} p_{Ti}\sin(\phi_i)}{\sum_{i=1}^{N} p_{Ti}\cos(\phi_i)}\right) \quad (1)$$

where the sum runs over all fragments. Here ϕ_i and p_{Ti} are the azimuthal angle in the laboratory coordinate and the transverse momentum of the i-th fragment, respectively. The multiplicity of protons in the Plastic Ball detector is around 8 in semi-central collisions. A minimum of three protons are required for this analysis. The observed Φ_0 distribution has a variation of less than 3% due to the detector biases such as dead channels and inefficiency. In the following flow analysis, we have corrected for this effect by weighting with the inverse of the yield.

In order to study how well the fragment flow direction is defined, we have performed the subevent analysis [12]. As expected, the correlation observed for semi-central events is significantly larger than for very central events.

2.2. Directed Flow

Azimuthal anisotropies of the particle emission are evaluated by means of a Fourier expansion [21,22]. The Fourier coefficients $v_n (n = 1, 2)$ are extracted from the azimuthal distribution of identified particles with respect to the reaction plane;

$$\frac{1}{N}\frac{dN}{d(\phi - \Phi_0)} = 1 + 2v_1'\cos(\phi - \Phi_0) + 2v_2'\cos(2(\phi - \Phi_0)), \quad (2)$$

where ϕ is the measured azimuthal angle with respect to Φ_0. The Fourier coefficient v_1' quantifies the directed flow, whereas v_2' quantifies the elliptic flow. Using the accurate procedure and interpolation formula of Ref. [22] one obtains $\langle\cos(\Phi_0 - \Phi_r)\rangle = 0.377 \pm 0.018$ for the semi-central ($100 < E_T < 200$ GeV) event selection. The dependence of the v_1 fit parameter on centrality, as determined by the measured transverse energy (E_T), is shown in Fig. 1. For convenience an impact parameter scale is also shown. The E_T scale has been converted to an impact parameter scale assuming a monotonic relationship between the two quantities, and equating $d\sigma/dE_T$ with $d\sigma/db$. As seen in Figure 1, the strength of the directed flow of protons increases with centrality and reaches a maximum value for semi-central collisions with $b \approx 8$ fm. It is interesting to note that the strongest flow effect appears at larger impact parameters than observed at lower incident energy for similar systems (where $b \approx 4$ fm) [8,17]. For comparison, RQMD 2.3 [6] model predictions are shown subjected to the same analysis after applying the Plastic Ball detector acceptance, but using the true reaction plane. RQMD predicts a significantly stronger correlation for protons than observed.

Also shown in Fig. 1 is the strength of the directed flow of π^+, identified in the Plastic Ball. A clear anti-correlation, or anti-flow [23], is observed between the fragment and π^- flow directions. This behavior has been observed at incident energies from 1 A GeV to SPS energies and has been explained as resulting from preferential absorption of the pions emitted in the target spectator direction [8,23-25]. The absorption results in an oppositely directed apparent

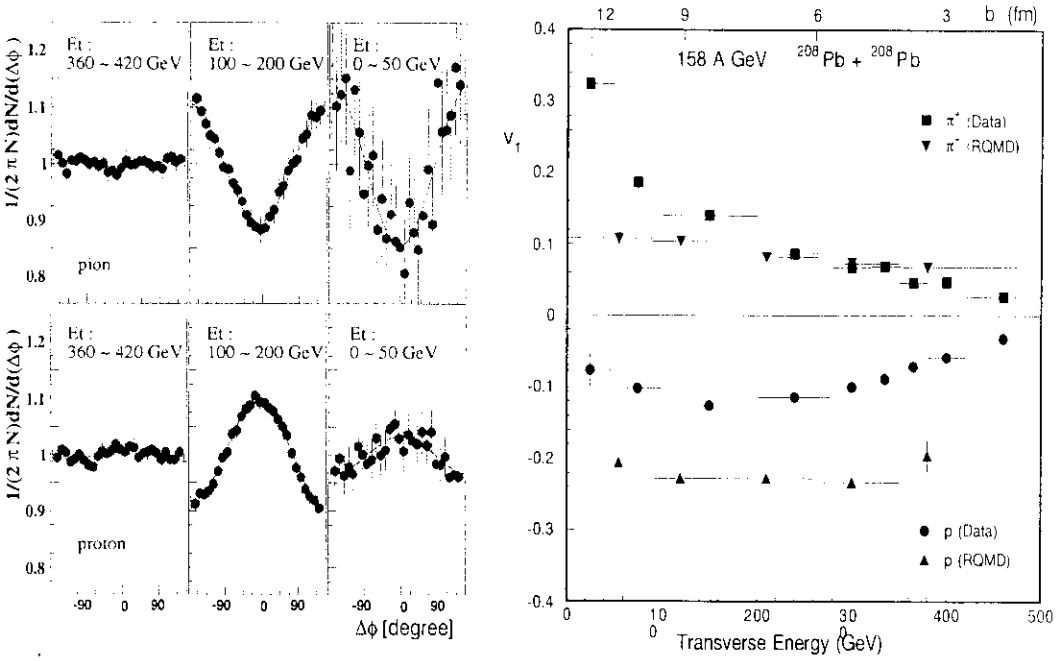

Figure 1. left: Azimuthal angle distributions with respect to the Φ_0 for identified pions and protons in various centrality regions. right: The centrality dependence of the directed flow coefficient v_1 for protons (circles) and π^+ (squares). Triangles are results from RQMD model calculations. The data have been corrected for the event-plane resolution. The vertical bars indicate the uncertainty of the fit and resolution correction. The horizontal bars indicate the E_T bin intervals (or impact parameter intervals for RQMD).

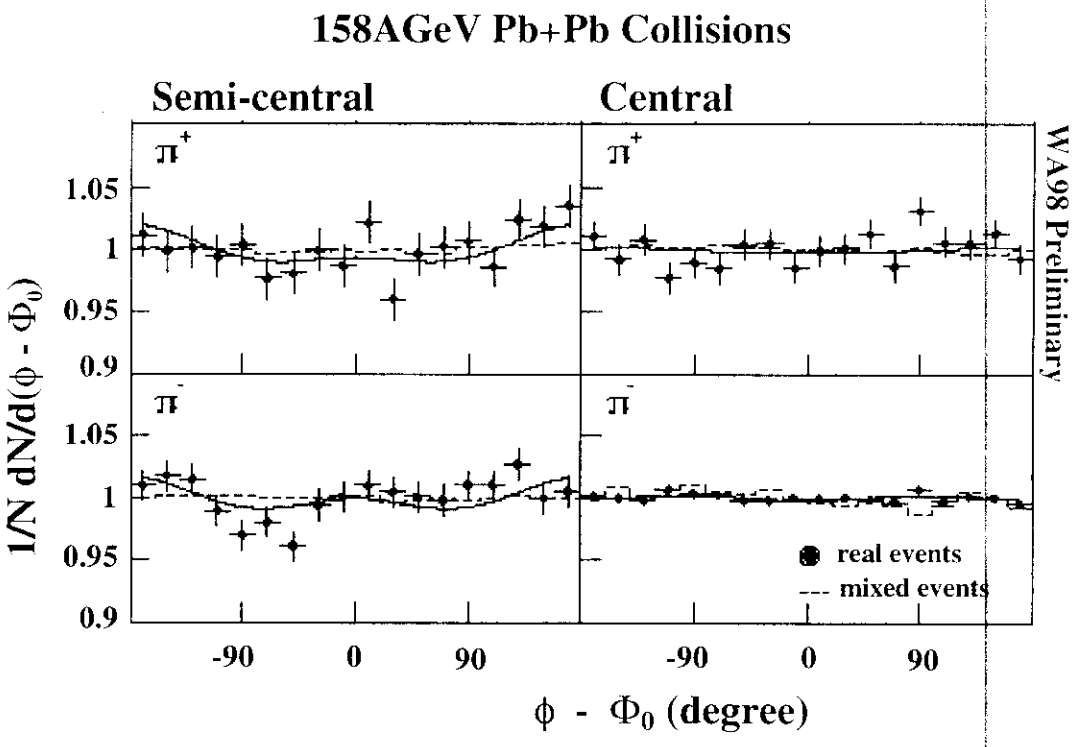

Figure 2. The azimuthal distributions of π^+ and π^- mesons with respect to the reaction plane for semi-central and central 158 A·GeV ^{208}Pb + ^{208}Pb collisions. The solid curves show the fits using Eq.(1.2). Solid circles show the results for real events. Dashed histograms show the mixed event results.

π^+ flow. The strength of the anti-correlation increases for the most peripheral events, indicating the increasing role of absorption.

Fig. 2 shows the azimuthal distributions of π^+ and π^- mesons with respect to the reaction plane for semi-central ($50 < E_T < 250$ GeV in MIRAC) and central ($320 < E_T < 500$ GeV) Pb+Pb collisions. In semi-central collisions, a $\cos(2(\phi - \Phi_0))$ component, namely elliptic flow, could be visible for $\pi^\pm$, while in central collisions, the distributions have less structure as expected from the azimuthal symmetry of the collision. For $\pi^\pm$ mesons in semi-central collisions, the azimuthal distributions exhibit maxima at $\phi - \Phi_0 = 0^o$ and $\phi - \Phi_0 = \pm 180^o$, which indicates an enhanced emission in the reaction plane. The azimuthal distributions for the mixed-events are flat which indicates that the observed anisotropies are not due to detector effects.

The values have been corrected for the reaction plane resolution as described above. At SPS energy, results from NA49 [11] have shown that protons and pions exhibit in-plane emission near mid-rapidity. Our $\pi^\pm$ data agree with the NA49 results within errors. The RQMD calculation agrees with the measured results for $\pi^\pm$.

Particle	y	p_T (GeV/c)	v_1	v_2
π^+	$2.4 \sim 3.6$	$0.0 \sim 1.0$	-0.015 $\pm$ 0.009	0.044 $\pm$ 0.037
π^-	$2.0 \sim 3.2$	$0.05 \sim 1.0$	-0.015 $\pm$ 0.006	0.054 $\pm$ 0.028

Table 1
Results of the fit to the azimuthal distributions of π^+ and π^- mesons with respect to the reaction plane for semi-central 158 A·GeV ^{208}Pb + ^{208}Pb collisions. The values are integrated over the indicated y and p_T ranges. The v_1 and v_2 values are corrected for the experimental resolution of the reaction plane determination. The statistical fit errors are given.

Centrality	E_t	λ	R_t
Centrality I	50-290 GeV	0.43±0.03	4.0±0.3
Centrality II	290-340 GeV	0.43±0.04	4.4±0.4
Centrality III	340-500 GeV	0.46±0.02	5.0±0.2

Table 2
Centrality dependence of the pion source parameters R_t and λ.

2.3. Two-Particle Correlation

The correlation function as a function of the relative momentum of pion pairs on the transverse plane Q_t is studied near mid-rapidity region with an increased data sample [12]. The data is analyzed in the "Longitudinal Center-of-Mass System" (LCMS). Correction for the finite momentum resolution has not been applied in this analysis yet. The source parameters are extracted by fitting the corrected correlation function $C_2^{corr}(q)$ with a Gaussian distribution formula, where Q_l is required to be below 20MeV/c. Figure 3 shows the centrality dependence of the correlation function for identified pions. The preliminary results show larger transverse source size parameter R_t in central collisions compare to the semi-central collisions. The tendency of this results is consistent with the source distribution based on a simple geometrical model.

The azimuthal angle dependence of the shape of the two-particle correlation function is performed with respect to the direction of the proton flow measured at target rapidity. The transverse momentum in the x component (px) is enhanced by limiting the azimuthal acceptance ϕ^{par} of ARM2 from -60° to 60° ($\mid px \mid > \mid py \mid$). In this analysis, the azimuthal flow angle Φ_0 is categorized into three types of events, $in-plane$ events, and $out-of-plane$ events to have less biases and higher statistics of pairs. Fig. 4 (left) shows the experimental two-pion correlation functions as a function of Q_t for the event types, $in-plane$ and $out-of-plane$. Statistical errors are presented in this figure. The data correspond to the semi-central part of the reaction cross section, ($50GeV < Et < 290GeV$). Event mixing is carefully applied by taking the same event samples in each event type. One of the interesting results is that the shape of the correlation function might depend on the direction of the emitted particle relative to the reaction plane. The fitted results show larger source size parameter R_t and λ parameter for the $in-plane$ events and relatively smaller R_t and λ for the $out-of-plane$ events in semi-central collisions. Fig. 4(right) shows the two-pion correlation functions for the most

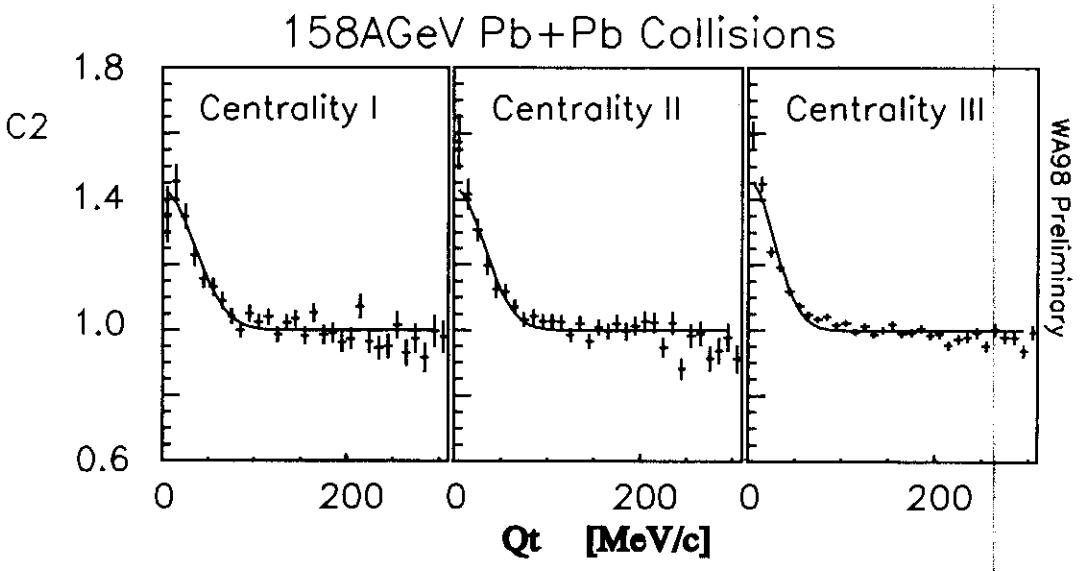

Figure 3. The centrality dependence of the two-pion correlation function in Pb+Pb collisions. Only statistical error is presented. The extracted source parameter R_t increases with the centrality.

Centrality	E_t	Reaction Plane	λ	R_t
Semi-Central	(a) 50-290 GeV	In-Plane	0.61±0.09	5.6±0.6
	(b) 50-290 GeV	Out-of-Plane	0.39±0.05	3.6±0.4
Central	(a) 340-500 GeV	In-Plane	0.42±0.03	5.1±0.3
	(b) 340-500 GeV	Out-of-Plane	0.44±0.03	4.7±0.3

Table 3
Reaction plane dependence of the two-pion correlation function. The source parameters R_t and λ are extracted by fitting the Gaussian source distribution.

central collisions ($340GeV < Et$). The results show no significant dependence of correlation shape as a function of the azimuthal flow angles within statistical errors. Based on geometrical model, this results support that the differences in semi-central collisions is not caused by the detector biases. The difference of the correlation function could be caused by the geometrical propagation of freeze-out and flow in the reaction plane.

On the other hand, it should be remembered that there is a positive correlation between the extracted parameters λ and source size R_t, so that possibility of the statistical fluctuation should be also taken into account in the analysis.

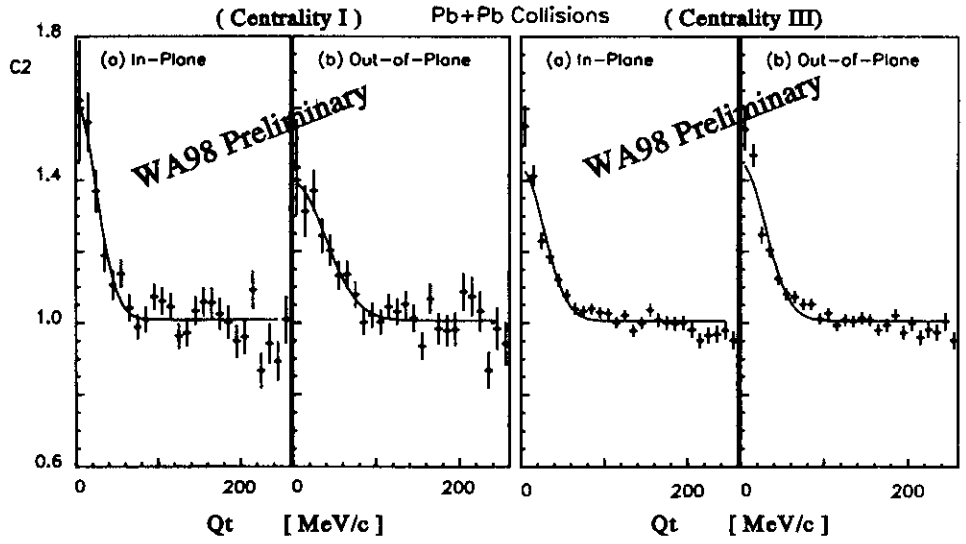

Figure 4. Two-pion correlation functions for semi-central (left: $50 < E_t < 290GeV$) and central (right: $340GeV < E_t$) Pb+Pb collisions. For semi-central collisions, relatively larger source size parameter is obtained for the $in-plane$ events compare to the $out-of-plane$ events. While, no significant difference is observed between two types of events in central collisions.

3. Summary

In summary, the directed flow of protons and π^+ has been studied in 158 A GeV ^{208}Pb + ^{208}Pb collisions. Our preliminary results shows that the directed flow seem to be largest for impact parameter $\approx$ 8 fm, which is considerably more peripheral than observed at lower incident energies. The π^+ directed flow is in the direction opposite to the protons, similar to observations at 11 A GeV energy [8]. The magnitude of the proton directed flow seems to be much less than cascade mode RQMD model predictions. We have measured the elliptic emission patterns of $\pi^\pm$ mesons near mid-rapidity. In semi-central collisions, $\pi^\pm$ mesons seems to be emitted in the reaction plane. The RQMD cascade calculation reproduces the v_2 values for $\pi^\pm$. The shape of the two pion correlation function has been investigated relative to the event plane. Preliminary results show a possible dependence of the correlation shape with respect to the reaction plane in semi-central Pb+Pb collisions.

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REFERENCES

1. H. Stöcker and W. Greiner, Phys. Rep. **137**, (1986) 277.
2. J.-Y. Ollitrault, Phys. Rev. D **46**, 229 (1992); J.-Y. Ollitrault, Phys. Rev. D **48**, 1132 (1993); J.-Y. Ollitrault, Nucl. Phys. **A638**, 195c (1998).
3. C.M. Hung and E.V. Shuryak, Phys. Rev. Lett. **75**, 4003 (1995).
4. N.S. Amelin et al., Phys. Rev. Lett. **67**, 1523 (1991).
5. D.H. Rischke, Nucl. Phys. **A610**, 88c (1996); D.H. Rischke and M. Gyulassy, Nucl. Phys. **A597**, 701 (1996).
6. H. Sorge, Phys. Rev. **C52**, 3291 (1995); H. Sorge, Phys. Rev. Lett. **78**, 2309 (1997).
7. E802 Collaboration, L. Ahle, *et al.*, Phys. Rev. **C57**, 1416 (1998).
8. E877 Collaboration, J. Barrette, *et al.*, Phys. Rev. Lett. **73**, 2532 (1994); J. Barrette, *et al.*, Phys. Rev. **C55**, 1420 (1997); J. Barrette, *et al.*, Phys. Rev. **C56**, 3254 (1997); S.A. Voloshin, *et al.*, Nucl. Phys. **A638**, 455c (1998).
9. E895 Collaboration, H. Liu *et al.*, Nucl. Phys. **A638**, 451c (1998).
10. NA45 Collaboration, F. Ceretto, *et al.*, Nucl. Phys. **A638**, 467c (1998).
11. NA49 Collaboration, T. Wienold, *et al.*, Nucl. Phys. **A610**, 76c (1996); H. Appelshäuser, *et al.*, Phys. Rev. Lett. **80**, 4136 (1998); A.M. Poskanzer, *et al.*, Nucl. Phys. **A638**, 463c (1998).
12. WA98 Collaboration, M.M. Aggarwal, *et al.*, preprint nucl-ex/9807004,submitted to Phys. Rev. Lett.; S. Nishimura, *et al.*, in proceedings of Jaipur, 158p. ICPA-QGP(1997); M. Kurata, *et al.*, in proceedings of Jaipur, 549p. ICPA-QGP(1997). S. Nishimura, *et al.*, Nucl. Phys. **A638** 459c (1998).
13. Plastic Ball Collaboration, H.Å. Gustafsson et al., Phys. Lett. **B142**, 141 (1984); H.A. Gustafsson, *et al.*, Phys. Rev. Lett. **52**, 1590 (1984); H.H. Gutbrod, *et al.*, Phys. Lett. **B216**, 267 (1989); H.H. Gutbrod, *et al.*, Rep. Prog. Phys. **52**, 1267 (1989); H.Å. Gustafsson, *et al.*, Phys. Rev. **C42**, 640 (1990).

14. KaoS Collaboration, D. Brill, *et al.*, Phys. Rev. Lett. **71**, 336 (1993); D. Brill, *et al.*, Z. Phys. **A355**, 61 (1996); D. Brill, *et al.*, Z. Phys. **A357**, 207 (1996).
15. FOPI Collaboration, J.L. Ritman, *et al.*, Z. Phys. **A352**, 355 (1995); N. Bastid, *et al.*, Nucl. Phys. **A622**, 573 (1997).
16. WA98 Collaboration, Proposal for a large acceptance hadron and photon spectrometer. 1991, Preprint CERN/SPSLC 91-17, SPSLC/P260.
17. W. Reisdorf and H.G. Ritter, Ann. Rev. Nucl. Part. Sci. **47**, 663 (1997).
18. Goldhaber et al., Phys. Rev. **120**, 300 (1960).
19. T. Chujo, et al., Nucl. Inst. and Methods, **A383** 409 (1996).
20. A. Baden, et al., Nucl. Inst. **203**, 185 (1982).
21. S.A. Voloshin and Y. Zhang, Z. Phys. **C70**, 665 (1996).
22. A.M. Poskanzer and S. A.Voloshin, Phys. Rev. **C58**, 1671 (1998).
23. A. Jahns, *et al.,* Phys. Rev. Lett. **72**, 3463 (1994).
24. A. Kugler, *et al.,* Acta Phys. Pol. **25**, 691 (1994).
25. WA80 Collaboration, T.C. Awes, *et al.,* Phys. Lett. B **381**, 29 (1996).