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Δ^{++} production in 158 A GeV ^{208}Pb + ^{208}Pb interactions at the CERN SPS

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Abstract

The Δ^{++}-resonance production in central 158 A GeV ^{208}Pb $+$ ^{208}Pb collisions at the CERN SPS has been studied. The Δ^{++} production was estimated from the invariant mass spectrum of pπ^{+}-pairs by subtracting a mixed event background. The measured Δ^{++} abundance is compared with the results from other experiments at lower energies, and with a model calculation assuming thermal and chemical equilibrium.

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Energetic heavy ion collisions provide the means for studies of nuclear matter under extreme conditions in the laboratory. The copious interactions between pions and nucleons in the final state of ultra-relativistic heavy ion collisions make the determination of the $\Delta(1232)$ abundance an interesting probe of the thermal conditions during the collision.

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The Δ-resonance, apart from playing a role in particle production and interaction dynamics, may probe the conditions in heavy-ion collisions at early freeze-out times and high freeze-out densities [1]. It has been suggested that a chemical freeze-out temperature can be extracted from the $\Delta(1232)/$nucleon ratio [2]. The Δ-resonance is known to be readily produced in photon [3]- lepton [4]- and hadron [5]-induced nuclear interactions and the cross sections for production of Δ-resonances in elementary nucleon-nucleon collisions are large [6].

Recently, results on $\Delta(1232)$ production in nucleus-nucleus collisions at 95 A MeV [7], at 1 and 2 A GeV [8] and at 13.7 A GeV [9] have been reported. In this paper we present measurements on the production of Δ^{++} by means of an invariant mass analysis of $p\pi^+$-pairs in 158 A GeV central ^{208}Pb $+^{208}$Pb central collisions at the CERN SPS. The measurement utilizes the new high resolution tracking arm of WA98 [10], which consists of multi-step avalanche chambers, streamer tube detectors and a high resolution Time-Of-Flight system.

The fixed target experiment WA98 is a large-acceptance photon and hadron spectrometer designed to study ultra-relativistic heavy-ion collisions. Charged particles, produced in the interactions, traverse a large magnet and are deflected into two tracking arms, horizontally placed on both sides of the beam which allow for momentum determination and particle identification. For the Δ^{++} measurements, reported in this paper, we use the full data sample from the tracking arm for the positively charged particles [11]. This second tracking arm was installed and operated for only a portion of the final WA98 run period.

The tracking arm consists of two planes of Multi-Step Avalanche Chambers (MSACs) [12,13] and two planes of streamer tube detectors, all equipped with electronic pad readout and a highly segmented Time-Of-Flight (TOF) wall. Fig. 1a shows a schematic drawing of the second tracking arm as seen from above, with two tracks entering the acceptance. Here the z-axis is pointing along the beam and the x-axis is parallel to the bending plane of the magnet. The position resolution of the MSACs was $\sigma_x = 0.5$ mm in the horizontal direction, and $\sigma_y = 1.7$ mm in the vertical direction whereas the streamer tube detectors had an intrinsic resolution of $\sigma_x = 3.0$ mm and $\sigma_y =$ 6.5 mm. The time resolution of the TOF wall was better than 90 ps and its spatial resolution was $\sigma_x = 12.5$ mm and $\sigma_y = 26.4$ mm. Fig. 1b and 1c show p versus $t_{tof} - t_{exp}$ assuming pion and proton mass, respectively. Here p is the momentum, t_{tof} the measured flight time of the particle and t_{exp} the expected flight time calculated from the track length and momentum of the particle. Separation between different particle species, especially for pions and protons, is good over a wide range of momenta. Kaons and pions are no longer separable at momenta above 4 GeV/c and thus a small contamination of kaons is present among the pions at larger momenta. The momenta of the particles are first approximated assuming a uniform magnetic field and straight line fits through the tracking arm and then corrected by GEANT [14] calculations using the measured field. The momentum resolution, $\Delta p/p$, is limited by the multiple scattering, mainly in the air between the target and the detectors, the intrinsic detector resolution and by methodical uncertainties. Based on GEANT simulations we estimate $\Delta p/p$ to be about 1% at 2 GeV/c and 2% at 5 GeV/c.

The most interesting events are those where the bulk of the nuclear matter interacts, i.e. the most central events. A trigger based on the transverse energy as measured by the Mid-Rapidity Calorimeter (MIRAC) is used to enhance central collisions. The present analysis has been performed using the 8.5% most central events of the WA98 minimum bias cross section (6450 mb for the used data set) based on an offline cut on the measured transverse energy. To reject beam particles other than Pb and possible event pile-up, lower and upper cuts in the ADC and TDC values from the start-counters, placed in the beam, were performed.

During and shortly after electrical discharges, the MSACs exhibited reduced efficiencies. This has been discussed in a previous paper [12]. Thus events recorded within a short time after such a discharge, are removed from the analysis.

The tracking procedure connects hits in at least three out of the four tracking planes, by means of straight line fits, and combines a track with a valid time measurement in the TOF wall at the correct position. Due to the excellent two-track resolution and two-dimensional position resolution of the tracking planes, this procedure works almost without

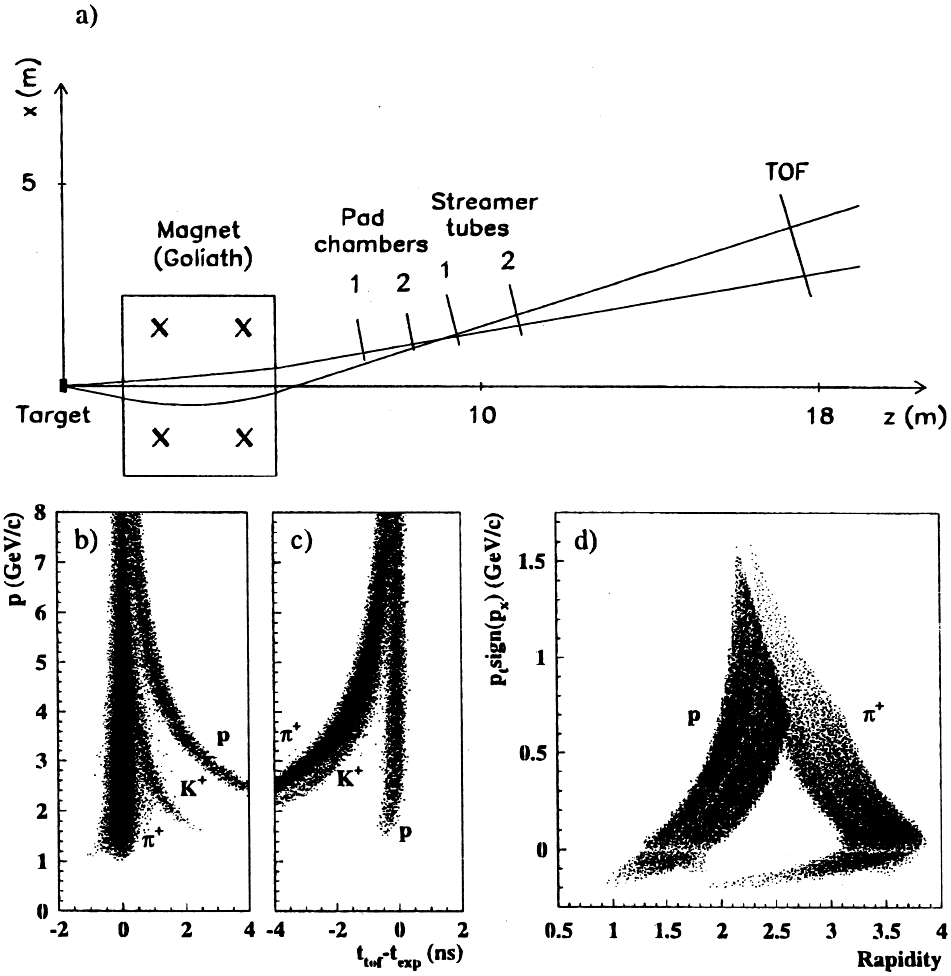

Fig. 1. (a) Overview of the tracking arm with two tracks within the acceptance. (b) Particle identification bands calculated assuming that all particles have the pion mass. (c) as in (b) assuming proton mass. (d) The distribution of accepted particles in terms of p_t and rapidity for protons and π^+.

ambiguities, in spite of the large track multiplicity within the acceptance. Cuts have been applied on the hit association in the TOF wall and on the vertical distance between the track extrapolation and the interaction point. Finally, the particle identity is obtained by cuts in $t_{\mathrm{tof}} - t_{\mathrm{exp}}$. This works up to a particle momentum of 8 GeV/c, where the separation no longer can be done unambiguously. In order not to lose any observed Δ^{++} resonances, we have chosen to use particles up to 16 GeV/c, thereby introducing a small systematic error. The small amount of contaminating kaons among pions above 4 GeV/c only gives marginal effects on the extracted Δ^{++} yield. This sort of contamination will also be present in the mixed events and its effects are to a large extent removed.

Fig. 1d shows the distributions of accepted particles for the second tracking arm in terms of transverse momentum p_t and rapidity for protons and pions. Notice the sign(p_x) factor, which unfolds the spectrum for particles with negative p_x and momentum low enough to bend across the beam line. Furthermore, a momentum cut of 8 GeV/c has been applied.

For all pairs of identified p and π^+, the invariant mass, $M_{\rm inv}$, was calculated from

$$M_{\rm inv} = \sqrt{(E_\pi + E_{\rm p})^2 - (\boldsymbol{p}_\pi + \boldsymbol{p}_{\rm p})^2}\,.$$

The mass resolution of the $p\pi^+$-pair, estimated from the momentum resolution, is a few MeV. An invariant mass spectrum of such pairs (real spectrum) will consist of one part where the pion and the proton are coming from the same Δ^{++}-decay and an essentially uncorrelated combinatorial background. Due to the high multiplicity of protons and pions, the combinatorial background will be by far the dominant contribution to the invariant mass spectrum. To account for this combinatorial background, the invariant mass spectrum was calculated also with protons and pions taken from different events (mixed event). To extract the fraction ξ, of Δ^{++}, among the $p\pi^+$-pairs, $N_{\rm pair}$, we assume that the mixed event invariant mass spectrum has the same shape as the combinatorial background in the real spectrum. This assumption has been verified by studies of ratios between real spectra and mixed event spectra. To essentially eliminate the statistical errors in the mixed event spectrum, it contains about ten times the statistics in that of the real spectrum. The real spectrum, $F(M_{\rm inv})$ can then be written as

$$F(M_{\rm inv}) = N_{\rm ev} \cdot N_{\rm pair}(\xi \cdot BW(M_{\rm inv}, M_0, \Gamma) + (1-\xi)\, g(M_{\rm inv})). \quad (1)$$

$\mathrm{BW}(M_{\rm inv}, M_0, \Gamma)$ is a modified Breit-Wigner function, filtered through our geometrical acceptance, normalized to unity. M_0 and Γ are the peak position and width respectively of the modified Breit-Wigner function. Note that neither the real spectrum nor the mixed event spectrum are corrected for acceptance. $N_{\rm ev}$ is the number of events and $g(M_{\rm inv})$ is the unit normalized mixed event spectrum. The modified Breit-Wigner function, before filtering, is given by

$$BW(M_{\rm inv}, M_0, \Gamma) \propto \frac{q^3}{(q^3+\mu^3)} \frac{1}{((M_{\rm inv}-M_0)^2 + (\Gamma/2)^2)},$$

where q is the momentum of the proton (or pion) in the rest-frame of the pair, i.e half of the relative momentum, and $\mu = 180$ MeV/c [15]. The real spectrum can now be fitted using Eq. (1), treating ξ, M_0 and Γ as free parameters.

Fig. 2a shows the distribution of accepted Δ^{++} obtained from FRITIOF7.02 [16] events filtered through GEANT, i.e. for Δ^{++} where both decay particles fall inside the acceptance of the arm. The spectrum is unfolded in the same way as in Fig. 1d. Fig. 2b shows the invariant mass spectrum of

$$F(M_{\rm inv}) - N_{\rm ev} \cdot N_{\rm pair} \cdot (1-\xi)\, g(M_{\rm inv}),$$

i.e. the real spectrum with the background subtracted. Also shown by the solid curve is

$$N_{\rm ev} \cdot N_{\rm pair} \cdot \xi \cdot BW(M_{\rm inv}, M_0, \Gamma),$$

i.e. the acceptance-filtered modified Breit-Wigner function obtained from the best fit.

The extracted number of Δ^{++} has to be corrected for acceptance and inefficiencies. Table 1 gives the values of the different correction factors with their estimated errors.

The efficiency for Δ^{++} detection is the product of the efficiencies for protons and pions. The efficiency factors given in the table are the ratio between those Δ^{++} efficiencies and the corresponding efficiencies for protons. $k_{\rm trk}$, which is about 80%, is the probability for a particle entering the arm, resulting in a track seen in at least three out of the four

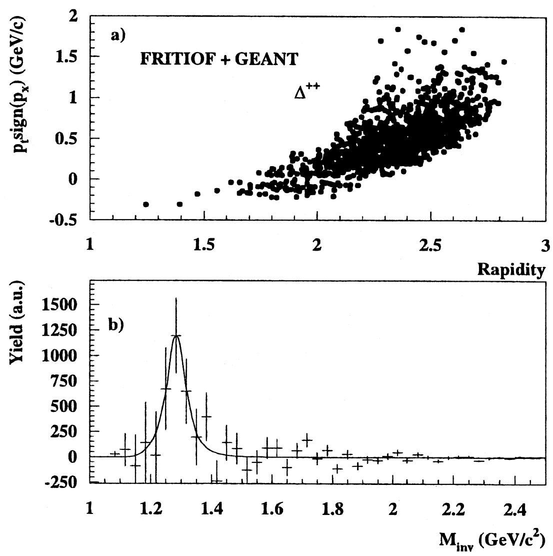

Fig. 2. (a) The distribution of accepted Δ^{++} obtained from Fritiof events. (b) The extracted Δ^{++} resonance together with the corresponding acceptance-filtered modified Breit-Wigner.

Table 1
Summary of the different correction factors and their estimated systematic errors.

Correction factors	Value
tracking efficiency, k_{trk}	0.79 ± 0.02
identification efficiency, k_{pid}	0.60 ± 0.02
geometrical acceptance, k_{geo}	0.145 ± 0.005

tracking planes and with a quality sufficient to pass the applied cuts, i.e. vertex association, χ^2 of the straight-line fit, et cetera. The k_{pid} factor corrects for the particle identification efficiency, including hardware efficiencies, effects of applied cuts on the flight times and particles decaying before reaching the TOF wall. The k_{geo} factor corrects the Δ^{++}/proton ratio for the limited azimuthal coverage of the arm estimated by GEANT simulations. The values of all the correction factors depend on the cuts we apply on the data and the systematic errors were estimated by varying these cuts within reasonable limits.

Table 2 gives the reconstructed and corrected ratio between the number of Δ^{++} and protons within the arm. Within our acceptance RQMD2.3 [17] predicts about 2.4 protons/central event and FRITIOF7.02 predicts about 5.5 protons/central event. Thus our proton multiplicity, which is about 1.83 proton per central event after efficiency corrections, seem to be in fair agreement with RQMD, whereas FRITIOF seems to overestimate.

The extraction of the Δ^{++} signal is by no means trivial as the peak is broad and the combinatorial background is large. Three different extraction methods were applied to simulated data to investigate the influence of the methods on the reconstructed number of Δ^{++} [18]. The method described above proved to be the most robust for different projectiles p, Si and Pb upon Pb target at the relevant beam energy.

Regarding the error of the extracted ratio we note that this is dominated by the statistical fluctuations in the number of combinatorial pairs under the resonance peak. Thus it is impossible to obtain the ratio with higher precision with the given statistics, independent of the extraction method. A study based on simulation results with different event generators, and variation of cuts applied to the data, indicates that the systematic error contributions resulting from the various cuts and correction factors applied to the data are considerably smaller (of the order of 10% of the obtained value) and therefore negligible in comparison to the statistical error.

However, it was observed that the chosen extraction method tended to systematically overestimate the number of Δ^{++} in simulations. A special simplified Monte Carlo event generator was constructed in order to study this effect. With this generator, several hundreds of samples of the same size as the real data sample was studied [19]. The reason for the overestimation is that although the background estimated with mixed events is almost identical to the background in the data, small differences are present. For instance, correlations between the decay products from different Δ^{++} resonances are believed to add to the systematic error of the extraction method. Pairs with the pion and proton from two different Δ^{++} decays, are almost identical to a pair originating from the same Δ^{++} due to the restricted acceptance of the tracking arm. The magnitude of the overestimation and associated error has been determined from the simulations and a correction has been applied for the ratio and error as shown in Table 2. The correction leads to an increased relative error in the ratio.

The ratio of $\Delta(1232)$/nucleons has been studied and an increase as a function of incoming beam energy has been established [8]. In a thermal model this can be interpreted as an increase of the freeze-out temperature which determines the relative population of the nucleonic resonances. The same ratio can be estimated from our data. In an isospin symmetric system, one could obtain the total number of $\Delta(1232)$ resonances, i.e. Δ^-, Δ^0, Δ^+ and Δ^{++}, by multiplying the number of Δ^{++} by an isospin factor four. In the same way, the number of nucleons, including those from resonance decays, could be estimated by multiplying the measured number of protons with a factor two. In our case, where we have an isospin

Table 2
Summary of the results.

119677 central events	Δ^{++}/proton ratio
reconstructed (uncorrected)	0.031 ± 0.015
corrected for systematic fitting error	0.021 ± 0.013
full ϕ and eff. corrected	0.309 ± 0.190

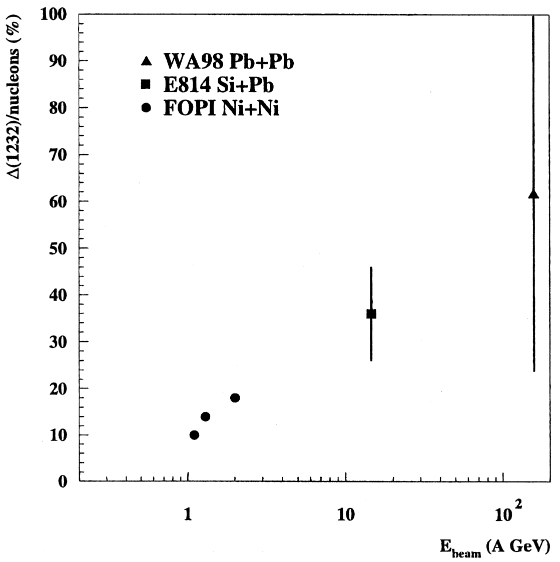

Fig. 3. The ratio $\Delta(1232)/$nucleons as a function of beam energy/nucleon.

asymmetry, in a first approximation the nucleons and the Δ-resonances are affected in the same way, and thus no correction for the isospin asymmetry is applied. Only a small contribution of baryon number is present in deuterons and weakly decaying hyperons, where the decay proton might be lost in the tracking due to the secondary vertex being far from the interaction point.

Our obtained ratio for nucleons originating from $\Delta(1232)$ resonances, is found to be quite large at central rapidities, 0.62 ± 0.38. Fig. 3 shows our results in comparison with similar results from experiments at lower beam energies. Note that the target and projectile rapidities are separated by 5.8 units at 158 A GeV. In this experiment the influence of spectator matter is thus much less than at lower beam energies.

Our obtained value of the $\Delta(1232)/$nucleon ratio can be compared to the ratio obtained from thermal model calculations, assuming chemical and thermal equilibrium. In such a calculation the maximum ratio obtained is around 0.33 [2]. Furthermore this ratio is obtained over a large range of temperatures and baryon densities, used as input to the calculations.

However, it should be pointed out that the experimental ratio also contain contributions from prior to freeze-out. For this and other reasons, e.g. the saturation of the ratio as a function of temperature, it is premature to use the experimentally extracted ratio for a precise temperature estimation and any temperature above 100 MeV seems to be in qualitative agreement with the obtained ratio.

Besides the yield, the fitting procedure also provides the width and mass of the delta peak. However the systematic errors in these values, estimated by changing cuts and extraction methods and by applying the methods to Monte Carlo samples with known parameters, are sufficiently large to preclude a meaningful discussion of a possible mass shift or changes of the width of the delta peak.

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