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Measurement of pion enhancement at low transverse momentum and of the Δ resonance abundance in Si–nucleus collisions at AGS energy

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Abstract

We present measurements of pion transverse momentum (p_t) spectra in central Si–nucleus collisions in the rapidity range $2.0 < y < 5.0$ for p_t down to and including $p_t = 0$. The data exhibit an enhanced pion yield at low p_t compared to what is expected for a purely thermal spectral shape. This enhancement is used to determine the Δ resonance abundance at

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freeze-out. The results are consistent with a direct measurement of the Δ resonance yield by reconstruction of proton–pion pairs and imply a temperature of the system at freeze-out close to 140 MeV.

Collisions of heavy nuclei at ultrarelativistic energies produce a zone of hot, compressed matter. Information from measurements of transverse energy production [1,2] and baryon distributions [3–5] indicate that baryon densities up to ten times normal nuclear matter density are reached during the collision [6–8]. This highly compressed system then expands [9] until its constituents cease to interact, i.e. "freeze out". The expansion is reflected in the slopes of transverse momentum spectra at midrapidity, which systematically become flatter with increasing particle mass [10,11]. Very recently [12] sidewards flow was directly identified for Au + Au collisions at AGS energy. The connection between the transverse momentum spectra of hadrons and the temperature of the fireball at freeze-out is thus complicated by additional parameters such as flow velocities and flow profile.

To provide information on the composition of the fireball formed in the collision, and to get an independent measurement of the freeze-out temperature we report here measurements of the double differential cross sections for charged pions at forward rapidity ($y > 2.0$) in central ^{28}Si + Al, Pb collisions at $p_{lab} = 14.6$ GeV/c per nucleon. The experimental status of low p_t phenomena in high energy nuclear collisions and possible interpretations have been summarized recently [13]. At AGS energies a major source of the enhancement is expected to be [14,15] the pions produced by the decay of the Δ(1232) resonance. The decay preferentially populates the spectrum at low p_t wherefrom the abundance of the Δ at freeze-out and thereby the system's true temperature can be inferred. To provide further support for the feeding scenario and independent information on the Δ abundance, we also present the results for direct reconstruction of the Δ^{++} using the pπ^+ invariant mass.

The experiment was performed using the E814 apparatus at the AGS at Brookhaven National Laboratory. The apparatus is described in detail elsewhere [1–3,17]. A 14.6 GeV/c per nucleon ^{28}Si beam was incident upon Pb targets of thicknesses of 1.1 and 2.2 g/cm^2 and Al targets of 0.33 and 0.66 g/cm^2, corresponding to 1.2% and 2.4% of a silicon interaction length, respectively. Collision centrality was determined via a charged particle multiplicity measurement in the interval $0.85 < \eta < 3.8$. Experimental details and the connection between centrality and charged particle multiplicity are discussed in [18].

Particles emitted in the forward direction were accepted and analyzed by a forward spectrometer. We define z along the incident beam, y vertically upward and x so as to make a right-handed coordinate system. The spectrometer aperture -115 mr $< \theta_x < 14$ mr and $|\theta_y| < 21$ mr was defined by a Pb/steel collimator. Accepted particles pass through a dipole magnet and are momentum analyzed via a pair of drift/pad tracking chambers. The momentum resolution of the spectrometer has been modelled using the GEANT package [19]. The resolution in momentum p is dominated by multiple scattering with $\delta p/p \sim 4.1\%$ for the momentum range considered here. Scattering in the target creates a distortion in p_t without significantly altering p. This effect together with all other imperfections implies that $\delta p_t < 4$ MeV/c for $p_t < 100$ MeV/c and $\delta p_t/p_t = 4\%$ for larger p_t values. All data are presented in 10 MeV/c p_t bins.

Time-of-flight, and hence velocity, is determined by one of two scintillator hodoscopes located 12 and 31 m from the target with 200 and 350 ps resolution, respectively. The spectrometer is capable of separating protons and pions up to $p = 7$ GeV/c. Background in the pion sample due to kaons and unrecognized decays is less than 10%. Possible electron contamination was investigated in two ways. First, for momenta below 0.5 GeV/c electrons can be separated via time-of-flight. In this momentum range, the electron to pion ratio is observed to decrease with increasing p and is close to 5% at 0.5 GeV/c in accordance with simulations showing that the primary source of electron contamination is photon conversion in the target. A comparison of results for

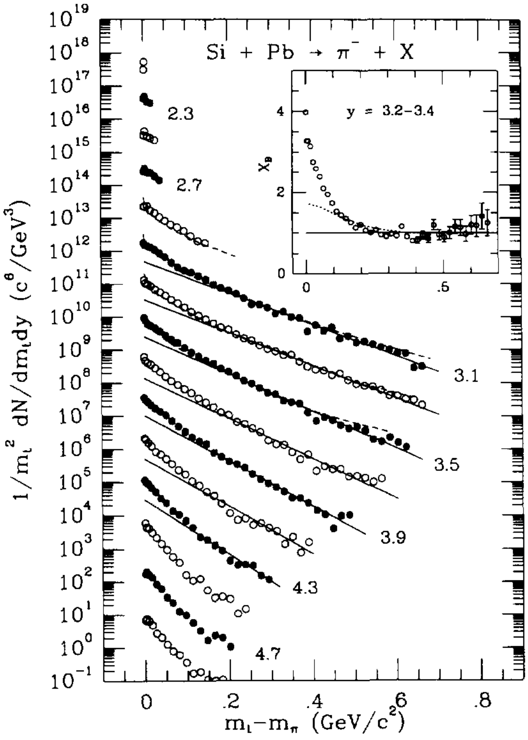

Fig. 1. Pion transverse mass spectra for central ($\sigma/\sigma_{geo} = 2\%$) Si + Pb collisions in different rapidity intervals. Starting with $y = 4.7$, the distributions in each successively lower y bin have been multiplied by increasing powers of 10. Shown in the inset are the ratios data/Boltzmann (points) and m_t exponential/Boltzmann (dotted line). For more details see text.

the 1% and 2% targets shows no statistically significant evidence for electron contamination and consequently, the data for the two target thicknesses were combined.

Fig. 1 shows a summary of the measured π^- transverse mass ($m_t = \sqrt{p_t^2 + m_\pi^2}$) spectra for central ($\sigma/\sigma_{geo} \leq 2\%$) Si + Pb collisions. The vertical axis is $1/m_t^2 \times d^2N/dm_t\, dy$, the representation in which a Boltzmann (or thermal) distribution is a pure exponentialPin m_t. Our acceptance in m_t is largest for rapidities $3.0 < y < 4.0$. The measurable range in m_t is limited by the geometrical opening of the spectrometer at low y and particle identification at high y. The solid curves in Fig. 1 show Boltzmann fits to the data, with the fit interval restricted to $m_t - m_\pi > 160$ MeV/c^2. The data exhibit a significant enhancement over this functional form at low m_t. This is most clearly seen in the inset which shows the ratio of the data to the thermal fit on a linear scale. The dotted line demonstrates that the data rise also faster than expected for an invariant distribution $1/m_t \times d^2N/dm_t\, dy \propto \exp(-m_t/T)$. Results for π^+, and for the Al target, (not shown here) exhibit enhancements of similar strength as those in Fig. 1. The strength of the enhancement does not vary significantly with centrality in the range $\sigma/\sigma_{geo} = (2–10)\%$.

The large stopping at AGS energies [3] implies that the fireball formed in the collision is baryon-rich. Baryonic resonances and in particular the $\Delta(1232)$, in the following simply denoted Δ, with its low decay momentum of 227 MeV/c are therefore anticipated to be the major contributors to pion spectra at low p_t [15,16]. One can extract from the pion spectra an estimate of the fraction of pions resulting from Δ decay. To do this we have computed the pion spectral shape by superposition of direct thermal pions (with spectral slope adjusted at high m_t and pions from Δ decay for various ratios $f = \pi_\Delta/\pi_{direct}$. Rapidity and p_t distributions of the Δ were taken to follow predictions by the RQMD model [20] but the assumption that the Δ distributions follow those of the measured [3] protons yields very similar results. Fig. 2 shows the ratio of the pion spectra to the fitted Boltzmann distribution. The data are compared to model calculations using $f = 0.4$ and 0.6. The calculations bracket the data and establish that the ratio $f = 0.5 \pm 0.1$ implying that 1/3 of all pions come from Δ decay without further interaction. The ratio between the number of pions and nucleons for central Si + Pb collisions is observed [11,21] to be $(\pi/N)_{exp} \approx 1.07$ yielding a fraction of nucleons excited to the Δ resonance at freeze-out of 0.36 ± 0.05. The rise above the Boltzmann fit in the pion spectra at the highest p_t indicates that obviously there is a systematic error in the decomposition at low p_t due to the chosen temperatures. However, at $p_t = 0$ the Δ component already accounts for 80% of the pion yield, a number that grows only slowly (and at most by 20%) with increasing slope of the direct component. A systematic error that would tend to decrease the Δ fraction is an unknown low p_t component from decay of mesonic resonances, primarily the η and ω. In full thermal and chemical equilibrium

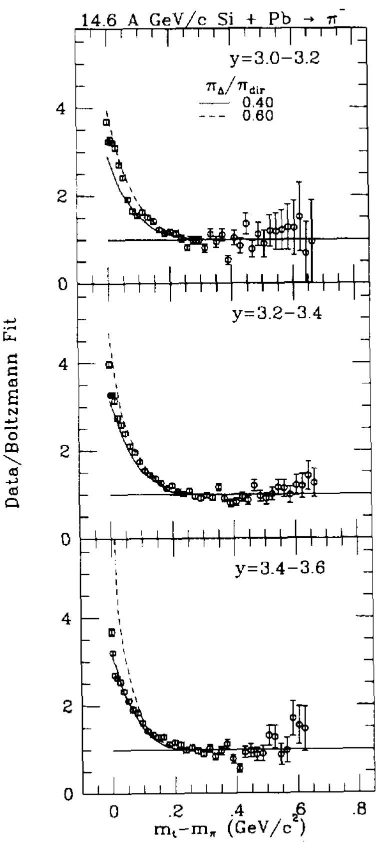

Fig. 2. Pion transverse mass spectra plotted as a ratio of the data to the best fit Boltzmann distribution ($m_t \geq 300 \mathrm{MeV}/c^2$). Also shown are predictions from a model containing direct pions and Δ decay pions in the ratios $\pi\delta/\pi_{\mathrm{direct}} = 0.4$ and 0.6.

their contribution to the low p_t enhancement could be just below 25% of the Δ's.

The measured pion spectra (for both charges and for both targets) are also well reproduced by cascade models such as RQMD [20] and ARC [8] which have the Δ resonance explicitly built into the collision dynamics. This is illustrated by the dashed lines in Fig. 1 representing the RQMD prediction, which accounts for shape and absolute yield of the data once the experimental trigger conditions are incorporated. The dominant source of the rise at low m_t in pion spectra calculated with RQMD can be traced back [20] to the $\Delta(1232)$ resonance decay. The overall predicted freeze-out Δ excitation probability of 0.35 is very close to the experimental value given above. Close inspection of Fig. 1 reveals that in addition to the low p_t enhancement discussed above there is also visible in the data an increase with even steeper slope at very low transverse momenta ($p_t <$ 50 MeV/c or $m_t - m_\pi < 0.01$ GeV/c^2) which has yet to be explained.

To get an independent measurement of the number of Δ's at freeze-out in Si + Pb collisions we have reconstructed the Δ^{++} via its decay to $p\pi^+$. This is the most easily measured of all Δ decays since (i) its branching ratio is nearly 100%, (ii) all particles in the final state are charged, and (iii) there is no interference from Λ decay (which could disturb Δ^0 measurements). Additionally, the asymmetry of the E814 spectrometer makes it best suited for like-sign pair measurements.

The invariant mass (M_{inv}) for $p\pi^+$ pairs was reconstructed for central ($\sigma/\sigma_{\mathrm{geo}} \leq 10\%$) collisions. Protons near beam rapidity ($y \geq 3.1$) were rejected from the sample since they are in part projectile fragments. Pions below rapidity 3.0 were rejected since the Δ decay kinematics does not permit such pions into the E814 spectrometer acceptance with the proton rapidity cut used.

Fig. 3 shows a summary of our measurement of the Δ^{++} using $p\pi^+$ pairs. The analysis employs the "mixed events" technique. One determines the shape of the combinatorial background by constructing an invariant mass spectrum using (uncorrelated) protons and pions from different events. The resulting distribution is normalized to the true pair spectrum and subtraction yields the signal. The combinatorial spectrum is fitted to the high mass end ($M_{\mathrm{inv}} > M_1$) of the true pair spectrum, by determining that normalization constant which minimizes χ^2. The net Δ^{++} yield was found to not differ beyond statistics using M_1 values in the range $1.4 < M_1 < 1.8$ GeV/c^2. Note that the true pair acceptance for decay of a nuclear resonance with $M \geq 1.4$ GeV/c^2 is negligible in our set-up. A value of $M_1 = 1.4$ GeV/c^2 was selected for the analysis. Fig. 3 shows the invariant mass distributions for the true pairs and the normalized combinatorial background.

The robustness of the analysis procedure was tested via Monte Carlo analysis. A "negative test" data sample of uncorrelated $p\pi^+$ pairs was generated using the measured single particle distributions. Analysis of these data shows no Δ signal. Additionally, a "positive test" was performed on $p\pi^+$ pairs

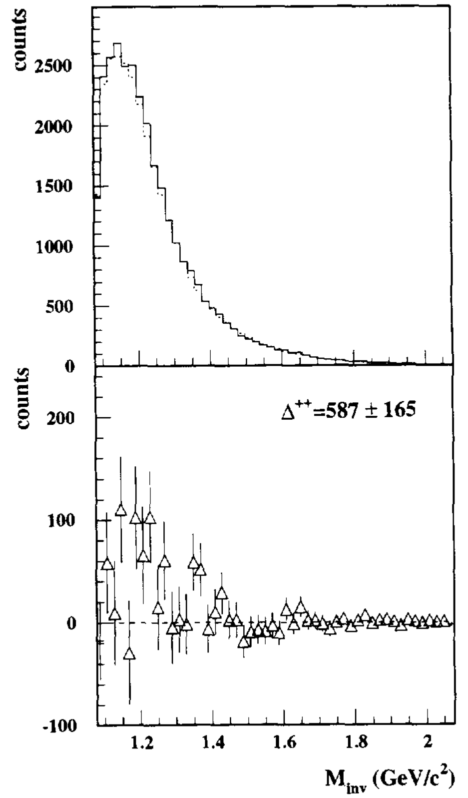

Fig. 3. Reconstruction of the Δ^{++} resonance. Shown in the top panel are the invariant mass spectra of $p\pi^+$ pairs from the same event (solid histogram) and of $p\pi^+$ pairs from mixed events (dashed histogram). The bottom panel shows the difference in the true pair and mixed event pair spectra.

from RQMD-generated events to verify that the Δ resonance is observed correctly there and agrees in shape with the data.

The invariant mass spectrum of $p\pi^+$ pairs after background subtraction is shown in the bottom panel of Fig. 3. The total yield into the E814 acceptance for 4.01×10^5 central collisions is 587 ± 165 Δ^{++}. We have computed the acceptance of the E814 spectrometer for Δ^{++} using GEANT. Over the rapidity interval $1.9 < y < 3.1$ covered by the experiment the acceptance varies between 3×10^{-4} at $y = 2$ and 1.2×10^{-2} at $y = 3$. Assuming that the shape of the Δ distribution in y and p_t is close to that measured for protons [3,17], and taking into account a reconstruction efficiency of 73% per track, the yield corresponds to 1.7 ± 0.5 Δ^{++} into $1.9 < y < 3.1$ per central Si + Pb collision. Using the Δ distributions in y and p_t from RQMD gives a very similar result.

The predicted Δ^{++} yield at freeze-out from the RQMD model is in good agreement with the measurement. Comparisons to the model must be made using the cascade history file since the nucleon and/or pion from Δ decay may interact strongly before leaving the collision zone. Freeze-out Δ^{++} decays (identified as those for which the decay proton or pion escapes) number 17.2 per central collision. Combining all four charge states 35% of all nucleons are in the Δ resonance at freeze-out. Reconstructable decays are either tagged as having both decay products leave the zone without further strong interaction or are estimated by a combinatorial background subtraction method as used for the data. Both methods yield the same prediction of 14.7 ± 0.9 reconstructable Δ^{++} decays per central collision. Into the rapidity interval $1.9 < y < 3.1$, the RQMD prediction is 1.6 ± 0.3 observable Δ^{++} per event, in remarkable agreement with our measurement.

A measurement in pn collisions at $p_{lab}/A = 19$ GeV/c [22] yields a cross section for Δ^{++} formation of 4.1(6) mb and an overall Δ multiplicity of 0.36 or 18% relative to nucleons. A recent measurement for p + Ag/Br collisions at $p_{lab}/A = 20.8$ GeV/c [23] reports a Δ^{++} abundance of 0.21(7) for central collisions. For incident Si projectiles we estimate an upper limit of $28 \times 0.21 = 5.9$ Δ^{++} to be compared to a number of 17.2 for the present measurement.

Assuming thermal equilibrium, the measured Δ abundance yields information [15] on the freeze-out temperature, T, of the system. We have calculated the number density of all nonstrange baryonic resonances with masses less than 2 GeV/c^2 as a function of temperature. The calculation closely follows that of [15] but takes, in addition, into account the widths of all states. The results for population ratios (which are essentially independent of baryon chemical potential) are presented in Fig. 4. Using the population ratio for Δ's of 0.36 ± 0.05 determined from our data we extract the freeze-out temperature to be $T = 138^{+23}_{-18}$ MeV.

In summary, we have shown that pion spectra from Si–nucleus collisions at AGS energy exhibit a significant enhancement at low p_t. A simple model incorporating pions from Δ decay accounts quite

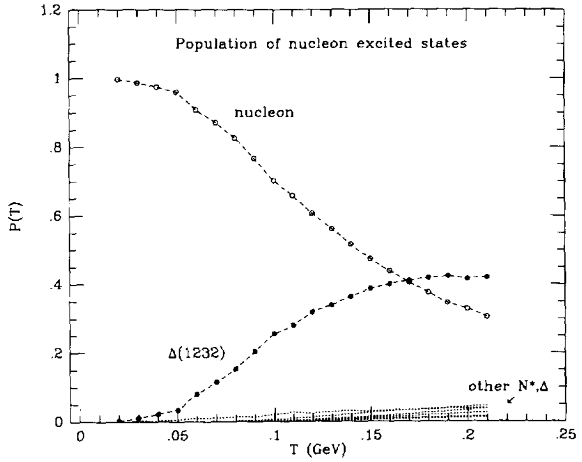

Fig. 4. Thermal occupation probabilities of non-strange baryons with mass $m < 2\ \mathrm{GeV}/c^2$ as function of temperature. For details see text.

accurately for the observed shape if Δ/nucleon ratios in the range 0.36 ± 0.05 are assumed. RQMD calculations are consistent with our result and also reproduce accurately the measured pion spectra. Additionally, the results from the analysis of spectral shapes are consistent with a direct measurement of the Δ^{++} abundance for Si + Pb, which yields 1.7 ± 0.5 Δ^{++} per collision in the rapidity interval $1.9 < y < 3.1$. Our measurement thus quantitatively establishes the importance of the Δ resonance to the dynamics of the collision. We find that the same concentration of freeze-out Δ's simultaneously explains our pion enhancement and the directly measured yield of Δ^{++}. Finally, the results imply that in central Si + Pb collisions a fireball is formed with substantial excitation of Δ baryons which freezes out at $T = 138^{+23}_{-18}$ MeV.

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