$(p,\pi^{\pm})$ Correlations in pA and AA Collisions at Relativistic Energies

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Abstract

The invariant mass analysis of (p,π^+) pairs in pA (A=C,Nb,Pb) collisions at 0.8 and 1.6 GeV incident proton energy reveals a strong correlation due to the Δ^{++} resonance. For all systems an effective Δ mass shift to lower values is observed. Similarly $(p,\pi^{\pm})$ correlations in the systems Au+Au (1 AGeV) and Ni+Ni (1.9 AGeV) also show the presence of Δ's in the final state of AA collisions. Δ mass spectra are presented, which are consistent with a free Δ for both systems.

1. Introduction

In nucleus - nucleus collisions around 1 AGeV beam energy, final state correlations between nucleons and pions are produced by various mechanisms. First of all, pion production is believed to proceed via the excitation of the $\Delta(1232)$ resonance in a two step process: $NN \rightarrow \Delta N$, $\Delta \rightarrow \pi N$. The two-body decay kinematics of the resonance introduces a weak correlation between the nucleon and the pion. The correlation is weak since the decay-width of the Δ is so large ($\Gamma = 115$ MeV), that the invariant mass of the (p,π) pair comes close to the value generated by an uncorrelated (p,π) pair, where the proton belongs to the hadronic background of the reaction. In other terms, the decay populates a large part of the phase space available for protons and pions in a heavy ion collision.

On the other hand, baryons exhibit strong collective behaviour, as is indicated by the existence of a reaction plane. Also Δ's take part in the collective motion of nuclear matter, which consequently influences the global emission pattern of pions. One established signal for collective effects is the so called 'squeeze-out' of pions[1]. Another example for pion-nucleon correlations on a global event scale is the phenomenon of 'pion flow', which was first observed in Ne + Pb collisions[2] and interpreted as due to absorption effects. Recently, indications for 'pion flow' have also been found for the symmetric system Au+Au (1 AGeV) by the FOPI collaboration[3]. Microscopically the origin of these correlations is the internal excitation of nucleons in the $NN \rightarrow N\Delta$ and $\pi N \rightarrow \Delta \rightarrow \pi N$ channels. The global emission pattern of pions with respect to the baryonic event topology emerges from complex rescattering and absorption processes[13].

In this contribution the emphasis is on the direct identification of the $\Delta \rightarrow \pi N$ channel. In solving this task, the collective pion-nucleon behaviour appears only as a disturbing secondary correlation to be identified and rejected. As the major number of pions is believed to escape the reaction zone at a rather late stage, information about Δ's can be expected only to reflect the conditions at freeze-out, i.e. when nuclear matter density has become small enough, that the decay particles escape without further scattering.

The Δ mass distribution at freeze-out strongly influences the apparent temperatures of the measured pions. As was shown in ref. 4-6, the pion energy spectrum is rather sensitive to the Δ mass but almost independent of the Δ temperature, i.e. pion emission in heavy ion collisions is decay dominated. In order to understand the difference between the proton ($T_{app} \simeq 100$ MeV) and pion ($T_{app} \simeq 50$ MeV) apparent temperatures, it is necessary to determine the mass distribution of the Δ. In addition protons show collective behaviour, which has to be disentangled from the disordered thermal motion, in order to extract some meaningful temperature at freeze-out.

Almost no experimental data exist about Δ properties in nucleus - nucleus collisions. So far the results are quite contradictory: Δ mass distributions extracted from pion energy spectra favour an effective shift to lower masses by about $40-100$ MeV[4,5,6], while mass distributions directly obtained by (p,π) correlations from nucleus - nucleus reactions at $0.8-10.$ AGeV are consistent with an essentially free Δ[10,12].

Before dealing with the rather complex problem of (p,π) correlations in heavy ion collisions and presenting first results from the FOPI experiment, it is worthwhile to recall the results of a proton - nucleus experiment performed by the DIOGENE group in the same energy domain[7].

2. (p,π) Correlations in pA Collisions

Proton - nucleus collisions probe nuclear matter at low temperature and normal nuclear density. Therefore they provide some complementary information to heavy ion collisions in the same energy range. In addition, the pA system is smaller and the multiple collision cascade of the reaction is less complex than in a heavy ion reaction. In this sense, the pA system can be regarded as being intermediate between the elementary NN and the complex AA process. Unfortunately, most microscopic models leave out detailed studies on pA but rather directly go to the complex transport problem involved in AA collisions.

The experimental setup has been described in ref. 7. The main feature is the coincident registration of protons and charged pions in an polar angle range of $\Theta > 14°$ with full azimuthal symmetry. This leads to a large detection efficiency for

Figure 1: Effective Δ^{++} masses E_0 for the studied pA systems. A shift of about $20 \ldots 40$ MeV to lower masses is observed compared to the value of the free Δ within the used parametrization (dotted line). The data of the p+C system indicate an increasing shift with larger proton multiplicity m_p of the regarded event class.

protons and pions, which is required for a correlation analysis. The systems studied were p + A (A = C, Nb and Pb) at an incident proton energy of 0.8 and 1.6 GeV. As the particle multiplicities were rather low, only event classes were analyzed, where a π^+ was registered in coincidence with m_p protons ($m_p = 1, 2, 3$).

The invariant mass distributions for (p, π^+) pairs contains for all systems a non-vanishing contribution of correlated pairs from the Δ resonance. The decomposition into a background and a resonance part has been obtained by event mixing. For the small carbon system a strong signal shows up, which becomes weaker by going to the heavier niobium or lead target nuclei. This behaviour can be explained as due to the increasing system mass, when more and more nucleons contribute to the background.

The extracted Δ mass distributions have been fitted using the parametrization given by Cugnon[8], which gives a valid description of π^+p scattering data. The extracted values for the resonance mass E_0 are summarized in Fig. 1 for different proton multiplicities m_p. The result is that for all systems, a deviation of the value for E_0

from the free value (in this parametrization 1215 MeV) is seen. This shift to lower masses seems to get stronger with increasing m_p, at least for the light carbon system. Cascade calculations could reproduce this effect, and the following interpretation was adopted: For $m_p = 1$ almost quasi-free Δ excitation takes place. Requiring higher m_p values selects events where multiple nucleon nucleon collisions occur more often during the pA reaction. In this way, the incident proton energy is dissipated among more nucleons, and less energy is available for a Δ excitation. This reduced excitation probability can also be inferred from the decreasing π^+ multiplicities with increasing proton multiplicity m_p. In this sense, the shift of the Δ to lower masses reflects the reduction in the available phase space or simply energy conservation. As can be seen within the Cascade calculations, the dominant parameter governing the effective mass shift is the number of individual NN collisions or Δ generations in the course of the pA process.

In terms of local thermal equilibrium, the primary proton incident on a single target nucleon can be considered as a 'hot spot', which rapidly cools down, as a larger number of nucleons gets involved. With respect to heavy ion collisions, the scenario is completely different, since the same energy is available to all NN pairs. A similar cooling mechanism, if at all, can only exist at a rather late stage of the collision, when the system freezes out. Furthermore it is well known, that pion multiplicity increases with proton or participant multiplicity in contrast to the pA system.

3. (p, π) Correlations in AA Collisions

The data presented for nucleus - nucleus collisions are the first studies of (p, π) correlations by the FOPI collaboration at GSI. Concerning this analysis, the most important characteristics of the experimental setup is the coincident measurement of protons and charged pions by the Central Drift Chamber in an angular range of $\Theta_{lab} \in [30°, 150°]$. So far the data sets of the two systems Au + Au (1.0 AGeV) and Ni + Ni (1.9 AGeV) have been analyzed.

The large solid angle angle covered leads to a large acceptance for protons ($\simeq 50\%$) and pions ($\simeq 70\%$). The experimental difficulty in identifying a Δ signal therefore is not an acceptance problem but rather comes from the strong contributions to the combinatorial background of protons not originating from the Δ decay. Typical multiplicities for the Au + Au system are $M(p) \simeq 32$, $M(\pi^-) \simeq 6$ and $M(\pi^+) \simeq 3$ within the FOPI acceptance. This corresponds to a central event class with an impact parameter range $b \leq 3.5$ fm. Assuming that at SIS energies all pions are produced by the Δ decay, the problem of identifying Δ's then reduces to the problem of finding the corresponding proton to each registered pion, by means of a correlation technique. Due to the large combinatorial contributions of wrong (i.e. uncorrelated) (p, π) pairs, the relative amount $\mathcal{R}$ of true pairs from Δ decay can be estimated to be rather small:

$$\mathcal{R} = \frac{N(p,\pi)_\Delta}{N(p,\pi)_{all}} = \frac{M(\pi)}{M(p)} \cdot \alpha \cdot \epsilon_f \cdot \epsilon_d \tag{1}$$

Figure 2: a) Invariant mass distribution of correlated pairs taken out of the same event. b) Invariant mass distribution of uncorrelated pairs (mixed events). c) Extracted Δ^0 resonance signal, which represents 0.4% of all pairs in a).

This ratio turns out to be mainly the ratio of pion to proton multiplicities times certain efficiency factors: α accounts for the fact that only charged particles are measured and (n, π) correlations are not registered, ϵ_f denotes the efficiency of the proton after Δ decay to escape the freeze-out volume and ϵ_d finally describes the efficiency to register the proton in the detector. In order to estimate the amount of correlations in the (n, π) channel, assumptions about the isospin composition have to be made. This is done with the help of the isobar model[9], which gives a rather accurate description of the π^-: π^+ ratio and is considered also to give valid numbers for the population of the different Δ isospin states at freeze-out. As beforehand nothing is known about ϵ_f, it is set tentatively to 1.

With the given numbers for the Au + Au system the relative occurence $\mathcal{R}$ of (p, π^+) pairs from Δ's to all pairs is only 3.3% and even a factor of two smaller for (p, π^-) pairs. Since in heavy ion collisions the pion multiplicity increases with proton multiplicity, these numbers are fairly independent of the measured proton multiplicity

Figure 3: The extracted resonance signal for all investigated systems. These distributions have been fitted employing the parametrization given by Cugnon[8], and the results are summarized in table 1.

or centrality.

The usual method to identify two particle correlations is by means of event mixing. In this case the invariant mass distribution $\frac{dN}{dM}(p,\pi)$ of proton - pion pairs belonging to the same event are compared to the distribution obtained with pairs taken from different events. The expected signal is very weak, and experimentally it is a non-trivial task to compare the two distributions in order to reveal differences on a percent scale, as systematic errors may enter the analysis.

The results from the previous pA experiment and model calculations indicate, that the Δ mass distribution at freeze-out may be different from the free Δ mass distribution. Therefore special care has to be taken to ensure that no secondary (p,π) correlations or systematic errors mimic this mass distribution.

Several secondary correlations between pions and protons could be identified in the course of the analysis:

(1) Protons show collective behaviour with regard to the reaction plane. Also pi-

Table 1: Fitparameters for all extracted resonances. The normalization constant $\mathcal{R}$ indicates the relative abundancy of the Δ -correlated (p, π) pairs compared to all pairs. The value ϵ_f indicates the difference of the extracted normalization compared to the values given by Eq. 1.

System	E_0[MeV]	Γ_0[MeV]	$\mathcal{R}$ [%]	ϵ_f
Au+Au (1 AGeV) Δ^{++}	1217(15)	251(21)	0.8(0.2)	0.24
Au+Au (1 AGeV) Δ^0	1229(19)	223(29)	0.4(0.1)	0.25
Ni+Ni (1.9 AGeV)Δ^{++}	1182(9)	207(12)	1.4(0.4)	0.22
Ni+Ni (1.9 AGeV)Δ^0	1198(12)	144(13)	0.8(0.2)	0.41
free Δ	1215	110		

ons exhibit a weak orientation with respect to the reaction plane. This phenomenon generates a secondary correlation between π and p, which disturbs the true Δ. This finding is consistent with recent identification of 'pion flow' in the same data sample[3].

(2) The (p, π) invariant mass distribution reflects the single particle phase space occupancy for protons and pions. The invariant mass turns out to depend rather sensitively on the proton multiplicity m_p (i.e. centrality) of the chosen data sample, due to the fact, that the apparent particle temperatures increase with increasing m_p. Therefore already small deviations of the m_p spectrum in the direct and mixed pairs data sample lead to disturbing correlations. Special attention was taken to ensure that, for both samples considered, the m_p distributions were identical.

(3) Experimental deficiencies (detector setup, tracking algorithm) cannot be neglected, but rather show up clearly within this correlation analysis. Especially large disturbing signals exist for small relative angles between protons and pions. These effects have to be avoided by certain cuts in the analysis.

The general rule applied to avoid secondary correlations was either to cut them out with proper conditions (e.g. small angle correlations) or to make sure they occur with identical strength in the direct and mixed pair data samples (e.g. reaction plane), so that they cancel during background subtraction. For a more detailed and critical treatment of event mixing techniques see ref. 10. The experimental resolution of the (p, π) invariant mass can be estimated from the recent identification of Λ hadrons in the Ni + Ni (1.9 AGeV) system[16]: The Λ peak appears at a (p, π^-) invariant mass of $E_0 = 1.118$ GeV with a gaussian width of $\sigma = 6.7$ MeV.

4. Results

Figs. 2a,b show as an example the (p, π^-) invariant mass distributions for the correlated (same event) and uncorrelated (mixed event) data samples in the Au + Au (1

Figure 4: The mass distribution of Δ^{++} resonances at freeze-out in the framework of the IQMD model[13,14]. A large effective shift of almost 100 MeV to lower masses compared to the free Δ is found. Included also is the influence of the FOPI detector acceptance[15].

AGeV) system. The mixed sample was constructed with three times the statistics to reduce fluctuations. The difference between the two spectra after a proper normalization, which required the smallest signal compatible with a non-negative threshold behaviour, is shown in Fig. 2c. Assuming that all secondary correlations have been properly subtracted, this remaining signal has to be attributed to the Δ^0 resonance.

The peak appears around the position of the free Δ and the width is slightly larger than that of the free resonance, which means a larger population of the higher masses.

Similar results are obtained also for Δ^{++} in the Au + Au data as well as for Δ^0 and Δ^{++} in the Ni + Ni data. The extracted Δ signals for all systems are displayed in Fig. 3.

In order to interpret the significance of the resonance signals, fits employing the Cugnon parametrization[8] were applied and included in the figures. The extracted values for Δ mass E_0, width Γ_0 and the normalization constant $\mathcal{R}$ are given in table 1. It should be stressed, that these numbers reflect the energy available for the excitation of nucleons at freeze-out rather than real in-medium modifications of the intrinsic properties of the Δ. The number ϵ_f denotes the efficiency, with which the Δ decay products, i.e. the proton and pion, were observed undistorted. It can be interpreted as a probability for the proton, to escape the freeze-out volume without further scattering, since the interaction of the pions with nuclear matter would lead to absorption.

5. Conclusions

The analysis of $(p, \pi^{\pm})$ pairs in the reaction Au + Au (1 AGeV) and Ni + Ni (1.9 AGeV) reveals the existence of a weak correlation signal, which has to be attributed to the decay of the Δ resonance. The peak positions for both accessible Δ charge states and both systems appear to be close to the free Δ mass. Compared to the free resonance a larger population of the higher masses was observed, which can be parametrized by a larger effective width.

This result is consistent with earlier measurements[10,12], which yield, over a wide range of energy and system size, resonance signals compatible with a free Δ. It is also in agreement with the expectation of a pure thermal picture[11], where the population of the higher nucleon states (Δ, N^*) shows an only weak dependence on the system temperature.

This experimental result is not consistent with the expectations from the IQMD model[13,14] for the Au + Au (1 AGeV) system. The population of Δ masses at freeze-out in IQMD, using a hard equation of state and including momentum dependence, is shown in Fig. 4. In order to make the comparison with the experimental data, only those Δ's were considered, where both, p and π, escape the reaction zone without further scattering. The influence of the FOPI detector acceptance is also shown[15]. The striking result of the calculation is the large shift of the Δ's effective mass, with a peak position around 1140 MeV.

This large deviation from a free resonance is not seen in the experimental data. Further detailed studies are necessary, which should clarify, how far the used correlation techniques lead to a distortion of the invariant mass spectrum, especially at low masses. As the analyzed data represent only about 25% of the recorded statistics, further studies should allow a more detailed selection of e.g. centrality and $p_t(\Delta)$, in order to reveal possible dependencies on the reaction dynamics.

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