In-medium modification of the \( \Delta(1232) \) resonance at SIS energies \(^*\)

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Abstract

From the pion production rates \( n_\pi/A_{\text{part}} \) and the pion charge ratios \( R_\pi = n_{\pi^-}/n_{\pi^+} \) and \( S_\pi = n_{\pi^0}/(n_{\pi^-} + n_{\pi^+}) \), measured in p + a and A + A reactions, it is concluded that the mass of the \( \Delta(1232) \) resonance is reduced in dense nuclear matter. This conclusion is supported by the \( \Delta(1232) \) mass distribution extracted from correlated \((p,\pi^\pm)\) pairs and the \( \pi^\pm \) transverse momentum distributions.

1 Introduction

The experimental verification that the properties of hadrons are modified in the dense nuclear medium produced by relativistic nucleus-nucleus collisions is of great interest since the partial restoration of chiral symmetry would lead to such modifications, in particular it predicts the reduction of the \( K^- \) mass \([1]\). In this contribution I will survey the experimental information with regard to pions produced in p + A and A + A reactions at SIS energies. I will show that these data can be interpreted as the result of a \( \Delta(1232) \) mass reduction. This interpretation is based on two simple models, the thermal and the isobar models, and the conclusion is confirmed by the direct measurement of the \( \Delta(1232) \) mass distribution.

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2 The Thermal Model

In order to obtain the charge states of hadrons from the thermal model one has to introduce the isospin chemical potential $\mu_I$, besides the baryon chemical potential $\mu_B$ and the temperature $T$. Defining $x = e^{-\mu_I/T}$ one obtains for the charges states of nucleons and pions:

$$n_p = \frac{n_N}{2} x^{+1}, \quad n_n = \frac{n_N}{2} x^{-1} \quad (1)$$

$$n_{\pi^+} = \frac{n_{\pi^+}}{3} x^{+2}, \quad n_{\pi^0} = \frac{n_{\pi^0}}{3}, \quad n_{\pi^-} = \frac{n_{\pi^-}}{3} x^{-2} \quad (2)$$

$$n_{\Delta^{++}} = \frac{n_{\Delta^{++}}}{4} x^{+3}, n_{\Delta^{+}} = \frac{n_{\Delta^{+}}}{4} x^{+1}, n_{\Delta^0} = \frac{n_{\Delta^0}}{4} x^{-1}, n_{\Delta^-} = \frac{n_{\Delta^-}}{4} x^{-3}, \quad (3)$$

where $n_N$, $n_\pi$, and $n_\Delta$ are determined by $\mu_B$ and $T$. Since charge and baryon number are conserved the following relations between $x$, the pion production rate $n_\pi/A_{\text{part}}$, and the N/Z ratio $\zeta_{\text{part}}$ of the participants should hold:

$$1 = \frac{\zeta_{\text{part}} + 1}{2} x + \frac{n_\pi}{A_{\text{part}}} \frac{\zeta_{\text{part}} + 1}{3} \left(x^2 - x^{-2}\right) \quad (4)$$

$$1 = \frac{\zeta_{\text{part}} + 1}{2} x + \frac{n_\pi}{A_{\text{part}}} \frac{\zeta_{\text{part}} + 1}{4} \left(2x^3 - x - x^{-3}\right). \quad (5)$$

The first equation is valid in case the participant region only contains nucleons and pions, the second if it contains only nucleons and $\Delta(1232)$ resonances, where the $\Delta(1232)$ after freeze-out decay into pions. The importance of these equations is due to the fact that they only depend on known ($\zeta_{\text{part}}$) and measured ($n_\pi/A_{\text{part}}$) quantities, and that $x$ can be deduced from the measured pion charge ratios $R_\pi = n_{\pi^-}/n_{\pi^+}$. Note that $n_\pi/A_{\text{part}}$ requires to know the production rates $n_{\pi^0}/A_{\text{part}}$ of neutral pions, these rates have been measured for a number of $A + A$ reactions by the TAPS collaboration [2], but they are unknown for the $p + A$ reactions considered here. In this latter case I have assumed $n_{\pi^0} = n_{\pi^-} + n_{\pi^+}$. This assumption has only little consequences for the present discussion, but its experimental confirmation would add support to the interpretation of the existing data advocated in this report.

The data have been measured for Ni + Ni [3], Au + Au [4], and p + C/Nb/Pb [5] reactions in the energy range between 1 to 2 AGeV and at several impact parameters $b$, I have chosen central collisions by extrapolating to $b \to 0$. The extrapolated results, which include the production rates of the $\Delta(1232)$ resonance [3] [6], are in conflict with the equations [3] if one assumes for each reaction a unique temperature and baryon chemical potential. In order to be consistent with charge and baryon number conservation the different observables would require in general different
Table 1: Participant temperatures $T$ extracted from different observables assuming a participant density $\rho = 0.3\rho_0$. The numbers in brackets give the incident energy in AGeV.

| reaction         | $T(R_\pi)$ | $T(n_\pi)$ | $T(n_\Delta)$ | $T$(slope) |
|------------------|------------|------------|---------------|------------|
| Au+Au(1.06)      | 56 ± 5     | 55 ± 2     | 66 ± 5        | 81 ± 24    |
| Ni+Ni(1.06)      | < 50       | 62 ± 2     | 75 ± 3        | 79 ± 10    |
| Ni+Ni(1.45)      | < 50       | 68 ± 2     | 84 ± 4        | 84 ± 10    |
| Ni+Ni(1.93)      | < 55       | 73 ± 2     | 93 ± 3        | 92 ± 12    |

Temperatures which are shown in table 1. In this table I have also included the temperature values which were deduced from the slopes of the energy spectra of various particles emitted from the participant region $[8] [9]$. One finds that the slope temperatures are within errors consistent with $T(n_\Delta)$, but that in general

$$T(R_\pi) < T(n_\pi) < T(n_\Delta).$$

(6)

In case of p + A reactions the data would not allow to obtain any meaningful solution to the equations $[3][4]$. This implies that within this very simple framework the thermal model is unable to explain the measured data, and the problem can be traced in case of the A + A reactions to the measured number of pions which is too small to accommodate the measured number of $\Delta(1232)$ resonances and the calculated number of thermally produced pions. In addition the $R_\pi$ ratios suggest that their values largely depend on the type of charge exchange reactions that occur between the pions and the nucleons of the participant region.

### 3 The Isobar Model

The isobar model allows to calculate the charge ratios of pions and nucleons with the assumption that pions are exclusively produced by the decay of baryon resonances $B$, which were excited in a first step by the reaction $N + N \rightarrow N + B$. Isospin conservation yields for this first step in the cases in which $B$ stands for the $\Delta$ resonance

$$n_{\pi^-} : n_{\pi^0} : n_{\pi^+} = \left(\zeta_P + \zeta_T + 10\zeta_P\zeta_T\right) : \left(2 + 4\zeta_P + 4\zeta_T + 2\zeta_P\zeta_T\right) : \left(10 + \zeta_P + \zeta_T\right),$$

(7)
where $\zeta_P, \zeta_T$ are the N/Z ratios of the projectile respectively the target. These relative numbers are modified when the emitted pions are reabsorbed in participant matter and form new $\Delta$ resonances which subsequently decay by pion emission. The final pion numbers depend on the number $n_{\text{loop}}$ of such $\pi N \Delta$ loops since two successive loops $i$ and $i + 1$ ($i < n_{\text{loop}}$) are coupled by the equations:

$$
\begin{align*}
n_{\pi^+}^{(i+1)} &= \left(n_p^{(i)}\frac{2}{3}n_{\pi^0}^{(i)} + n_n^{(i)}\frac{2}{3}n_{\pi^+}^{(i)} + n_n^{(i)}\frac{1}{3}n_{\pi^-}^{(i)}\right) / A_{\text{part}}, \\
n_{\pi^0}^{(i+1)} &= \left(n_p^{(i)}\frac{2}{3}n_{\pi^0}^{(i)} + n_n^{(i)}\frac{2}{3}n_{\pi^+}^{(i)} + n_n^{(i)}\frac{1}{3}n_{\pi^0}^{(i)}\right) / A_{\text{part}}, \\
n_{\pi^-}^{(i+1)} &= \left(n_p^{(i)}\frac{1}{3}n_{\pi^+}^{(i)} + n_n^{(i)}\frac{1}{3}n_{\pi^0}^{(i)} + n_n^{(i)}\right) / A_{\text{part}}.
\end{align*}
$$

The $n_{\pi}$ numbers do not change anymore once $n_{\text{loop}} > 10$ in the reactions considered here. For the $R_\pi$ ratios these saturation values are shown in Fig.1, and for the ratios $S_\pi = n_{\pi^0}/(n_{\pi^-} + n_{\pi^+})$ in Fig.2. Note that I have normalized the $R_\pi$ and $S_\pi$ values by the predictions derived from equation 7, i.e. $R_\pi^{(0)} = S_\pi^{(0)} = 1$ would imply that
Figure 2: As in Fig.4 but for the normalized neutral to charged pion ratio $S_{\pi}^{(0)}$. Experimental data (symbols) only exist for $A + A$ reactions.

the value of $n_{\text{loop}}$ is sufficiently small not to modify the ratios of the first step. The saturation values of $R_{\pi}^{(0)}$ and $S_{\pi}^{(0)}$ depend in case of $p + A$ reactions on the size $A_{\text{part}}$ of the participant, but not in case of $A + A$ reactions. The dependence on the excitation probability of the $\Delta$ resonance, listed in Fig.1 and 2 by the percentages, is only weak. The comparison with the data shown by symbols indicates that to explain the $p + A$ results one has to assume the presence of sufficiently many $\pi N \Delta$ loops, but that in the case of $A + A$ reactions the number of such loops is much smaller since for both ratios one observes $R_{\pi}^{(0)} \approx S_{\pi}^{(0)} \approx 1$.

There exist 2 possible explanations for this difference between the behavior of $p + A$ and $A + A$ reactions:

- The decay probability of $\Delta(1232)$ resonances decreases in participant matter which reduces the number of $\pi N \Delta$ loops,

- The absorption probability of $\Delta(1232)$ resonances via the $\Delta + N \rightarrow N + N$ reaction increases in participant matter which also reduces the number of $\pi N \Delta$ loops.

Of these two alternatives the second explanation is favored by the experimental observation that the pion production rate depends on the total system mass $A_0 = A_P + A_T$. The measured $n_\pi/A_{\text{part}}$ values, integrated over the impact parameter, may be fitted for incident energies from 1 to 2 AGeV by the relation

$$\frac{\langle n_\pi \rangle}{\langle A_{\text{part}} \rangle} = a_\pi \cdot (E_{\text{kin}} - 0.11),$$

\[ (9) \]
where the cm energy $E_{\text{kin}}$ is given in AGeV. The line in Fig. 3, it displays a linear decrease with rising system mass number $A_0$ except the one at $A_0 = 2$. It is evident that compared to $p + p$ reactions the pion production rate is suppressed in $A + A$ reactions, and the suppression is the stronger the heavier the system is, or the larger the participant density is which can be attained in nucleus-nucleus collisions. More insight into the mechanism which might cause the rise of the absorption cross section is gained by studying the $\Delta(1232)$ mass distribution in participant matter.

4 The $\Delta(1232)$ Mass Distribution

The mass distribution of the $\Delta(1232)$ resonance in participant matter can be reconstructed from the transverse momentum spectra $d\sigma/dp_t$ of pions, or from the invariant mass of $(p,\pi)$ pairs. The former technique was applied in $A + A$ reactions [7], the latter also in $p + A$ reactions [12]. I display the results for central Ni + Ni and Au + Au reactions in Fig. 4 lower panels, where the dark points correspond to the $d\sigma/dp_t$ technique and the stars to the $(p,\pi)$ technique. For the $p + C$ reaction the equivalent data are displayed in Fig. 4 upper panel. In general the mass distributions are shifted from the mass distribution of the free $\Delta(1232)$ resonance (dashed curves) towards smaller masses. In case of the $p + C$ reaction this shift can be explained in the framework of the thermal model by the finite temperature $T = 65$ MeV of the participants, the deviations from the expected mass distribution at higher masses are most likely due to first-chance $N + N$ collisions. Contrary to these findings, in Ni + Ni and Au + Au reactions the observed mass shifts are only
partly reproduced by the participant temperatures $T(n_\pi)$ of table 1 (dotted curves). To obtain a fit of the experimental mass distributions additional shifts of $\approx -100$ MeV/c$^2$ in case of Au + Au, and $\approx -50$ MeV/c$^2$ in case of Ni + Ni are necessary. The data do not allow to obtain a more quantitative result, in particular they do not allow to disentangle the medium effects onto the mass and the width of the distribution. The size of the in-medium modification depends on the system mass, and the result for Ni + Ni is in fair agreement with similar data for the Ni + Cu reaction published in [13].
5 Discussion

The analyses of the pion data from $p + A$ and $A + A$ reactions at SIS energies have yielded convincing evidence that

1. the $\Delta(1232)$ absorption increases,
2. the $\Delta(1232)$ average mass is reduced

as function of the average participant density which increases with the system mass. These two phenomena are indeed related by the "extended principle of detailed balance" via

$$\sigma_{n\Delta^{++} \rightarrow pp} = \frac{1}{4} \frac{\rho_N^2}{\rho_\Delta^2} \sigma_{pp \rightarrow n\Delta^{++}} \frac{1}{f_{(\sqrt{s-m_N})^2} \ f_{\Delta}(m^2) \ dm^2}, \quad (10)$$

where $\sigma_{n\Delta^{++} \rightarrow pp}$ is the partial absorption cross section for the $\Delta(1232)$ resonance in the reaction $\Delta + N \rightarrow N + N$, and $f_{\Delta}(m^2)$ is the in-medium mass distribution of the $\Delta(1232)$ resonance. The equation (10) has been studied in \[4\] and \[13\], the differences in these studies have to be resolved before a detailed comparison with the experimental results can be accomplished. It is of interest that in \[13\] the mass shift was found to become weaker with rising impact parameter. In terms of the presently advocated interpretation this implies a reduction of the pion absorption. Experimentally the pion production rate $n_\pi/A_{\text{part}}$ depends on $A_{\text{part}}$, however the dependence is different for $\pi^-$ and $\pi^+$ \[3\] \[4\]. Therefore Coulomb effects have to play an important role in the pion dynamics.

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