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$\pi\pi$ correlations in $\gamma + \mathrm{A}$ reactions

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Abstract. Preliminary differential cross-sections of the reactions $A(\gamma,\pi^0\pi^0)$ and $A(\gamma,\pi^0\pi^+ + \pi^0\pi^-)$ with $A = {}^1\mathrm{H}$, ${}^{12}\mathrm{C}$, and ${}^{\mathrm{nat}}\mathrm{Pb}$ are presented. A significant nuclear-mass dependence of the $\pi\pi$ invariant-mass distribution is found in the $\pi^0\pi^0$ channel. The dependence is not observed in the $\pi^0\pi^\pm$ channel. The in-medium observation in the $\pi^0\pi^0$ channel is consistent with an in-medium modification of the $\pi\pi$ interaction in the $I = J = 0$ channel, changing width and pole position of a $\pi\pi$ resonant state.

PACS. 13.60.Le Meson production – 21.65.+f Nuclear matter

1 Introduction

One of the challenges in nuclear physics is to study the properties of hadrons embedded in a nuclear many-body system. This contribution reports on the photoproduction of correlated pion pairs on nuclei in the scalar-isoscalar $J = I = 0$ channel, also known as the σ-meson. In ref. [1] the σ-meson is identified as the $f_0(400–1200)$. The large natural width in free space of $\Gamma = 400–500\,\mathrm{MeV}$ [2] makes it doubtful that this particle is a mesonic $q\bar{q}$ state. Alternatively, the σ-meson is considered to be a resonant state of two pions [3,4]. In vacuum, the $\pi\pi$ system is mildly attractive. However, in the nuclear medium the $\pi\pi$ interaction strength could increase thereby changing width and pole position of the resonant state. Experimental data on correlated $\pi\pi$ pairs in dense nuclear matter can clarify the nature of the σ-meson.

The first measurement of the in-medium $\pi\pi$ mass was obtained by a pion-induced experiment by the CHAOS Collaboration [5]. A rising accumulation of strength at low $\pi^+\pi^-$ mass was observed with increasing nuclear mass whereas such an enhancement was not seen in the $\pi^+\pi^+$-mass distributions. This effect was interpreted as a signature for an in-medium modification of the $\pi\pi$ interaction in the $I = J = 0$ channel. A similar effect was found by a pion-induced experiment of the Crystal Ball Collaboration [6] where a nuclear-mass dependence of the $\pi^0\pi^0$-mass distribution was observed.

For the interpretation of the pion-induced measurements the strong interaction of the initial-state pion with the medium has to be taken into account. As a result, only the surface of the nucleus is probed, leading to a small effective nuclear density. It was proposed to produce in-medium $\pi\pi$ pairs with electromagnetic probes which illuminate the complete nucleus and lead to a larger effective density.

In this contribution, measurements of $A(\gamma,\pi^0\pi^0)$ and $A(\gamma,\pi^0\pi^\pm)$ for $A = {}^1\mathrm{H}$, ${}^{12}\mathrm{C}$, and ${}^{\mathrm{nat}}\mathrm{Pb}$ are presented. The measurements allow to study the different $\pi\pi$-isospin states at average effective densities of 35% (${}^{12}\mathrm{C}$) to 65% (${}^{208}\mathrm{Pb}$) [7] of the interior nuclear density of $0.17\,\mathrm{fm}^{-3}$. Data are presented for an incident-photon energy of $E_\gamma = 400–460\,\mathrm{MeV}$. The energy was chosen to be small to minimize the effect of final-state interactions of the two pions with the medium and to prevent background from the $\eta \to 3\pi^0$ channel.

2 Experiment and analysis

The experiment was performed at the photon-beam facility at MAMI-B. Tagged photons [8] were produced with energies between 200 and 820 MeV. The beam intensity in the energy range of interest, $E_\gamma = 400–460\,\mathrm{MeV}$, was $10^7\,\mathrm{s}^{-1}$ with a photon-energy resolution of about 2 MeV. A series of measurements were carried out using liquid-hydrogen, carbon, and lead targets.

The angles and energies of the pions were measured using the TAPS photon spectrometer [9] consisting of 510 hexagonal BaF_2 scintillators. The detector is depicted in fig. 1. The complete setup covered $\approx 40\%$ of the total solid angle. Photons and charged pions were identified by exploiting the time-of-flight information of each detector. A 5 mm thick plastic scintillator was placed in front of each crystal to differentiate between neutral and charged particles.

Neutral pions were identified by an invariant-mass analysis of the two decay photons. For the identification of

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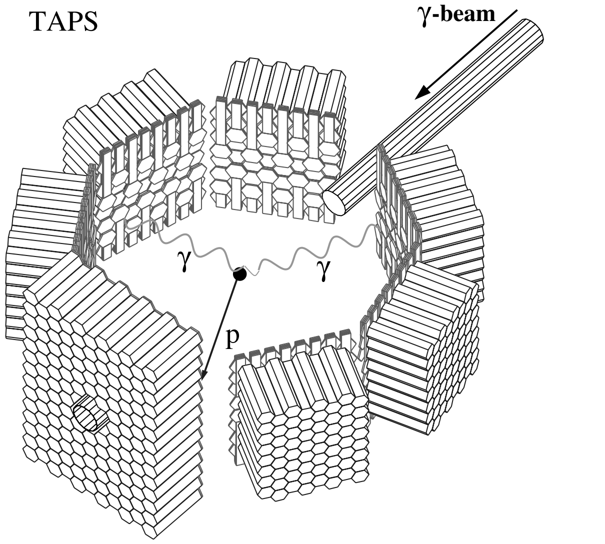

Fig. 1. The photon spectrometer TAPS consisting of 510 hexagonal BaF_2 scintillators and the 5 mm thick plastic scintillators. An event originating from π^0 production on a quasi-free proton is illustrated.

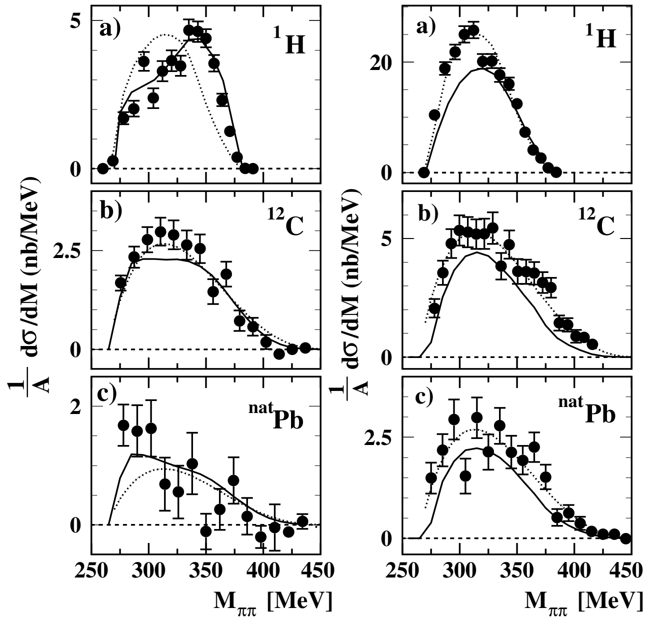

Fig. 2. Preliminary differential cross-sections of the reaction $A(\gamma, \pi^0\pi^0)$ (left panel) and $A(\gamma, \pi^0\pi^\pm)$ (right panel) for incident photons in the energy range of 400–460 MeV (solid circles). Error bars denote statistical uncertainties and the curves are explained in the text.

the $A(\gamma, \pi^0\pi^0)$ reaction, all four final-state photons were registered in the detector. Charged pions from $A(\gamma, \pi^0\pi^\pm)$ were selected by exploiting the information on the time-of-flight of the charged pion relative to the one of the photons of the π^0 decay and its deposited energy in the BaF_2 crystals [10]. Since the TAPS detector does not include a magnetic field, positively charged particles cannot be discriminated from negatively charged particles.

The dominant reaction mechanism in $A(\gamma, \pi^0\pi^0)$ and $A(\gamma, \pi^0\pi^\pm)$ channels is the quasi-free production on the constituent nucleons. Under this assumption, the undetected recoil nucleon was deduced from the incident photon energy and the momenta of the final-state pions. Its reconstructed mass distribution was found to be consistent with Monte Carlo simulations using a quasi-free event generator. The background of the $\eta \to 3\pi^0$ production channel does not contribute, since the incident-photon energy of $E_\gamma = 400$–460 is below the η production threshold.

3 Results and discussion

The measured $M_{\pi^0\pi^0}$-mass distributions for incident-photon energies of $E_\gamma = 400$–460 MeV are shown in the left panel of fig. 2. A strong increase in strength towards small $M_{\pi^0\pi^0}$ with increasing A is observed. The dotted curves in fig. 2 indicate phase space distributions. The experimentally observed peak position for $A = {}^1$H (a) lies higher than the phase space prediction, whereas for $A = {}^{12}$C (b) the measured mass distribution is compatible with phase space. For $A = {}^{nat}$Pb (c), most of the observed strength lies below the peak of the phase space distribution. The experimentally determined angular distributions in the $A(\gamma, \pi^0\pi^0)$ reaction of the $\pi^0\pi^0$ center-of-mass system are found to be isotropic [10] and are compatible with $J = 0$, supporting the conclusion that a significant A-dependence is found in the $\pi\pi$ $I = J = 0$ channel in photon-induced reactions.

The right panel of fig. 2 depicts preliminary results of the reactions $A(\gamma, \pi^0\pi^\pm)$. The data do not show an A-dependence in shape as was observed in the corresponding $M_{\pi^0\pi^0}$ distributions. For all targets, the data follow the phase space distributions depicted as dotted curves, indicating that significant in-medium effects in the isospin $I = 1$ channel are not observed. Furthermore, this observation indicates that the in-medium modification in the $\pi^0\pi^0$ channel cannot be explained by final-state interactions of the individual pions with the medium, as a similar behaviour for both exit channels would otherwise be expected.

The solid curves in fig. 2 are predictions by Roca *et al.* [4,7]. Here, the meson-meson interaction in the scalar-isoscalar channel is studied in the framework of a chiral-unitary approach at finite baryonic density. The model dynamically generates the σ-resonance, reproducing the meson-meson phase shifts in vacuum and accounts for the absorption of the pions in the nucleus. It qualitatively predicts a mass shift as observed in the $\pi^0\pi^0$ data. The basic ingredient driving this shift is the p-wave interaction of the pion with the baryons in the medium, resulting in an in-medium modification of the $\pi\pi$ interaction. A similar calculation [11] is not able to describe the observed A-dependence effect in the $A(\pi^-, \pi^0\pi^0)$ data [6], which might be due to the interaction of the initial-state pion. Since the σ-resonance does not couple to $\pi^0\pi^\pm$, the model does not show significant change in the shape of the mass distributions between $A =$ H, $A = {}^{12}$C, and $A = {}^{nat}$Pb,

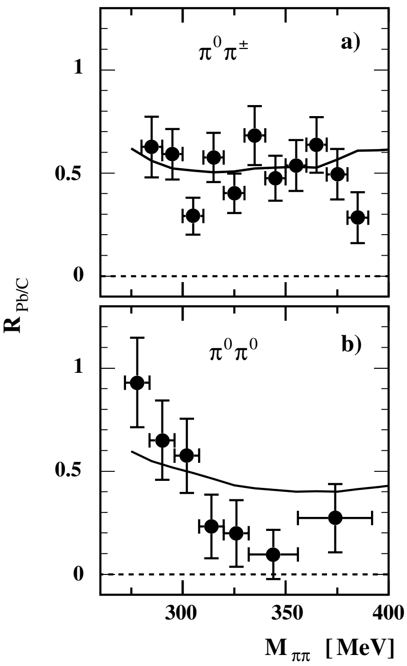

Fig. 3. Preliminary ratios between the differential cross-sections for $A = {}^{nat}$Pb and $A = {}^{12}$C for $A(\gamma, \pi^0\pi^\pm)$ (a) and $A(\gamma, \pi^0\pi^0)$ (b). The solid curves represent predictions by Roca *et al.* [4,7].

which agrees with the experimental observation as shown in the right panel of fig. 2.

Figure 3 shows the ratio $R_{\mathrm{Pb/C}}$ between the differential cross-sections per nucleon for $A = {}^{nat}$Pb and $A = {}^{12}$C of the reactions $A(\gamma, \pi^0\pi^\pm)$ (a) and $A(\gamma, \pi^0\pi^0)$ (b) up to $M_{\pi\pi}$ masses of 400 MeV. The ratio $R_{\mathrm{Pb/C}}$ indicates that about half of the final-state pions is absorbed in the nucleus. The final-state effects of the pions become larger with increasing mass number A. The experimentally determined ratio $R_{\mathrm{Pb/C}}$ for the $\pi^0\pi^\pm$ reaction is found to be flat, indicating that final-state interactions, absorption, and rescattering of the individual pions with the medium do not modify the shape in the mass distribution significantly. The model of Roca *et al.* [7] supports this conclusion as can be observed from the solid curve. Furthermore, the predictions for $R_{\mathrm{Pb/C}}$ agree in magnitude with the experimental data, which indicates that the final-state effects of pions are properly taken into account by the calculations. In contrast to the $\pi^0\pi^\pm$ data, a significant in-medium shape effect is observed in the ratio $R_{\mathrm{Pb/C}}$ for the $\pi^0\pi^0$ channel as depicted in fig. 3(b). Since final-state interactions of neutral and charged pions are expected to be similar, such large effect cannot be explained by an A-dependence in the final-state interactions of the individual pions with the medium. Hence, the observed in-medium effect points to an A-dependence in the $I = J = 0$ $\pi\pi$ interaction. The prediction by Roca *et al.* [4] with a theoretical uncertainty of 10% [7] is depicted as the solid curve in fig. 3(b).

4 Conclusion

An effect consistent with a significant in-medium modification in the $A(\gamma, \pi^0\pi^0)$ $(I = J = 0)$ channel has been observed. With increasing A, the strength in these distributions is shifting towards smaller invariant masses. Earlier measurements using pion beams found a similar, but less pronounced effect. Photon-induced experiments have the advantage that initial-state interactions are absent and larger effective densities can be reached which enhance in-medium effects. The distortion of the $\pi\pi$-mass distribution due to final-state interactions of the individual pions with the constituents of the nucleus has been studied by measuring the $\pi^0\pi^\pm$ mass distribution concurrently. A significant in-medium effect was not observed. According to Roca *et al.* [4], a dominant part of the modification observed in the $\pi^0\pi^0$-mass distributions can be attributed to a change of the $\pi\pi$ interaction. The comparison with the experimental data hints at the nature of the σ-meson as a $\pi\pi$-resonance.

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