In-Medium Modifications of the $\pi\pi$ Interaction in Photon-Induced Reactions

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Differential cross sections of the reactions $(\gamma, \pi^0\pi^0)$ and $(\gamma, \pi^0\pi^{+/-})$ have been measured for several nuclei (^{1}H,^{12}C, and ^{nat}Pb) at an incident-photon energy of $E_\gamma = 400$–460 MeV at the tagged-photon facility at MAMI-B using the TAPS spectrometer. A significant nuclear-mass dependence of the $\pi\pi$ invariant-mass distribution is found in the $\pi^0\pi^0$ channel. This dependence is not observed in the $\pi^0\pi^{+/-}$ channel and is consistent with an in-medium modification of the $\pi\pi$ interaction in the $I = J = 0$ channel. The data are compared to π-induced measurements and to calculations within a chiral-unitary approach.

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One of the challenges in nuclear physics is to study the properties of hadrons and the modification of these properties when the hadron is embedded in a nuclear many-body system. Although much has been learned about the properties of hadrons in free space, there is a lack of information for particles in a dense environment. In this Letter, an experiment is described which has measured correlated pion pairs photoproduced on nuclei in the scalar-isoscalar $J = I = 0$ channel, also known as the σ mode. 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 MeV [2] makes it doubtful that this particle is a mesonic state, and has initiated many discussions on its nature. An in-medium study of the $I = J = 0$ channel could provide a better insight into the nature of the σ meson.

Within some theoretical approaches of quantum chromodynamics (QCD) [3–5], the σ is treated as a pure $q\bar{q}$ state ($J^P = 0^+$) and regarded as the chiral partner of the pion ($J^P = 0^-$). Chiral symmetry is spontaneously broken in the QCD vacuum, resulting in a mass difference between the pion and the σ. For large baryon densities, it is predicted that chiral symmetry is partially restored, leading to a degeneracy in mass of the pion and the σ. Since the pion approximates a Goldstone boson, the pion mass is not expected to change dramatically with increasing nuclear density ρ. Hence, these models predict a significant drop in the mass of the σ. A measurement of the in-medium $\sigma \rightarrow \pi\pi$ mass distribution might be essential for the understanding of the mechanism of chiral-symmetry breaking.

Alternatively, the in-medium σ mode can be considered to be a resonant state of two pions [6–9]. 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 the density dependence of pion-pair interactions in the nuclear medium can provide evidence for this phenomenon.

The first measurement of the in-medium $\pi\pi$ mass was obtained by a pion-induced experiment by the CHAOS Collaboration [10–12]. 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 [13] where a nuclear-mass dependence of the $\pi^0\pi^0$-mass distribution was observed.

For the interpretation of the previously described pion-induced measurements two issues have to be addressed. The first one results from the final-state interactions, rescattering and absorption, of the pions. Such effects distort the actual $\pi\pi$-mass measurement. To minimize pion final-state interactions, the incident-beam energy was chosen such that the energies of the outgoing pions were small, thereby maximizing their mean-free path. The second issue is the strong interaction of the initial-state pion with the medium. As a result, only the surface of the nucleus is probed, leading to a small effective nuclear density. The authors of Ref. [14] estimate an average density of 24% of the interior nuclear density $\rho_0 = 0.17$ fm^{-3} for ^{40}Ca. It was therefore 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 Letter, we present measurements of $A(\gamma, \pi^0\pi^0)$ and $A(\gamma, \pi^0\pi^{+/-})$ for $A = {}^1$H, ^{12}C, and ^{nat}Pb. These measurements allow a study of the different $\pi\pi$-isospin states at average effective densities of 35% (^{12}C) to 65% (^{208}Pb) [15] of ρ_0 and are statistically superior to

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previously published data on photon-induced double-pion production [16,17]. Data are presented for an incident-photon energy of $E_\gamma = 400$–460 MeV. The centroid of this interval corresponds to the same center-of-mass energy as was used in the pion-induced experiments, enabling a direct comparison and minimizing the effect of final-state interactions of the two pions with the medium.

The experiment was performed at the photon-beam facility at MAMI-B. Tagged photons [18,19] were produced with energies between 200 and 820 MeV. The beam intensity in the energy range of interest, $E_\gamma = 400$–460 MeV, was 10^7 s^{-1} with a photon-energy resolution of about 2 MeV. After collimation, the photon beam was transported to a nuclear target in an evacuated beam line. A series of measurements were carried out using liquid-hydrogen, carbon, and lead targets with thicknesses of 10 cm, 2.5 cm, and 5 mm, respectively. The photon-conversion ($\gamma \rightarrow e^+ e^-$) probability for all targets is smaller than 10%.

The angles and energies of the pions were measured using the TAPS photon spectrometer [20]. In this experiment, the TAPS detector consisted of 510 hexagonal BaF_2 scintillators. Sixty-two crystals, arranged in an 8×8 matrix, formed a TAPS block. Six blocks were mounted coplanar with the target at a distance of 55 cm and polar angles of $\pm 55°$, $\pm 105°$, and $\pm 155°$ with respect to the photon-beam direction. The remaining 138 BaF_2 crystals were arranged in a rectangular forward wall which covered polar angles between 5° and 38°. 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. The two-photon invariant-mass resolution (σ) for π^0 is 5.7%. A kinematic fit was applied to improve the pion-energy resolution [21]. For the identification of the $A(\gamma, \pi^0\pi^0)$ reaction, all four final-state photons were registered in the detector. The two-π^0 invariant-mass ($M_{\pi^0\pi^0}$) resolution (σ) varies between 2.0% and 2.5% in the incident-photon energy range of interest.

The capability to detect and distinguish neutral from charged pions is essential for comparing pion pairs of different isospin. Charged pions from $A(\gamma, \pi^0\pi^{+/-})$ 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 [22]. Since the TAPS detector does not include a magnetic field, positively charged particles cannot be discriminated from negatively charged particles. The two-pion mass resolution (σ) in the $\pi^0\pi^{+/-}$ channel is $<3.3\%$.

The dominant reaction mechanism in $A(\gamma, \pi^0\pi^0)$ and $A(\gamma, \pi^0\pi^{+/-})$ channels is the quasifree 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 quasifree event generator. The background of the $\eta \rightarrow 3\pi^0$ production channel does not contribute, since the incident-photon energy of $E_\gamma = 400$–460 is below the η-production threshold.

Cross sections were deduced from the yield of the $\pi\pi$ events divided by the thickness of the targets, the photon flux, efficiencies, geometrical acceptances, and the branching ratio $\pi^0 \rightarrow \gamma\gamma$. The intensity of the photon beam was determined by counting the postbremsstrahlung electrons in the focal plane of the tagger. The loss of photon intensity due to collimation was measured with a 100%-efficient BGO detector which was moved into the photon beam at lowered beam intensity. The geometrical acceptance and inefficiencies due to cuts and thresholds were deduced from a Monte Carlo simulation based on GEANT3 [23] libraries and an event generator assuming a quasifree production mechanism. The generator was modified such that energy and angular distributions of the final-state particles agreed well with the observed distributions [22]. The obtained acceptance was found to be typically (0.2–0.4)%.

The measured $M_{\pi^0\pi^0}$-mass distributions for incident-photon energies of $E_\gamma = 400$–460 MeV are shown in Fig. 1. A strong increase in strength towards small $M_{\pi^0\pi^0}$ with increasing A is observed. The dotted curves in Fig. 1 indicate phase-space distributions determined by the Monte Carlo model. 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), the data disagree with phase space with a probability of more than 99.8%. Most of the observed strength lies below the peak of the phase-space distribution. A similar, but less pronounced, effect has been observed in pion-induced reactions $A(\pi^-, \pi^0\pi^0)$ [13] at a comparable center-of-mass energy. 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 [22] 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 solid curves in Fig. 1 are predictions by Roca *et al.* [9]. 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. The data are described well by the model considering a theoretical uncertainty of 20% [15]. It qualitatively predicts a mass shift as observed in the data. The basic ingredient driving this shift is the p-wave interaction of the pion with the baryons in the medium, resulting in an

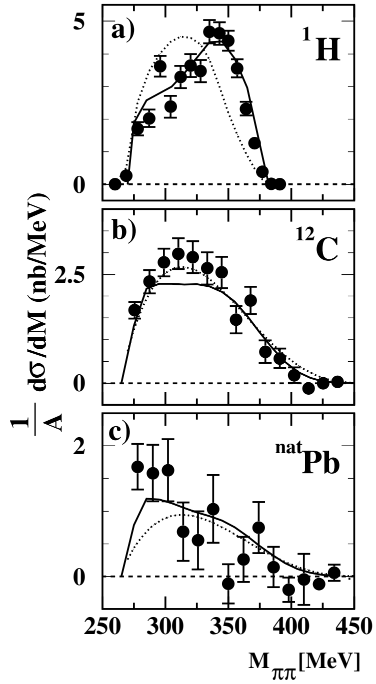

FIG. 1. Differential cross sections of the reaction $A(\gamma, \pi^0\pi^0)$ with $A = {}^1$H, ^{12}C, ^{nat}Pb for incident photons in the energy range of 400–460 MeV (solid circles). Error bars denote statistical uncertainties and the curves are explained in the text.

in-medium modification of the $\pi\pi$ interaction. A similar calculation [14] is not able to describe the observed A-dependence effect in the $A(\pi^-, \pi^0\pi^0)$ data [13], which might be due to the interaction of the initial-state pion.

In order to compare the TAPS results with the pion-induced measurements by the CHAOS Collaboration $[A(\pi^+, \pi^+\pi^-)]$, the composite ratio $C_{\pi\pi}$ is introduced [12]

$$C_{\pi\pi}(Pb/C) = \frac{[d\sigma(Pb)/dM]/\sigma(Pb)}{[d\sigma(C)/dM]/\sigma(C)}.$$

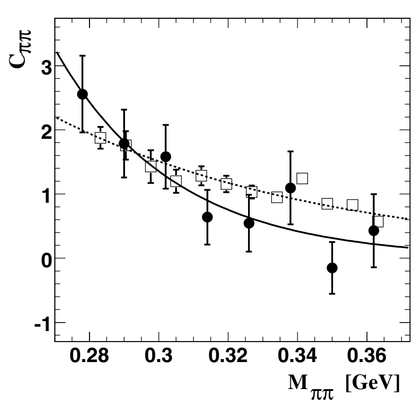

FIG. 2. The composite ratio $C_{\pi\pi}$ for $A(\gamma, \pi^0\pi^0)$ (solid symbols) compared to $A(\pi^+, \pi^+\pi^-)$ (open squares) obtained by the CHAOS Collaboration [10–12]. The curves are second-order polynomial fits through the data.

The results are shown in Fig. 2. The photon-induced $A(\gamma, \pi^0\pi^0)$ data (solid circles) are compared to the pion-induced $A(\pi^+, \pi^+\pi^-)$ measurement by the CHAOS Collaboration [10–12] (open squares). The solid and dashed curves represent empirical second-order polynomial fits through the photon-induced and pion-induced data, respectively. In both cases, an increase in strength towards small $M_{\pi\pi}$ masses is observed. This increase is stronger in $A(\gamma, \pi^0\pi^0)$ than in $A(\pi^+, \pi^+\pi^-)$ reactions, which could be related to photons probing the entire nucleus leading to larger effective densities than with pion beams.

To study the nuclear-mass dependence of the double-pion mass in a different isospin channel than $I = 0$, we have concurrently measured differential cross sections of the reactions $A(\gamma, \pi^0\pi^{+/-})$. The same energy interval of $E_\gamma = 400$–460 MeV was chosen. The results for $A = {}^1$H, ^{12}C, and ^{nat}Pb are depicted in Fig. 3. 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. The solid curves represent predictions by Roca *et al.* [15] and are performed in a similar framework as the model for $M_{\pi^0\pi^0}$ distributions [9]. The model underestimates the experimentally determined cross sections by $\approx 20\%$ for all nuclei, while describing the shape of the data rather

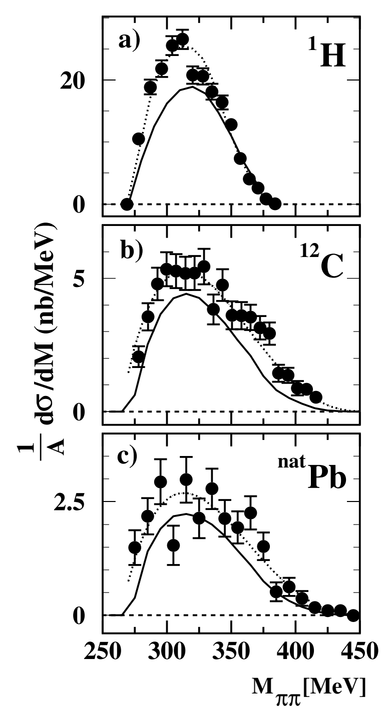

FIG. 3. Differential cross section of the reactions $p(\gamma, \pi^0\pi^+)$ (a) and $A(\gamma, \pi^0\pi^{+/-})$ with $A = {}^{12}$C, ^{nat}Pb (b), (c) for incident photons in the energy range of 400–460 MeV (solid circles). Error bars denote statistical uncertainties and the curves are explained in the text.

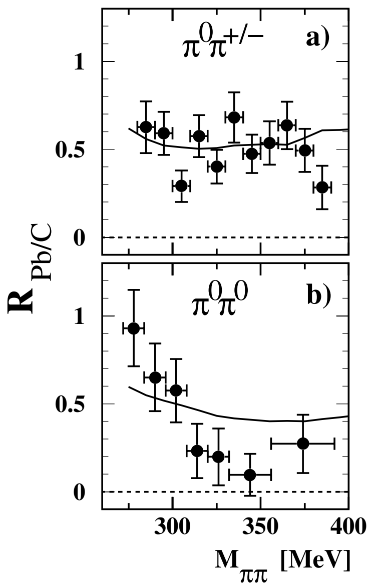

FIG. 4. Ratios between the differential cross sections for $A = {}^{nat}$Pb and $A = {}^{12}$C for $A(\gamma, \pi^0\pi^{+/-})$ (a) and $A(\gamma, \pi^0\pi^0)$ (b). The solid curves represent predictions by Roca *et al.* [9,15].

accurately. Since the σ resonance does not couple to $\pi^0\pi^{+/-}$, the model shows no shift in strength towards smaller $M_{\pi\pi}$ masses with increasing A.

Figure 4 shows the ratio $R_{Pb/C}$ between the differential cross sections per nucleon for $A = {}^{nat}$Pb and $A = {}^{12}$C of the reactions $A(\gamma, \pi^0\pi^{+/-})$ (a) and $A(\gamma, \pi^0\pi^0)$ (b) up to $M_{\pi\pi}$ masses of 400 MeV. The experimentally determined ratio $R_{Pb/C}$ for the $\pi^0\pi^{+/-}$ 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.* [15] supports this conclusion as can be observed from the solid curve. A significant in-medium shape effect is observed in the ratio $R_{Pb/C}$ for the $\pi^0\pi^0$ channel as depicted in Fig. 4(b). Since an in-medium modification is not seen in the $\pi^0\pi^{+/-}$ reaction, this effect cannot be explained by A dependencies in the production mechanism and final-state interactions of the individual pions with the medium. The prediction by Roca *et al.* [9] with a theoretical uncertainty of 10% [15] is depicted as the solid curve in Fig. 4(b).

In conclusion, we have observed an effect consistent with a significant in-medium modification in the $A(\gamma, \pi^0\pi^0)$ $(I = J = 0)$ channel. For the first time, the A dependence of the $\pi\pi$-mass distributions in photon-induced reactions on nuclei has been measured. 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 A dependencies in the production mechanism and final-state interactions of the individual pions with the constituents of the nucleus have been studied by measuring the $\pi^0\pi^{+/-}$ mass distribution concurrently. A significant in-medium effect was not observed. According to Roca *et al.* [9], 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. It would be most desirable to confront this observation with QCD models which treat the σ as a $q\bar{q}$ state and explicitly take chiral-symmetry restoration into account.

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