In-medium modifications of the $\pi\pi$ interaction in photon-induced reactions

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Differential cross sections of the reactions $(\gamma,\pi^\pm\pi^\mp)$ and $(\gamma,\pi^0\pi^{\pm/-})$ 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 $\pi$-induced measurements and to calculations within a chiral-unitary approach.

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 $\sigma$ mode. In Ref. [1] the $\sigma$ meson is identified as the $f_{0}(400-1200)$. The large natural width in free space of $\Gamma=400-500$ MeV 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 $\sigma$ meson.

Within some theoretical approaches of quantum chromodynamics (QCD) the $\sigma$ 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 $\sigma$. For large baryon densities, it is predicted that chiral symmetry is partially restored, leading to a degeneracy in mass of the pion and the $\sigma$. Since the pion approximates a Goldstone boson, the pion mass is not expected to change dramatically with increasing nuclear density $\rho$. Hence, these models predict a significant drop in the mass of the $\sigma$. 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 $\sigma$ mode can be considered to be a resonant state of two pions. 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 [11,12]. 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 to study the different $\pi\pi$-isospin states at average effective densities of 35% ($^{12}$C) to 65% ($^{208}$Pb) of $\rho_0$ and are statistically superior to previously published data on photon-induced double-pion production [15,16]. 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 fa-
cility 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 liquidhydrogen, 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 $\pm 55^\circ$, $\pm 105^\circ$, and $\pm 155^\circ$ 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 ($\sigma$) for $\pi^0$ 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-$\pi^0$ invariant-mass ($M_{\pi^+\pi^-}$) resolution ($\sigma$) 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 $A(\gamma, \pi^0\pi^+/\pi^-)$ were selected by exploiting the information on the time-of-flight of the charged pion relative to the one of the photons of the $\pi^0$ 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 ($\sigma$) in the $\pi^0\pi^+/\pi^-$ channel is $< 3.3\%$.

The dominant reaction mechanism in $A(\gamma, \pi^0\pi^0)$ and $A(\gamma, \pi^0\pi^+/\pi^-)$ 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 $\eta \rightarrow 3\pi^0$ production channel does not contribute, since the incident-photon energy of $E_\gamma=400-460$ is below the $\eta$-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 post-bremstrahlung 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 quasi-free production mechanism. The generator was modified such that energy and angular distributions of the final-state particles agreed well with the observed distributions [24]. The obtained acceptance was found to be typically 0.2-0.4%.

The measured $M_{\pi^+\pi^-}$ mass distributions for incident-photon energies of $E_\gamma=400-460$ MeV are shown in Fig. 1. A strong increase in strength towards small $M_{\pi^+\pi^-}$ 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 $A(\pi^-\pi^-\pi^-\pi^0)$ [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. \cite{12}. 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 \( \sigma \) 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\% \cite{13}. 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 in-medium modification of the \( \pi \pi \) interaction. A similar calculation \cite{14} is not able to describe the observed \( A \)-dependence effect in the \( A(\pi^-, \pi^0 \pi^0) \) data \cite{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 \cite{10,11,12} (open squares). The solid and dashed curves represent empirical second-order polynomial fits through the data.

The curves are second-order polynomial fits through the photon-induced and pion-induced \( \pi^0 \pi^0 \) \( M_{\pi^0 \pi^0} \) distribution \cite{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 \( \sigma \) resonance, reproducing the meson-meson phase shifts in vacuum and accounts for the absorption of the pions in the nucleus, resulting in an in-medium modification of the \( \pi \pi \) interaction. A similar calculation \cite{14} is not able to describe the observed \( A \)-dependence effect in the \( A(\pi^-, \pi^0 \pi^0) \) data \cite{13}, which might be due to the interaction of the initial-state pion.

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In order to compare the TAPS results with the pion-induced measurements by the CHAOS collaboration \cite{10,11,12} (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 \( A=^1H, ^{12}C \) 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. \cite{12} and are performed in a similar framework as the model for \( M_{\pi^0 \pi^0} \) distributions \cite{9}. The model underestimates the experimentally determined cross sections by \( \approx20\% \) for all nuclei, while describing the shape of the data rather accurately. Since the \( \sigma \) 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 3 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. \cite{12} 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).

\[ R_{\pi\pi}(\gamma, \pi^0/(\pi^0\pi^0)) (a) \text{ and } R_{\pi\pi}(\gamma, \pi^0/\pi^0) (b). \]

FIG. 4. Ratios between the differential cross sections for $A=^{nat}_{12}$C for $\gamma, \pi^0/(\pi^0\pi^0)$ (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 $\sigma$ meson as a $\pi\pi$ resonance. It would be most desirable to confront this observation with QCD models which treat the $\sigma$ as a $q\bar{q}$ state and explicitly take chiral-symmetry restoration into account.

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 $\sigma$ meson as a $\pi\pi$ resonance.

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