

Two-pion production in photon-induced reactions

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Abstract. Differences in the photoproduction of mesons on the free proton and on nuclei are expected to reveal changes in the properties of hadrons. Inclusive studies of nuclear photoabsorption have provided evidence of medium modifications. However, the results have not been explained in a model independent way. A deeper understanding of the situation is anticipated from a detailed experimental study of meson photoproduction from nuclei in exclusive reactions. In the energy regime above the $\Delta(1232)$ resonance, the dominant double pion production channels are of particular interest. Double pion photoproduction from nuclei is also used to investigate the in-medium modification of meson-meson interactions.

Keywords. Meson production; photoproduction reactions.

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1. Introduction

The study of in-medium properties of mesons and nucleon resonances carries the promise to find signatures for partial chiral symmetry restoration at finite baryon density and temperature. Initially, the scaling law proposed by Brown and Rho indicated a direct connection between the vector meson masses and the chiral condensate [1]. This prospect has caused great interest in the properties of light mesons in a dense and hot environment [2–5]. Various theoretical predictions indicate that the observation of an in-medium modification of the vector meson masses can provide a unique measure for the degree of chiral symmetry breaking in the strongly interacting medium [6,7]. However, in [8], it is shown that QCD sum rules could rather be fulfilled by increasing the width of the hadron in medium. In both scenarios, it is expected that hadronic strength is shifted towards lower masses. Some experimental observations are consistent with a modification of the ρ resonance in the nuclear medium [9,10]. Recently, an indication for a downward mass shift of the ω meson has been observed in photon-induced reactions on nuclei [11].

2. Photoabsorption

Photoabsorption experiments on the free nucleon demonstrate the complex structure of the nucleon and its excitation spectrum. The lowest resonance is called $\Delta(1232)$ which is a P_{33} state in the common notation ($L_{(2I)(2J)}$) with a pole mass

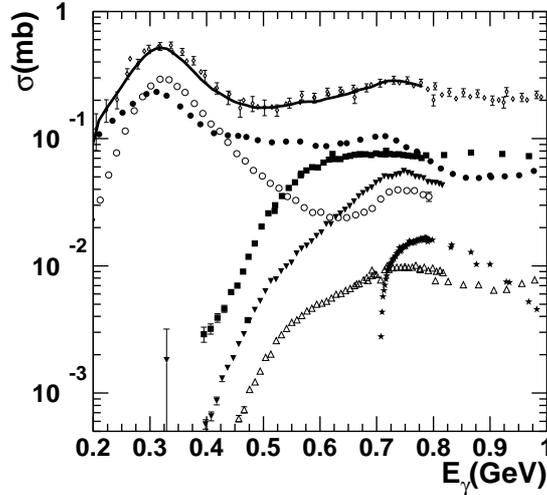


Figure 1. Photoabsorption cross-section on the proton and decomposition into meson production channels. Small open circles are the photoabsorption data compilation from [12]. The experimental meson production cross-sections are: single π^+ (solid circles) from [13,14], single π^0 (open circles) from [15], $\pi^+\pi^-$ (solid squares) from [16,17], $\pi^+\pi^0$ (downward solid triangles) from [18], $\pi^0\pi^0$ (upward open triangles) from [19,20], and η (stars) from [21,22]. The solid line is the sum of the meson channels up to 800 MeV.

of 1232 MeV. It is prominently excited by incident photons of 0.2–0.5 GeV. The following group of resonances, $P_{11}(1440)$, $D_{13}(1520)$ and $S_{11}(1535)$, is called the second resonance region ($E_\gamma = 0.5\text{--}0.9$ GeV). The observed resonance structures have been studied using their decay via light mesons, showing that the photoabsorption spectrum can be explained by the sum of π , $\pi\pi$ and η production cross-sections. Figure 1 shows the photoabsorption cross-section on the proton along with the experimental meson photoproduction cross-sections. The shapes of the meson cross-sections reflect the resonance structures observed in photoabsorption showing that the mesons are mostly decay products of the respective resonances. Single pion production is dominant in the region of the $\Delta(1232)$ resonance. Also, the three resonances comprising the second resonance region, decay to $\sim 50\%$ via single pion emission. This fact has been extensively exploited in partial wave analyses. Above $E_\gamma \approx 0.4$ GeV, the photoproduction of two pions is kinematically possible and single π production loses in dominance. The solid line in figure 1 represents the sum of the meson cross-sections up to 0.8 GeV and demonstrates that the photoabsorption cross-section on the proton can be explained by its decomposition into meson production.

The η production threshold is located at $E_\gamma \approx 700$ MeV. The steeply rising η cross-section in figure 1 is characteristic for an s -wave resonance. The angular distributions of the η emission are consistent with this observation and the cross-section peaks around the mass pole of the $S_{11}(1535)$ resonance [21,22]. This resonance is unique in the sense that it has a strong decay branch of 30–55% into η mesons. Thus, η production is considered as a characteristic for the $S_{11}(1535)$ resonance.

Above the η threshold, the cross-section basically displays the resonance line shape enabling detailed studies of that state. However, the contribution to the total is small.

3. Nuclear photoabsorption

Photon-induced reactions are particularly well-suited to study in-medium effects in dense nuclear matter since photons probe the entire nuclear volume. The first experimental investigation of the nuclear response to photons was performed with total photoabsorption measurements from nuclei with mass numbers ranging from ${}^7\text{Li}$ to ${}^{238}\text{U}$. The nuclear cross-sections are practically identical when scaled by the atomic mass number, thus scaling expectedly with the nuclear volume. However, the measurements indicate a depletion of the resonance structure in the second resonance region [23–25]. Bianchi *et al* [25] reported that, while in the Δ -resonance region strength is only redistributed by broadening effects, strength is missing in the $D_{13}(1520)$ region. This observation has been one of the first indications of a medium modification.

Figure 2 shows the nuclear photoabsorption cross-section per nucleon as an average over the nuclear systematics [26]. The Δ resonance is broadened and slightly shifted while the second and higher resonance regions seem to have disappeared.

Mosel *et al* [27] have argued that an in-medium broadening of the $D_{13}(1520)$ resonance is a likely cause of the suppressed photoabsorption cross-section. Recent calculations are based on the BUU equation and are described in [28–30]. Hirata *et al* [31] have discussed a change of the interference effects in the nuclear medium as one of the most important reasons for the suppression of the resonance structure.

It may be concluded that inclusive reactions like total photoabsorption do not allow a detailed investigation of in-medium effects. A deeper understanding of the situation is anticipated from the experimental study of meson photoproduction on nucleons embedded in nuclei in comparison to studies on the free nucleon.

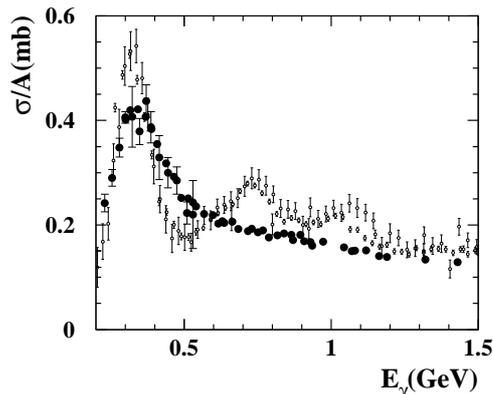


Figure 2. Nuclear photoabsorption cross-section per nucleon as an average over the nuclear systematics [26] (full symbols) compared to the absorption on the proton [12] (open symbols).

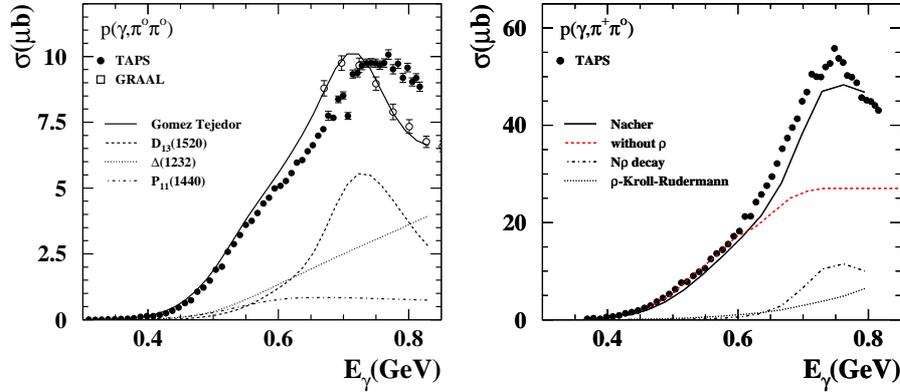


Figure 3. $\pi^0\pi^0$ (left) and $\pi^0\pi^\pm$ (right) photoproduction from the proton [32]. Calculations by [33].

4. Double pion photoproduction

Single as well as double pion production channels display structure at the corresponding resonance mass, i.e. around $E_\gamma \approx 760$ MeV. As already seen in figure 1, the meson production channels involving charged pions are dominant as expected in electromagnetic excitation processes. Two-pion production is characteristic for the $D_{13}(1520)$ and $P_{11}(1440)$ resonances. Furthermore, the dominant resonance contribution comes from the $D_{13}(1520)$ resonance having the strongest coupling to the incident photon. Because of the importance for reactions on the proton, it is expected that double pion production plays an important role in the understanding of the medium modifications as observed in nuclear photoabsorption.

On the proton, three isospin combinations of pion pairs can be produced. The corresponding cross-sections are shown in figure 3 along with theoretical calculations [33]. The study of $p(\gamma, \pi^0\pi^0)$ (left panel of figure 3) revealed that Δ intermediate states are important. The N^* contribution to double pion photoproduction by itself is not large but rather stems from an interference with other terms [33,34]. A similar behavior is found in $(\gamma, \pi^+\pi^0)$ reactions, shown in the right panel of figure 3. Additionally, the peak in the $(\gamma, \pi^+\pi^0)$ cross-section can only be explained by contributions from ρ production terms, with a decay branch of 20% for $D_{13} \rightarrow N\rho$ [18]. This decay mode is forbidden in $(\gamma, \pi^0\pi^0)$ reactions.

5. Double pion photoproduction from nuclei

The left panel of figure 4 shows preliminary cross-sections for $\pi^0\pi^0$ photoproduction on a series of nuclei from a recent analysis [35] of data taken with the TAPS detector at the MAMI-B accelerator (Mainz, Germany). The nuclear cross-sections are divided by $A^{2/3}$ and compared to results from nucleons bound in deuterons. With a scaling of $A^{2/3}$, the nuclear data agree almost exactly with the cross-sections on

the nucleon. Thus, the total nuclear $\pi\pi$ cross-sections do not seem to show any modification beyond absorption effects.

The right panel of figure 4 summarizes the systematic study of the total production cross-sections for single π^0 , η , and $\pi\pi$ cross-sections over a series of nuclei. The studies have not provided an obvious hint for a depletion of resonance structure. The observed reduction and change of shape in the second resonance region are mostly as expected from absorption effects, Fermi smearing and Pauli blocking, and collisional broadening. The solid line in figure 4 is the sum of the available meson cross-sections between 400 and 800 MeV demonstrating the persistence of the second resonance bump when at least one neutral meson is observed. Here, it would be desirable to complete the picture by investigating single charged pion as well as $\pi^+\pi^-$ production from nuclei. In [36], it is suggested that there is a large difference between quasi-free meson production from the nuclear surface and non-quasi-free components. The quasi-free part scales with the nuclear surface and does not show a suppression of the bump in the second resonance region. Meanwhile, the (unobservable) non-quasi-free meson production would have larger contributions from the nuclear volume.

However, in the reaction $\pi^0\pi^\pm$, the two pions can stem from the decay of the ρ meson while the decay $\rho \rightarrow \pi^0\pi^0$ is forbidden. Meanwhile, $\pi^0\pi^0$ pairs can stem from the decay of the elusive σ meson. Accordingly, detailed studies of differential cross-sections might reveal different modifications of the $\pi\pi$ correlations.

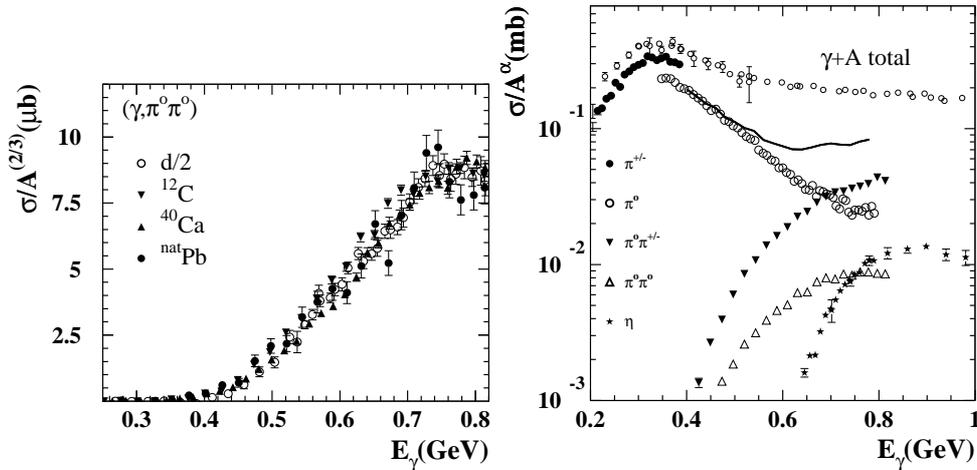


Figure 4. Left: Preliminary total cross-sections for $\pi\pi$ photoproduction from different nuclei [36] along with results from the deuteron [37]. The nuclear cross-sections are divided by $A^{2/3}$, the $\pi^0\pi^0$ deuteron cross-section by 2. Right: Status of the decomposition of nuclear photoabsorption into meson production channels (scaled with A^α , $\alpha = 2/3$). Small open circles are the average nuclear photoabsorption cross-section per nucleon ($\alpha = 1$) [26]. Meson production data are from a carbon target [36,38–41]. The solid line is the sum of the available meson cross-sections between 400 and 800 MeV.

6. $\pi\pi$ Correlations in the nuclear medium

The idea of strong threshold effects due to the $\pi\pi$ interaction in a dense nuclear medium was first suggested by Schuck *et al* in [42]. In the prediction made by Bernard *et al* [43], a linear decrease with baryon density is assumed for moderate densities: $m_\sigma = m_{\sigma_0} \cdot (1 - \alpha \cdot \rho/\rho_0)$. A change in the shape of the invariant mass distribution is also predicted for $\alpha = 0$ as a result of the p -wave coupling of pions to particle-hole and Δ -hole states. The in-medium behavior of scalar mesons is one of the key issues for in-medium studies. Here, the elusive σ meson would be a prime candidate in the search for a signature of chiral restoration because it is the lightest meson possessing the same quantum numbers as the QCD vacuum.

Some theoretical models expect a dropping of the σ meson mass as a function of nuclear density on account of partial restoration of chiral symmetry [44–46]. Recent theoretical papers consider this possibility where the pion ($J^P = 0^-$) and the σ meson ($J^P = 0^+$) are regarded as chiral partners. Several models describe the density dependence of the σ and π mass. Being a Goldstone boson, the pion mass does not change dramatically with density. In order to reach the chiral limit of mass degeneracy, the σ mass would have to reduce. With the main decay mode of the σ meson being the decay into pion pairs, a number of authors have performed calculations for the expected mass distributions predicting sizeable $\pi\pi$ mass shifts already at normal nuclear densities.

Roca *et al* [47] interpreted the σ meson as a scalar $\pi\pi$ scattering resonance and predicted a decrease of the $\pi\pi$ invariant mass with increasing nuclear density, resulting from an in-medium modification of the $\pi\pi$ interaction. Here, the meson-meson interaction in the scalar-isoscalar channel is studied in the framework of a chiral unitary approach at finite baryon density. The calculation dynamically generates the f_0 and σ resonances reproducing the meson-meson phase shifts in vacuum. These theoretical results also find a drop of the σ resonance pole together with a reduction of the resonance width in the nuclear medium. In this case, the basic ingredient driving the mass decrease is the p -wave interaction of the pion with the baryons in the medium.

In-medium modifications of the $\pi\pi$ interaction have been studied in pion-induced reactions on nuclei like $A(\pi^+, \pi^+\pi^-)$ [48] and $A(\pi^-, \pi^0\pi^0)$ [49]. However, pion-induced reactions occur at fractions of the normal nuclear density. This complicates the interpretation of the data in terms of medium effects.

Photon-induced reactions can reach normal nuclear densities and should thus be more sensitive to in-medium modifications. A first result came from the investigation of $\pi\pi$ invariant mass distributions in the incident photon energy range of 400–460 MeV [50]. In this energy regime, the final state pions undergo some absorption and little final state interactions, like rescattering. The results indicate an effect consistent with a significant in-medium modification in the $A(\gamma, \pi^0\pi^0)$ ($I = J = 0$) channel. Figure 5 shows the threshold $\pi\pi$ production on nuclei measured with the TAPS spectrometer at MAMI-B. The systematics includes p , C, Ca, and Pb. They reveal a shape change of the $\pi^0\pi^0$ invariant mass with increasing mass number as predicted in [47] and would also be consistent with a dropping of the σ meson in medium. It was confirmed that another isospin channel, here $\pi^0\pi^\pm$,

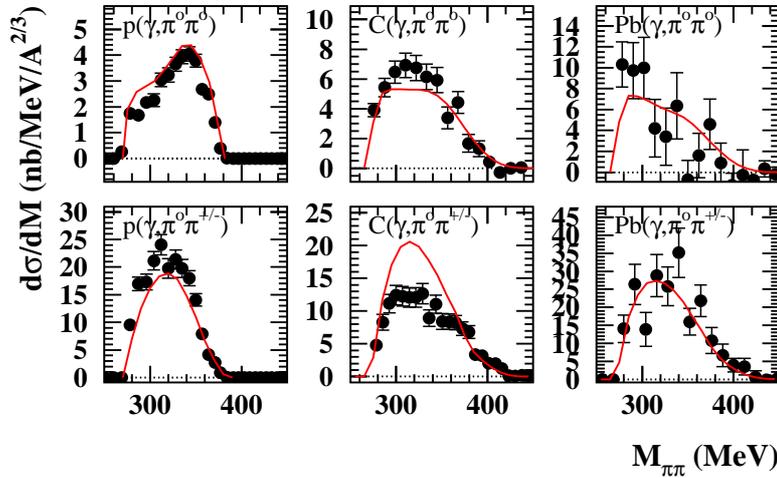


Figure 5. Differential cross-sections of the reaction $A(\gamma, \pi^0\pi^0)$ (top) and $A(\gamma, \pi^0\pi^\pm)$ (bottom) with $A = {}^1\text{H}, {}^{12}\text{C}, {}^{\text{nat}}\text{Pb}$ for incident photons in the energy range of 400–460 MeV [50]. Solid lines are the predictions from [47].

does not show such a behavior (lower row of figure 5). A rigorous comparison to theoretical predictions could shed light on the nature of the σ meson.

7. Summary and outlook

The systematic study of the total production cross-sections for single π^0 , η , and $\pi\pi$ cross-sections over a series of nuclei has not provided an obvious hint for a depletion of resonance yield. The observed reduction and change of shape in the second resonance region are mostly as expected from absorption effects, Fermi smearing and Pauli blocking, and collisional broadening. It has to be concluded that the medium modifications leading to the depletion of cross-section in nuclear photoabsorption are a subtle interplay of effects. Their investigation and the rigorous comparison to theoretical models require a detailed study of differential cross-sections and a deeper understanding of meson production in the nuclear medium.

One such study investigates the possible change in the correlation between low-momentum pion pairs in the nuclear environment. First results have been presented and are found to be consistent with a significant in-medium modification in the $A(\gamma, \pi^0\pi^0)$ ($I = J = 0$) channel. For a rigorous comparison to theoretical predictions, improved statistics on an extended systematics of nuclei is being acquired [51].

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