Double Pion Photoproduction from Nuclei

Susan Schadmand¹

¹ Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany

Received November 19, 2018

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 Δ(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
PACS: 13.60.Le, 25.20.Lj

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][3][4][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 $\omega$ meson has been observed in photon-induced reactions on nuclei [11].

2. 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 [12, 13, 14]. Bianchi et al. [14] reported that, while in the $\Delta$-resonance region strength is only redistributed by broadening effects, strength is missing in the $D_{13}(1520)$ region. This observation has been taken as one of the first indications of a medium modification.

Fig. 1 shows the nuclear photoabsorption cross section per nucleon as an average over the nuclear systematics [15]. The $\Delta$ resonance is broadened and slightly shifted while the second and higher resonance regions seem to have disappeared.

Mosel et al. [17], 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 [18, 19, 20]. Hirata et al. [21] 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

![Fig. 1. Nuclear photoabsorption cross section per nucleon as an average over the nuclear systematics (full symbols) compared to the absorption on the proton (open symbols).](image-url)
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.

### 3. Elementary and Nuclear Double Pion Photoproduction

![Graphs of double pion photoproduction](image)

**Fig. 2.** $\pi^0\pi^0$ (left) and $\pi^0\pi^+/-$ (right) photoproduction from the proton \[22\]. Calculations by \[23\].

In the second resonance region, single pion production can stem from the three resonances, $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$. Here, the $S_{11}(1535)$ has the strongest decay via $\eta$ mesons and is thus said to be tagged by $\eta$ production. The single as well as double pion production channels display structure at the corresponding resonance mass, at $E_\gamma \approx 760$ MeV. In particular, 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 Fig. 2 along with theoretical calculations \[23\]. The study of $p(\gamma, \pi^0\pi^0)$ (left panel of Fig. 2) revealed that $\Delta$ 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 \[24\] \[23\]. A similar behavior is found in $(\gamma, \pi^+\pi^0)$ reactions, shown in the right panel of Fig. 2. Additionally, the peak in the $(\gamma, \pi^+\pi^0)$ cross section can only be explained by
contributions from $\rho$ production terms, with a decay branch of 20% for $D_{13} \rightarrow N\rho$. This decay mode is forbidden in $(\gamma, \pi^0 \pi^0)$ reactions.

Fig. 3 shows preliminary cross sections for $\pi^0 \pi^0$ and $\pi^0 \pi^\pm$ photoproduction on calcium and lead from a recent TAPS analysis. The nuclear cross sections are divided by $A^{2/3}$ and compared to results from the free proton and from nucleons bound in deuterons. With the scaling with $A^{2/3}$, 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.

Fig. 4 summarizes the systematic study of the total production cross sections for single $\pi^\circ$, $\eta$, and $\pi\pi$ cross sections over a series of nuclei. The studies have 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. The solid line in Fig. 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 [33], it is suggested that there is a large difference between quasifree meson production from the nuclear surface and non-quasifree components. The quasifree part scales with the nuclear surface and does not show a suppression of the bump in the second resonance region. Meanwhile, the (unobservable) non-quasifree 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 $\rho$ meson while the decay $\rho \rightarrow \pi^0 \pi^0$ is forbidden. Meanwhile, $\pi^\circ \pi^\circ$ pairs can stem from the decay of the elusive $\sigma$ meson. Accordingly, detailed studies of differential cross sections might reveal different modifications of the $\pi\pi$ correlations.
Fig. 4. Status of the decomposition of nuclear photoabsorption into meson production channels (scaled with $A^{\alpha}$, $\alpha=2/3$). Solid circles are the average nuclear photoabsorption cross section per nucleon ($\alpha=1$) [15]. For reference, the elementary cross section [28] is shown (dashed curve). Meson production data are from [29, 30, 31, 32, 25]. The solid line is the sum of the available meson cross sections between 400 and 800 MeV.

4. $\pi\pi$ 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 in [34]. In the prediction of [35], 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 $\Delta$-hole states. The in-medium behavior of scalar mesons is one of the key issues for in-medium studies. Here, the elusive $\sigma$ 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 $\sigma$ meson mass as a function of nuclear density on account of partial restoration of chiral symmetry [36, 37, 38]. Recent theoretical papers consider this possibility where the pion ($J^P = 0^-$) and the $\sigma$ meson ($J^P = 0^+$) are regarded as chiral partners. Several models describe the density dependence of the $\sigma$ and $\pi$ 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 $\sigma$ mass would have to reduce. With the main decay mode...
of the $\sigma$ 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, Oset et al. interpret the $\sigma$ meson as a scalar $\pi\pi$ scattering resonance and predict a decrease of the $\pi\pi$ invariant mass with increasing nuclear density, resulting from an in-medium modification of the $\pi\pi$ interaction [39]. 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 $\sigma$ resonances reproducing the meson-meson phase shifts in vacuum. These theoretical results also find a drop of the $\sigma$ 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 $A(\pi^+,\pi^+\pi^-)$ [40] and $A(\pi^-,\pi^0\pi^0)$ [41]. 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 [42]. 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

![Differential cross sections of the reaction $A(\gamma,\pi^0\pi^0)$ (left) and $A(\gamma,\pi^0\pi^\pm)$ (right) with $A=^1\text{H},^{12}\text{C},\text{nat}\text{Pb}$ for incident photons in the energy range of 400–460 MeV [42]. Solid lines are the predictions from [39].](image-url)
Double Pion Photoproduction from Nuclei

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 [39] and would also be consistent with a dropping of the $\sigma$ meson in medium. It was confirmed that another isospin channel, here $\pi^0\pi^\pm$, does not show such a behavior (right panels of Fig. 5). A rigorous comparison to theoretical predictions could shed light on the nature of the $\sigma$ meson.

5. Summary and Outlook

The systematic study of the total production cross sections for single $\pi^0$, $\eta$, 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 photoproduction are a subtle interplay of effects. Their investigation and the rigorous comparison to theoretical models requires 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 [43].

References

1. G. E. Brown, M. Rho, Phys. Rev. Lett. 66 (1991) 2720–2723.
2. M. Asakawa, C. M. Ko, Phys. Rev. C48 (1993) 526–529.
3. R. Rapp, J. Wambach, Adv. Nucl. Phys. 25 (2000) 1.
4. M. Post, U. Mosel, Nucl. Phys. A699 (2002) 169–172.
5. D. Cabrera, E. Oset, M. J. Vicente Vacas, Nucl. Phys. A705 (2002) 90–118.
6. T. Hatsuda, S. H. Lee, Phys. Rev. C46 (1992) 34–38.
7. T. Hatsuda, Y. Koike, S.-H. Lee, Nucl. Phys. B394 (1993) 221–266.
8. S. Leupold, U. Mosel, Phys. Rev. C58 (1998) 2939–2957.
9. D. Adamova, et al., Phys. Rev. Lett. 91 (2003) 042301.
10. J. Adams, et al., Phys. Rev. Lett. 92 (2004) 092301.
11. D. Trnka, et al., to be published Phys. Rev. Lett.
12. T. Frommhold, et al., Phys. Lett. B295 (1992) 28–31.
13. T. Frommhold, et al., Z. Phys. A350 (1994) 249–261.
14. N. Bianchi, et al., Phys. Lett. B325 (1994) 333–336.
15. V. Muccifora, et al., Phys. Rev. C60 (1999) 064616.
16. K. Hagiwara, et al., Phys. Rev. D66 (2002) 010001.
17. U. Mosel, Prog. Part. Nucl. Phys. 42 (1999) 163–176.
18. J. Lehr, M. Effenberger, U. Mosel, Nucl. Phys. A671 (2000) 503–531.
19. M. Effenberger, A. Hombach, S. Teis, U. Mosel, Nucl. Phys. A614 (1997) 501–520.
20. P. Muhlich, L. Alvarez-Ruso, O. Buss, U. Mosel, Phys. Lett. B595 (2004) 216–222.
21. M. Hirata, N. Katagiri, K. Ochi, T. Takaki, Phys. Rev. C66 (2002) 014612.
22. B. Krusche, S. Schadmand, Prog. Part. Nucl. Phys. 51 (2003) 399–485.
23. J. C. Nacher, E. Oset, M. J. Vicente, L. Roca, Nucl. Phys. A695 (2001) 295–327.
24. J. A. Gomez Tejedor, E. Oset, Nucl. Phys. A600 (1996) 413–435.
25. S. Janssen, PhD thesis, University of Giessen (2002) and to be published.
26. A. Zabrodin, et al., Phys. Rev. C55 (1997) 1617–1620.
27. V. Kleber, et al., Eur. Phys. J. A9 (2000) 1–4.
28. D. E. Groom, et al., Eur. Phys. J. C15 (2000) 1–878.
29. J. Arends, et al., Z. Phys. A305 (1982) 205.
30. B. Krusche, et al., Phys. Rev. Lett. 86 (2001) 4764–4767.
31. M. Roebig-Landau, et al., Phys. Lett. B373 (1996) 45–50.
32. H. Yamazaki, et al., Nucl. Phys. A670 (2000) 202–205.
33. B. Krusche, et al., Eur. Phys. J. A22 (2004) 347–351.
34. P. Schuck, W. Norenberg, G. Chanfray, Z. Phys. A330 (1988) 119–120.
35. V. Bernard, U. G. Meissner, I. Zahed, Phys. Rev. Lett. 59 (1987) 966.
36. M. Lutz, S. Klimt, W. Weise, Nucl. Phys. A542 (1992) 521–558.
37. T. Hatsuda, T. Kunihiro, H. Shimizu, Phys. Rev. Lett. 82 (1999) 2840–2843.
38. R. Rapp, et al., Phys. Rev. C59 (1999) 1237–1241.
39. L. Roca, E. Oset, M. J. Vicente Vacas, Phys. Lett. B541 (2002) 77–86.
40. F. Bonelli, et al., Nucl. Phys. A677 (2000) 213–240.
41. A. Starostin, et al., Phys. Rev. Lett. 85 (2000) 5539–5542.
42. J. G. Messchendorp, et al., Phys. Rev. Lett. 89 (2002) 222302.
43. S. Schadmand, Proposal CrystalBall@MAMI and TAPS collaborations MAMI A2/3-03.