2π⁰ photoproduction from nuclei

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Abstract. The photoproduction of π pairs (π⁰π⁰, π⁰π⁺) from ⁴⁰Ca has been measured with high statistical accuracy with the TAPS detector at the Mainz MAMI accelerator. Total cross sections and invariant mass distributions of the ππ pairs have been measured for incident photon energies from threshold up to 820 MeV. Evidence of a nuclear-mass dependence of the ππ invariant-mass distribution is found in the π⁰π⁰ channel while this dependence is not observed in the π⁰π⁺ channel. This indicates an in-medium modification of the ππ interaction in the I=J=0 channel. The total cross sections for both double pion channels agree with the elementary cross sections on the free nucleon, when the Ca cross section is scaled by A²/³.

INTRODUCTION

The study of the in-medium properties of nucleons and mesons is one of the main challenging topics in nuclear physics. Although many changes of the fundamental properties in the nuclear medium are predicted, our knowledge of these in-medium effects is still poor. Measuring the reaction A(γ,π⁰π⁰) allows to address simultaneously two different topics. The in-medium modifications of the meson-meson interaction and in-medium properties of nucleon resonances.

Correlated π pairs in the scalar-isoscalar J=I=0 channel are known as the sigma meson identified in the PDG as the f⁰(400-1200) [1]. Predictions of Roca et al. [2] study the meson-meson interaction in the scalar-isoscalar channel in the framework of a chiral-unitary approach at finite baryon density. The model dynamically generates the σ resonance, reproducing the meson-meson phase shifts in vacuum and accounts for the absorption of pions in the nucleus. A drop of the mass of the σ meson is also predicted for partial chiral symmetry restoration. This would occur at high densities and would induce a dropping of the σ mass down to the π mass (its chiral partner) [3]. The π, being a goldstone boson, is not expected to suffer from such mass modifications at such densities. This decrease of the σ mass should already be observable at normal nuclear densities, by measuring the σ through its 2π decay. The visible effect would there be a shift of the strength of the 2π mass distribution to smaller masses closer to the 2π production threshold with increasing baryons densities. A few years ago, the CHAOS collaboration [4] reported such an effect in pion induced reactions (π⁺A→π⁺π⁺A′ with Tπ⁺ = 283 MeV). Photon induced reactions allow the study of such effects without the complications from initial state interactions which shadow the interior of the nuclei in π induced reactions. Consequently, larger effective densities can be reached. Data are presented for an incident-photon energy of Eγ = 400-460 MeV, which correspond to
the same center-of-mass energy as was used in the pion induced experiment, enabling a
direct comparison of the results. This energy range minimizes also effects of final states
interactions with the medium as the outgoing \( \pi \) kinetic energy is such that the mean
free path is maximized [5]. To study the nuclear mass dependence of the \( 2\pi \) mass in a
different isospin channel than \( I=0 \), we measured simultaneously mass differential cross
sections of the reaction \( A(\gamma,\pi^0\pi^\pm) \) in the same energy range.

In-medium nucleon resonances are studied via the total \( \pi\pi \) cross section. Total pho-
toabsorption on the free proton shows a peak structure for incident-photon energies in
the range 600-800 MeV. This region, called the second resonance region of the nucleon
is made of three overlapping resonances (\( P_{11}(1440) \), \( D_{13}(1520) \), \( S_{11}(1535) \)). This peak
structure is not seen on nuclei (from lithium up to heavy nuclei like uranium) [6]. Many
explanations have been suggested to explain the suppression of the excitation strength
in this region. A much discussed one is an in-medium broadening of the resonances (in
particular the \( D_{13}(1520) \)) [7] [8]. The \( 2\pi \) channel, which is the predominant decay mode
of the \( D_{13}(1520) \), is then an obvious choice to study this region. Total cross section is
measured in both \( \pi^0\pi^0 \) and \( \pi^0\pi^\pm \) channels from threshold up to 820 MeV.

**EXPERIMENTAL SETUP AND DATA ANALYSIS**

The experiment was performed at the photon beam facility at MAMI. Tagged photons [9]
with energies up to 820 MeV were produced via Bremsstrahlung with the MAMI
electron beam [10]. Measurements were carried out using liquid hydrogen, carbon,
calcium, and lead targets with thicknesses of 10 cm, 25 mm, 10 mm and 0.5 mm. Results
for the carbon and lead targets have already been published in [11]. The angles and
energies of the pions were measured with the electromagnetic calorimeter TAPS [12].
In this experiment, TAPS consisted of 510 BaF\(_2\) hexagonal scintillators [13]. Each of
these modules has a length of 25 cm and an inner diameter of 5.9 cm. The crystals were
arranged in 6 blocks containing 8\( \times \)8 modules plus a rectangular forward wall of 138

![FIGURE 1.](image_url)

Left part: 2D plot of the two-photon invariant masses for events with four detected photons.
Right part: time-of-flight versus energy deposited in the BaF\(_2\). Three bands corresponding to deuterons,
protons and charged \( \pi \) are visible.
BaF$_2$. A 5 mm thick plastic scintillator was placed in front of each crystal to differentiate between charged and neutral particles.

The discrimination of photons from particles was done with the hit pattern of the Veto detectors, a time-of-flight analysis and a pulse shape analysis of the BaF$_2$ signals. The $\pi^0$-mesons where then identified with a standard invariant mass analysis of coincident photon pairs (see fig.1 left). Further details are described in [14]. A time-of-flight versus energy analysis was used to separate particles with different masses, in particular in order to identify charged pions ($\pi^\pm$) (see fig.1 right and [14]). Due to the absence of a magnetic field, the two charged states, $\pi^+$ and $\pi^-$, can’t be distinguished.

Above the $\eta$ production threshold, the $\eta \rightarrow 3\pi$ decay is a potential background channel via events where only two of the three decay pions are detected. Most of this background can be suppressed with a missing mass analysis. The remaining background is subtracted using the $\eta$ photoproduction cross section. This cross section is measured independently in the $2\gamma$ decay channel of the $\eta$ with an invariant mass analysis.

Absolute cross sections are normalized using the thickness of the targets, the photon flux, detection efficiencies, geometrical acceptances and the branching ratio ($\pi^0 \rightarrow \gamma\gamma$). The geometrical acceptance and inefficiencies due to cuts and thresholds were deduced from a Monte-Carlo simulation based on GEANT3 [15] libraries and an event generator assuming a quasi-free production mechanism.

**RESULTS**

In fig.2 left, the measured invariant mass distributions of the $\pi$ pairs are shown for incident-photon beam energy of $E_\gamma = 400$-460 MeV. The dotted lines represent phase space distributions. In the $\pi^0\pi^0$ channel, we observe that the $\pi\pi$ mass follows the phase space distribution for carbon [11] and is shifted to a lower mass for calcium. For lead [11], despite the low statistics, a stronger shift than for calcium is seen. For the $\pi^0\pi^\pm$ channel, the mass distributions follow always phase space. This means that there is some evidence for an in-medium effect in the $\pi-\pi$ interaction in the isospin I=0 channel that does not exist in the isospin I=1 channel. Final state interactions (FSI) of the pions are very unlikely responsible for that effect since they would also occur in the $\pi^0\pi^\pm$ channel. This finding is in line with the results from the pion induced reactions.

At higher incident photon beam energy (500-550 MeV) (see fig.2 right), no such difference can be clearly identified between the different isospin channels. This could be explained by stronger FSI which would shade effects like those seen closer to threshold (higher kinetic energy of the outgoing $\pi$ results in a shorter mean free path).

The total cross section is shown in fig.3 for both channels $\pi^0\pi^0$ and $\pi^0\pi^\pm$. When scaled like $A^{2/3}$, the calcium cross section agrees with the proton and neutrons cross sections in $\pi^0\pi^\pm$ and with the deuteron cross section normalized to the mass number (which is the average of proton and neutron) in $\pi^0\pi^0$. This indicates that, above the immediate threshold region, due to strong final state interactions, only the low density surface region of the nuclei contributes to the measurement. On the surface of the nuclei, we do not observe an unexpected suppression of the resonance strength, as observed in total photoabsorption, which is not inconsistent with a possible broadening of the
FIGURE 2. Differential cross sections of the reaction $A(\gamma, \pi^0\pi^0)$ and $A(\gamma, \pi^0\pi^\pm)$. Left part: with $A=^{12}\text{C}, ^{40}\text{Ca}, ^{nat}\text{Pb}$ for incident photons in the energy range of 400-460 MeV. Right part: with $A=^{40}\text{Ca}$ for incident photons in the energy range of 500-550 MeV. Error bars denote statistical uncertainties and the curves are phase space. The results for C and Pb are from [11].

FIGURE 3. Total cross section of $\pi^0\pi^0$ (left part) and $\pi^0\pi^\pm$ (right part) photoproduction normalized to $A^{2/3}$, compared to the average nucleon cross section ($\sigma_d/2$).
resonances at normal nuclear density in the nuclear volume.

SUMMARY

We observed a significant in-medium effect on the $\pi\pi$-mass in the $A(\gamma,\pi^0\pi^0)$ (I=J=0) channel at $E_\gamma=400-460$ MeV. With increasing A, the strength of these distributions is shifting towards smaller invariant masses. No such effect has been observed in the $A(\gamma,\pi^0\pi^\pm)$ (I=1) channel. A large part of these modifications may be attributed to a change of the $\pi\pi$ interaction.

The total cross section scaled with the nuclear surface ($A^{2/3}$) agree with the deuteron normalized to the mass number or the proton and neutron cross section. This shows no significant in-medium effect on the surface of the nuclei contrarily to what had been observed in total photoabsorption.

ACKNOWLEDGMENTS

We thank the accelerator group of MAMI as well as many other technicians and scientists of the Institut für Kernphysik of the university of Mainz for their excellent support. We are indebted to all members of the TAPS/A2 collaborations who participated in the experiment. This work was supported by the Schweizerischer Nationalfond, the Deutsche Forschungsgemeinschaft (SFB 201), and the U.K. Engineering and Physical Sciences Research Council.

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