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Photon-induced reactions

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Abstract. An overview over the experimental research programs with photon beams is given with the focus on the electromagnetic excitation of the nucleon and the subsequent decay via mesons. Photoproduction of mesons on the free proton and on nucleons embedded in nuclei up to 1 GeV incident-photon energy are discussed.

PACS. 13.60.Le Meson production – 13.60.Rj Baryon production – 14.20.Gk Baryon resonances with $S = 0$ – 25.20.Lj Photoproduction reactions

1 Introduction

The advent of continuous-wave electron accelerators providing intense electron beams and tagged photon beams has enabled high-quality measurements. The experimental programs discussed here concentrate on the structure of the nucleon and observe resonance decays via their decay into mesons. In sect. 2, the experimental status of meson photoproduction in the non-strange regime is summarized. A further aspect is the modification of hadron properties in the nuclear medium. The underlying questions are the origin of hadron masses in the context of spontaneous chiral symmetry breaking and their modification in a hadronic environment due to chiral dynamics and partial restoration of chiral symmetry [1,2]. Section 3 discusses recent advances in photon-induced reactions on nuclei.

2 Meson photoproduction on the proton

The complex structure of the nucleon is reflected in its excitation spectrum which is observed in photoabsorption experiments. Here, the photohadronic method is applied where a shower detector at small forward angles rejects electromagnetic events and a large solid-angle hadronic detector registers events at larger angles. Figure 1 shows a compilation of photoabsorption cross-sections as measured on the proton. Several resonance regions can be discerned containing the contributions of broad and overlapping nucleon resonances. The lowest resonance is called $\Delta(1232)$ which is a P_{33} state in the common notation ($L_{(2I)(2J)}$) with a pole mass of 1232 MeV. It is prominently excited by incident photons of 0.2–0.5 GeV. The following group of resonances is called second resonance region ($E_\gamma = 0.5$–0.9 GeV). The contributing states together with their width and the incident-photon energies needed to produce their pole mass are listed in the following table:

State (Mass)	Width	E_γ
$P_{11}(1440)$	≈ 350 MeV	0.636 GeV
$D_{13}(1520)$	≈ 120 MeV	0.763 GeV
$S_{11}(1535)$	≈ 150 MeV	0.787 GeV

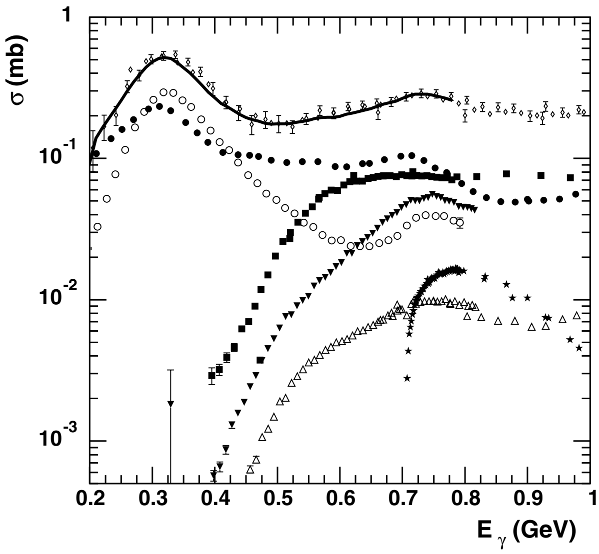

Fig. 1. The photoabsorption cross-section on the proton and its decomposition into the meson production channels. Diamonds are the photoabsorption data compilation from [3]. The experimental meson production cross-sections are: single π^+ (solid circles) from [4,5], single π° (open circles) from [6], $\pi^+\pi^-$ (solid squares) from [7,8], $\pi^+\pi^\circ$ (downward solid triangles) from [9], $\pi^\circ\pi^\circ$ (upward open triangles) from [10,11], and η (stars) from [12,13]. The solid line is the sum of the meson channels up to 800 MeV.

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Figure 1 also provides the status of meson photoproduction cross-sections. The shapes of the meson cross-sections reflect the resonance structure observed in photoabsorption showing that they are mostly decay products of the respective resonances. In the region of the Δ-resonance single-pion production is dominant. The π° (open circles) and π^+ (full circles) cross-sections are shown. The three resonances in the second resonance region decay roughly to 50% via single-pion emission which is used for partial wave analyses. Above $E_\gamma \approx 0.4$ GeV, the production of two pions is kinematically possible and single-π production looses its dominance. It can also be noted that the meson production channels involving charged pions are dominant as expected in electromagnetic excitation processes.

The η production threshold is located at $E_\gamma \approx 700$ MeV. The steeply rising η cross-section in fig. 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. This resonance is the only one with a strong decay branch of 30–55% into η-mesons and 35–55% into single pions. Thus, η production is considered 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. At the production threshold, studies of ηN final-state interactions are currently investigated and discussed in the contribution by S. Schneider (this issue, p. 421).

In the second resonance region, pion production can stem from the three resonances, $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$. The dominant contribution comes from the $D_{13}(1520)$-resonance which has the strongest coupling to the incident photon. The single- as well as the double-pion production channels display structure at the corresponding resonance mass, *i.e.* around $E_\gamma \approx 760$ MeV. On the proton, three isospin combinations of pion pairs can be produced. $\pi^\circ\pi^\circ$ and $\pi^+\pi^-$ production revealed that the resonance decays sequentially via an intermediate Δ state. In $\pi^+\pi^\circ$ the same behavior was found and a decay branch of 20% $N^\star \rightarrow N\rho$ is deduced. On account of its dominance, the $D_{13}(1520)$-resonance is said to be tagged by double-pion production. In calculations by Gomez Tejedor and Oset [14], the N^* contribution to double-pion photoproduction by itself is not large but rather stems from an interference with other terms. At ca. 0.52 GeV, the threshold for $\pi\pi\pi$ production opens up, part of which stems from the $\eta \rightarrow 3\pi$ decay. Finally, the solid line in fig. 1 represents the sum of all 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.

3 Meson photoproduction on nuclei

Experiments on nuclear photoabsorption and photofission have provided intriguing results. Figure 2(a) shows the nuclear photoabsorption data on carbon and averaged over a series of nuclei. For comparison, the photoabsorption

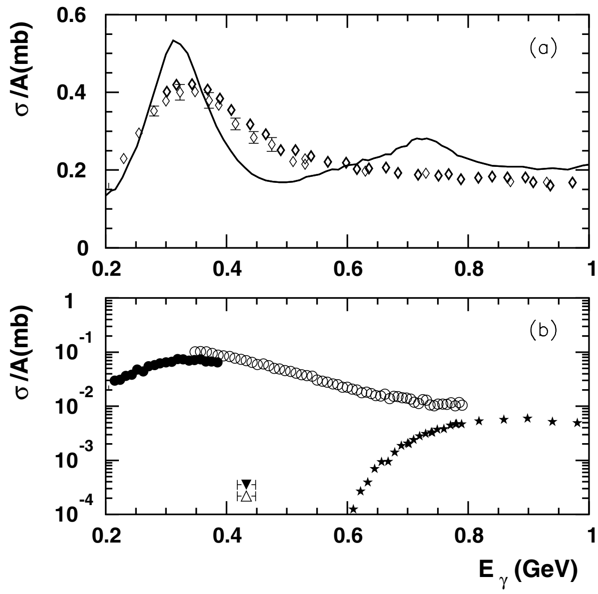

Fig. 2. The photoabsorption cross-section per nucleon on carbon (a) and its decomposition into the meson production channels (b). Diamonds are nuclear photoabsorption data from [15], the solid line shows the $\gamma + p$ cross-section. The experimental meson production cross-sections are: single π^+ (solid circles) from [16], single π° (open circles) from [17], $(\pi^\circ\pi^+ + \pi^\circ\pi^-)$ (solid triangles) and $\pi^\circ\pi^\circ$ (open triangles) from [18], and η (stars) from [19,20]. The solid line represents a fit to photoabsorption from the proton [15].

cross-section on the proton is also shown. The $\Delta(1232)$-resonance appears broadened and slightly shifted in position. In contrast, the nuclear cross-section does not show any sign of resonance structure above 0.6 GeV. It has been shown in systematic studies that nuclear cross-sections from nuclei heavier than ^{6}Li show this behavior. Overall, the cross-sections scale with the atomic mass number due to the fact that the photon probe illuminates the entire nucleus. The comparative study of the nuclear and the elementary photoabsorption cross-section yields several observations:

- The cross-sections follow a universal behavior $\sigma \sim 1/A$.
- The Δ-resonance is broadened and slightly shifted.
- The higher resonance regions appear to have "disappeared".
- The absolute value of the cross-section for incident-photon energies above 0.6 GeV is reduced.

"Trivial" medium effects on baryon resonance parameters cannot explain the disappearance of resonance structure. These effects are summarized in the following table:

Mechanism	Modification
Fermi motion	Resonance broadening
Collisions $N^\star N \rightarrow N^\star N$	Resonance broadening
Quenching $N^\star N \rightarrow NN$	Reduction of meson yield
Meson decay $N^\star \rightarrow N + \text{meson}$	Pauli blocking

The depletion of nuclear cross-sections in the second resonance region has been taken as evidence for modifications of hadron properties in the nuclear medium which have to date not been explained in a model-independent way. The phenomenon is commonly referred to as the disappearance of the D_{13}-resonance because of its dominant excitation in the $\gamma + p$ reaction.

It has been argued by Mosel *et al.* [21] that an in-medium broadening of the $D_{13}(1520)$-resonance is a likely cause of the suppressed photoabsorption cross-section. The broadening could arise from a coupling of the resonance to the $N\rho$ final state since the ρ-meson itself is expected to be appreciably broadened in the nuclear medium [22]. In the approach of Hirata *et al.* [23], the main point is a modification of double-pion production. The model predicts the disappearance of the peak around the position of the D_{13}-resonance via a cooperative effect of the interference in double-pion production processes, Fermi motion, collision broadening of the Δ- and N^*-resonances, and pion distortion in the nuclear medium.

A deeper understanding of the situation is anticipated from a detailed experimental study of meson photoproduction from nuclei. The investigations aim at various aspects, the meson-meson and meson-nucleus interaction and medium modifications of the excited states of the nucleon. Three different reaction mechanisms can contribute to meson production from nuclei. In coherent production the reaction amplitudes from all nucleons add coherently and the nucleus remains in its ground state while in incoherent production the nucleus is excited in the final state. In breakup reactions at least one nucleon is knocked out of the nucleus. At sufficiently high energies, it can be assumed that a quasifree reaction has taken place, in accordance with the coherence wavelength of the incident photon. Thus, in-medium properties of the nucleon resonances in the second resonance region have been investigated via quasifree pion or eta photoproduction. The meson resonances themselves are influenced by absorption as well as rescattering processes (final-state interactions). Any modification of meson properties can feed back on the baryon resonance parameters. The modification of the pion-pion interaction in the nuclear medium is of current interest and is discussed in the contributions of J. Messchendorp (this issue, p. 417) and M.J. Vicente Vacas (this issue, p. 479).

Compared to the elementary case, experimental information on meson photoproduction off nuclei is scarce. Figure 2(b) provides an overview over the experimental π, $\pi\pi$, and η total cross-sections that are currently available for carbon (^{12}C). Single-charged-pion cross-sections have only been measured below the double-pion production threshold ($E_\gamma \approx 0.4\,\text{GeV}$). The cross-section $\sigma_{\pi^+}(E_\gamma)$ is displayed, which is roughly the same as $\sigma_{\pi^-}(E_\gamma)$. The single-pion cross-sections exhibit a broad maximum between 0.2 and 0.4 GeV and explain the shape of the photoabsorption data indicating that the $\Delta(1232)$-resonance is a dominant producer of single pions.

Single-π° photoproduction has also been studied in the second resonance region. The systematic study over a series of nuclei has not provided any hint for a depletion of the resonance yield. The observed reduction and change of shape can be explained by trivial effects like absorption, Fermi smearing and Pauli blocking, and collision broadening. A similar result is obtained in systematic studies of η photoproduction cross-section from nuclei. The data shown in fig. 2(b) clearly show the line shape of the $S_{11}(1535)$-resonance. This means that the two resonances of the second resonance region, $D_{13}(1520)$ and $S_{11}(1535)$, which are dominantly excited by photons, seem to maintain their structure in the nuclear medium and do not contribute to an explanation for the disappearance of the second resonance region. However, judging from the elementary case as seen in fig. 1, the neutral final meson states do not contribute dominantly to the total reaction cross-section. Total cross-sections for charged- and double-pion production channels are needed in order to complete the picture. Figure 2 shows first total cross-sections for double-pion photoproduction from carbon which need to be determined for higher energies.

4 Summary and outlook

As an introduction to photon-induced reactions, meson production on the free proton and on nucleons embedded in nuclei have been discussed. In this contribution, an overview of the available total meson production cross-sections in the non-strange regime has been given. These studies are successfully employed to study the structure of the nucleon by tagging on the broad and overlapping nucleon resonances via their characteristic meson decay. The experimental results from photoabsorption on nuclei show clear signs of in-medium modifications of hadron properties by the fact that the resonances above the $\Delta(1232)$ seem to have disappeared. This phenomenon is not yet understood in a model-independent way. A deeper understanding can come from detailed studies of meson photoproduction from nuclei where the meson-meson and meson-nucleus interaction and medium modifications of the excited states of the nucleon could be traced.

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