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Letter

Surface and volume effects in the photoabsorption of nuclei

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Abstract. Recent experimental results for meson photoproduction from nuclei obtained with TAPS at MAMI are analyzed in view of the suppression of the second nucleon resonance region in total photoabsorption. The cross-sections can be split into a component from the low-density surface region of nuclei and a component which scales more like the nuclear volume. The energy dependence of the surface component is similar to the deuteron cross-section, it shows a clear signal for the second resonance peak assigned to the excitation of the $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$. The volume component behaves differently, it is lacking the second resonance peak and shows an enhancement at intermediate photon energies.

PACS. 13.60.Le Meson production – 25.20.Lj Photoproduction reactions

1 Introduction

The in-medium properties of hadrons is a hotly debated topic, although up to now the experimental evidence for significant modifications of meson or baryon properties is scarce and partly contradictory. In-medium modifications can arise from many different effects. Undisputed are "trivial" effects like nuclear Fermi motion, Pauli blocking of final states or additional decay channels of nucleon resonances like $N^\star N$ collisions. Such effects have been investigated in particular for the $P_{33}(1232)$ Δ-resonance. More exciting perspectives are in-medium modifications of mesons as a consequence of partial chiral restoration effects. An example is the predicted shift and broadening of the ρ-meson mass distribution in the nuclear medium [1–4], which has been searched for in dedicated heavy-ion experiments at CERN (see, *e.g.*, [5,6]). Such an effect would also influence the in-medium behavior of those nucleon resonances which have a significant decay branching ratio into $N\rho$. Another much discussed effect is the in-medium modification of the $\pi\pi$ interaction in the scalar-isoscalar channel observed in pion and photon-induced double-pion production reactions [7–9].

One of the clearest experimental observations of in-medium effects is the complete suppression of the second resonance peak in total photoabsorption (TPA) experiments [10,11]. TPA on the free proton shows a peak-like structure at incident photon energies between 600 and 800 MeV which is attributed to the excitation of the $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$ nucleon resonances. This structure is not visible in nuclear TPA over a wide range of nuclei from lithium to uranium. The average over the nuclear data, normalized to the mass numbers of the nuclei, ("universal curve") shows only the peak of the $P_{33}(1232)$-resonance and is flat at higher incident photon energies. Many different effects have been invoked as an explanation. A broadening of the excitation function due to nuclear Fermi motion certainly contributes, but cannot explain the full effect. Kondratyuk *et al.* [12] and Alberico *et al.* [13] have argued for an in-medium width of the relevant nucleon resonances, in particular the $D_{13}(1520)$, on the order of 300 MeV, *i.e.* a factor of two broader than for the free nucleon. This assumption brings model predictions close to the data, but it is not clear what effect could be responsible for such a large broadening of the excited states [4,14]. Possible effects resulting from the collisional broadening of the resonances have been studied in detail in the framework of transport models of the BUU type (see, *e.g.*, [15]) but up to now the complete disappearance of the resonance structure has not been explained.

The resonance bump on the free proton consists of a superposition of reaction channels with different energy dependences [16–21], which complicates the situation [22].

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Much of the rise of the cross-section towards the maximum around 750 MeV is due to the double-pion decay channels, in particular to the $n\pi^0\pi^+$ and $p\pi^+\pi^-$ final states. Gomez Tejedor and Oset [23] have pointed out that for the latter the peaking of the cross-section is related to an interference between the leading Δ-Kroll-Rudermann term and the sequential decay of the D_{13}-resonance via $D_{13} \rightarrow \Delta\pi$. Hirata *et al.* [24] have argued that the change of this interference effect in the nuclear medium is one of the most important reasons for the suppression of the bump. Recently, an investigation of the reaction $\gamma p \rightarrow n\pi^0\pi^+$ has shown that the D_{13}-resonance couples strongly to the $N\rho$ decay channel [25,26]. Consequently, any shift of the in-medium spectral strength of the ρ to lower masses would have a large effect on the decay width of $D_{13} \rightarrow N\rho$.

Inclusive measurements like TPA give no further clues to effects related to specific reaction channels. Therefore, during the last few years, exclusive meson production from nuclei has been studied in the second resonance region [22, 27–29]. In all cases no significant broadening or suppression of the resonance structure beyond trivial nuclear effects was found in the experiments. On the other hand, models [4,14] predict such modifications. However, in contrast to TPA exclusive meson production reactions are dominated by the nuclear surface. This is mainly due to the final-state interaction (FSI) of the mesons and can be further enhanced by density-dependent partial decay widths of nucleon resonances [30]. It was found for all investigated exclusive reaction channels that the cross-sections scale with $A^{2/3}$ ($A =$ atomic mass number), which indicates that due to the strong FSI only the low-density ($\rho \approx \rho_0/2$) nuclear surface contributes. This leaves open the possibility that the effect observed in TPA is related to a broadening of nucleon resonances in the nuclear volume at normal nuclear density ρ_0. In the meantime, all quasifree meson production reactions with neutral mesons, *i.e.* the final states η, π^0, $\pi^0\pi^0$, and $\pi^0\pi^\pm$ [27,22] have been measured. Furthermore, inclusive $X\pi^0$ production was investigated [22]. This reaction includes not only the quasifree processes but also components which are strongly affected by FSI like double-pion production with one pion re-absorbed in the nucleus. These experimental results allow for the first time to some degree a separation of surface and volume contributions in the nuclear response.

2 Results from photoproduction of pions

The results for the inclusive cross-section for neutral meson production $\sigma_{\rm nm}$ on the deuteron and on heavy nuclei are summarized in fig. 1 [21,22]. Shown is the sum of the cross-sections of all photoproduction reactions with at least one π^0- or η-meson in the final state, with no condition on quasifree reaction kinematics. The insert compares for the deuteron the neutral meson production cross-section $\sigma_{\rm nm}(d)$ to the cross-section $\sigma_{\rm cm}(d)$ for pure charged-meson final states ($\pi^\pm$, $\pi^+\pi^-$). The latter was constructed from:

$$\sigma_{\rm cm}(d) = \sigma_{\rm abs}(d) - \sigma_{\rm nm}(d) - \sigma_{\rm brk}(d)\,, \qquad (1)$$

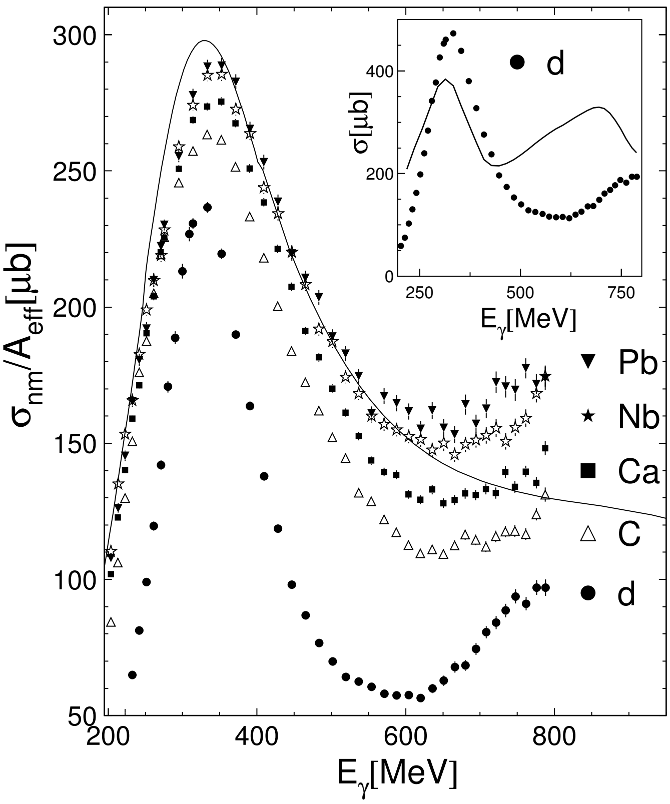

Fig. 1. Total inclusive π^0 photoproduction cross-section $\sigma_{\rm nm}$ (see text). Data scaled by $A_{\rm eff}$, $A_{\rm eff} = 2$ for the deuteron, $A_{\rm eff} = A^{2/3}$ for heavy nuclei. Solid curve: "universal curve" of TPA from nuclei scaled to data. Insert: $\sigma_{\rm nm}$ (full symbols) and $\sigma_{\rm cm}$ (charged mesons, solid curve) for the deuteron.

where $\sigma_{\rm abs}(d)$ is the TPA cross-section on the deuteron [19] and $\sigma_{\rm brk}(d)$ is the cross-section for the photon-induced two-body breakup of the deuteron [31].

The comparison of the excitation functions for neutral meson production to the "universal curve" for TPA from nuclei shows that the second resonance bump is much less suppressed in the meson production reactions.

In the case of all investigated exclusive photoproduction reactions it was found in [22] that nuclear and deuteron cross-sections are to a good approximation related by

$$\frac{\sigma_x^{\rm qf}(A)}{A^{2/3}} \approx \frac{\sigma_x^{\rm qf}(d)}{2}\,. \qquad (2)$$

This is the limiting case of strong FSI effects due to the short pion mean free path. We define the cross-section sum $\sigma_{\rm S}$ of all quasifree reaction channels with neutral mesons:

$$\sigma_{\rm S} = \sigma_{\pi^0}^{\rm qf} + \sigma_{\eta}^{\rm qf} + \sigma_{2\pi^0}^{\rm qf} + \sigma_{\pi^0\pi^\pm}^{\rm qf} \qquad (3)$$

and the difference to the inclusive cross-section:

$$\sigma_{\rm V} = \sigma_{\rm nm} - \sigma_{\rm S} \quad . \qquad (4)$$

Contributions from coherent single-π^0 production are included into $\sigma_{\pi^0}^{\rm qf}$ [22] and thus also into $\sigma_{\rm S}$. The cross-section $\sigma_{\rm V}$ belongs to reactions where one or more π^0-mesons are produced in non-quasifree kinematics. This

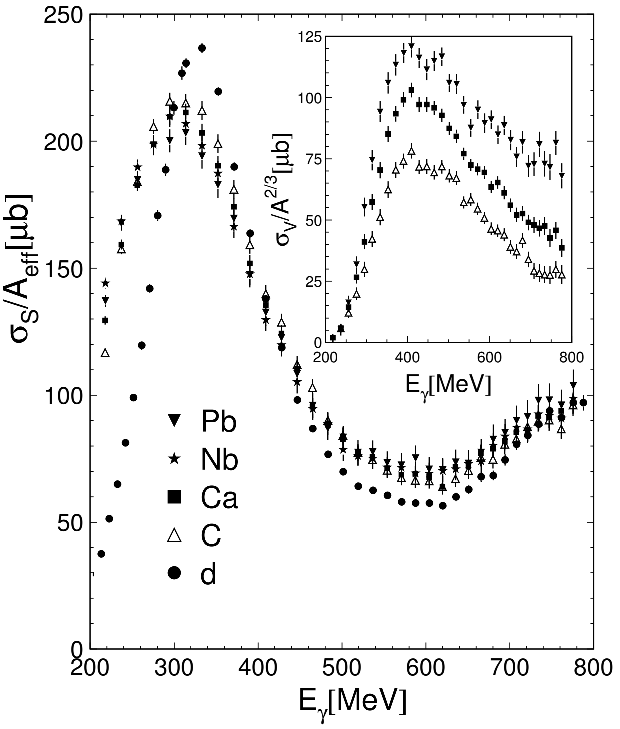

Fig. 2. Split-up of the inclusive cross-section $\sigma_{\rm nm}$ into the sum of quasifree exclusive partial channels $\sigma_{\rm S}$ (main plot) and the non-quasifree rest (insert), $A_{\rm eff}$ like in fig. 1 (see text).

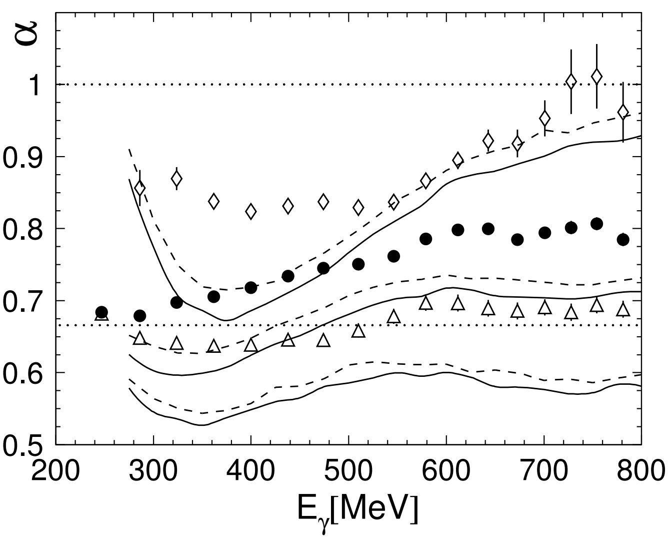

Fig. 3. Scaling of the total cross-sections with mass number. Filled circles: inclusive cross-section ($\sigma_{\rm nm}$), open diamonds: $\sigma_{\rm V}$, open triangles: $\sigma_{\rm S}$. Curves: BUU model, solid lines (dashed lines): P_{33} in-medium width from [32] ([33]), from bottom to top corresponding to $\sigma_{\rm S}$, $\sigma_{\rm nm}$, $\sigma_{\rm V}$.

can be due to propagation of the mesons in the nuclear matter, to absorption of one meson in double-pion production processes, or to production of mesons via two-body absorption processes [34]. The results obtained with the partial cross-sections from [21,22,27,35–37] are summarized in fig. 2. The properly scaled quasifree cross-sections $\sigma_{\rm S}$ for the nuclei are very similar to the deuteron and show

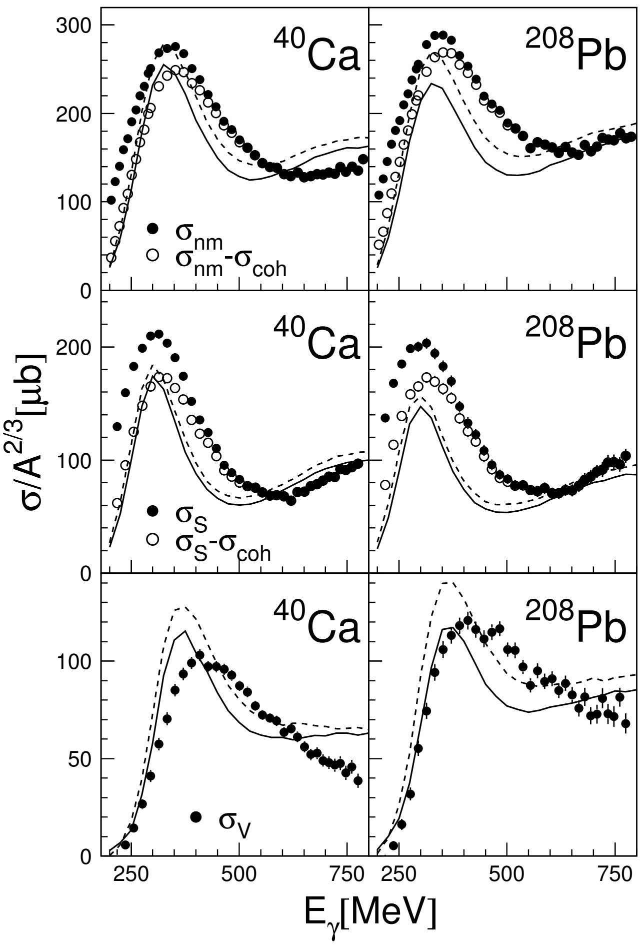

Fig. 4. Comparison of $\sigma_{\rm nm}$, $\sigma_{\rm S}$ and $\sigma_{\rm V}$ (full symbols) to BUU model calculations. Open symbols: $\sigma_{\rm nm}$, $\sigma_{\rm S}$ with coherent π^0 production subtracted. Curves: BUU model with different prescriptions for the $P_{33}(1232)$ in-medium width [15,22].

the same signal for the second resonance bump. The non-quasifree part on the other hand shows no indication of the second resonance peak (for the deuteron this component vanishes of course [21]). The scaling of these two components with the nuclear mass number is analyzed with the ansatz

$$\sigma(A) \propto A^{\alpha} \quad . \tag{5}$$

The scaling exponents α are shown in fig. 3. The quasifree part scales like $A^{2/3}$, *i.e.* like the nuclear surface. Therefore it is called $\sigma_{\rm S}$. The non-quasifree part has significantly larger scaling coefficients, between 0.8 and unity, which indicates that this contribution probes to some extent the nuclear volume. The corresponding cross-section is labeled $\sigma_{\rm V}$.

The data for calcium and lead are compared in fig. 4 to predictions of the BUU model (see [15,22] for details). The data for $\sigma_{\rm nm}$ and $\sigma_{\rm S}$ are also shown after subtraction of coherent π^0 production [38] which is not included in the model. The magnitude of the two components is reproduced by the model, but the resonance structures are overestimated. The model systematically underestimates the data at photon energies between 400 and 600 MeV,

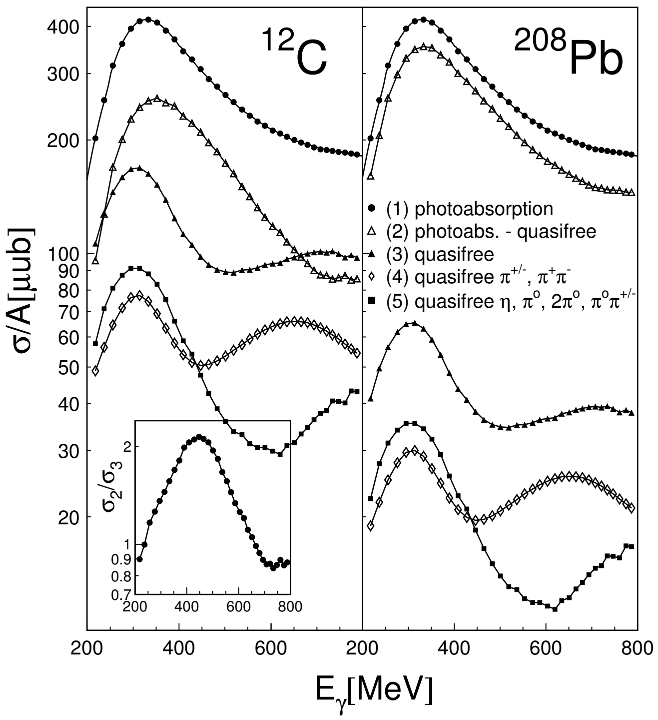

Fig. 5. Decomposition of the TPA cross-section for carbon and lead. Insert: ratio of (2) and (3) for carbon.

which is partly due to the neglect of two-body absorption processes of the photon, *e.g.* of the type $\gamma NN \rightarrow N\Delta$ [34].

3 Discussion and conclusion

The above results indicate a large difference between quasifree meson production from the nuclear surface and non-quasifree components. The quasifree part shows no suppression of the bump in the second resonance region, while this is completely absent for the non-quasifree meson production which has larger contributions from the nuclear volume.

There are no data available for the photoproduction of charged mesons from nuclei. However, since all neutral quasifree reactions follow the scaling eq. (2) and since charged pions will undergo similar FSI effects, it is reasonable to assume the same scaling behavior. Under this assumption, we can approximate the quasifree cross-section for charged-meson production from the deuteron cross-section (insert in fig. 1) with eq. (2). In order to account roughly for the stronger Fermi motion effects, the deuteron cross-section was folded with a typical momentum distribution for nuclei. The result for carbon is shown in fig. 5 (left side, curve (4)) together with the quasifree cross-section for neutral and mixed charged states (σ_{nm}, curve (5)), and the TPA cross-section (curve (1)). The behavior for heavier nuclei is qualitatively the same (see fig. 5, right side). The only difference is that due to the A scaling of the TPA and the $A^{2/3}$ scaling of the quasifree reactions the latter become less important. The sum of the quasifree meson production cross-sections (curve (3)) shows clear signals for the Δ-resonance and the second resonance region, although in the latter it is flatter than for the free proton. The flattening is mainly due to Fermi motion effects. This excitation function reflects the typical response of the low-density nuclear-surface regions to photons. The difference between this cross-section and TPA represents the typical response of the nuclear volume (curve (2)) where no isolated resonance peaks remain. The insert in the figure shows the ratio of these two excitation functions for carbon. The most striking feature is the buildup of strength at incident photon energies around 400 MeV in the volume component as compared to the quasifree surface reactions. It is known [34] that two-body absorption mechanisms like $\gamma NN \rightarrow N\Delta$ are non-negligible in this energy range, but it is unknown if they alone can explain the effect. Further progress in the models is necessary for an understanding of this behavior.

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