In-medium properties of nucleon resonances

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Abstract. Recent experimental results for the in-medium properties of nucleon resonances are discussed. The experiments were done with the TAPS detector at the tagged photon beam of the MAMI accelerator in Mainz. Measured was the photoproduction of mesons (final states $\pi^0X$, $\eta X$, $2\pi^0X$ and $\pi^0\pi^\pm X$) from the nuclei $^{12}$C, $^{40}$Ca, $^{93}$Nb, and $^{208}$Pb up to the second resonance region. The results were analyzed in view of the in-medium properties of the $P_{33}(1232)$, the $D_{13}(1520)$, and the $S_{11}(1535)$ resonances.

Keywords: photoproduction of mesons, nucleon resonances in the medium

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1. Introduction

QCD at high energies or short scales ($r < 0.1$ fm) is a perturbative theory with point-like quarks and gluons. However, at larger distances the perturbative picture breaks down. In the intermediate range ($0.1$ fm $< r < 1$ fm) the physics is governed by the excitation of nucleon resonances. This means that the full complexity of the nucleon as a many body system with valence quarks, sea quarks and gluons contributes. At even larger distances beyond 1 fm, QCD becomes the theory of nucleons and mesons (pions) and can be treated in the framework of chiral perturbation theory. Chiral symmetry is at the very heart of low energy QCD. However, it is well known, that chiral symmetry is spontaneously broken. This is connected to a non-zero expectation value of scalar $q\bar{q}$ pairs in the vacuum, the chiral condensate. A consequence of the chiral symmetry breaking in the hadron spectra is the non-degeneracy of parity doublets.

Model calculations indicate a significant temperature and density dependence of the chiral condensate (see e.g. [1]). It’s melting is connected with the prediction of a partial restoration of chiral symmetry at high temperatures and/or large densities. One consequence of the partial chiral symmetry restoration is a density dependence...
of hadron masses. An early prediction for this effect is the so-called Brown-Rho scaling [2]. Evidence for such effects has been searched for in many experiments. An example is the search for the predicted shift and broadening of the $\rho$-meson in the di-lepton spectra of heavy ion reactions with CERES at CERN [3 4].

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In-medium modifications of mesons will also influence the in-medium properties of nucleon resonances. Recently, Post, Leupold and Mosel [5] have calculated in a self consistent way the spectral functions of mesons and baryons in nuclear matter. The most relevant contributions to the self-energies are shown in fig. 1. In the vacuum, mesons couple only to meson loops (involving e.g. the pion) and nucleon resonances couple to nucleon - meson loops. However, in the medium mesons couple also to resonance - hole states. This influences not only the spectral functions of the mesons, but also the resonances, which in turn couple to the modified mesons loops. The predicted effects are in particular large for the $\rho$ meson and the $D_{13}(1520)$ resonance. The close-by $S_{11}(1535)$ resonance is much less effected [5].

During the last few years, the TAPS collaboration has studied the in-medium properties of mesons and nucleon resonances and the meson - nucleus interactions with photon induced reactions. This program covers four different major topics:

- The investigation of resonance contributions to $\eta$, $\pi$, $2\pi$ meson production reactions from light and heavy nuclei [6 7 8 9 10 11 12 13].
- The search for $\eta$ - nucleus bound states ($\eta$-mesic nuclei), which would be the ideal testing ground for the investigation of the $\eta$ - nucleus interaction [14 15].
- The investigation of the $\pi\pi$ invariant mass distributions for $2\pi$ production from nuclei, aiming at the in-medium behavior of the $'\sigma'$-meson [16].
- The measurement of the resonance shape of the $\omega$ meson in nuclear matter from its $\pi^0\gamma$ decay.
Nucleon resonances in the medium

Only the first topic will be discussed in this contribution, the status of the double pion production experiments is reviewed by S. Schadmand and the latest results from $\omega$-photoproduction are discussed by D. Trnka in the same topical issue of Acta Phys. Hungarica A.

2. Experiments

The experiments were carried out at the Glasgow tagged photon facility installed at the Mainz microton MAMI. They used Bremsstrahlung photons produced with the 850 MeV electron beam in a radiator foil. The meson from the production targets were detected with the electromagnetic calorimeter TAPS \cite{17, 18}, which consists of more than 500 hexagonally shaped BaF$_2$ scintillators of 25 cm length corresponding to 12 radiation lengths. The separation of photons from massive particles makes use of the plastic veto detectors (only charged particles), a time-of-flight measurement, and the excellent pulse shape discrimination capabilities of BaF$_2$-scintillators. The identification of neutral mesons ($\pi^o$ and $\eta$) is done by a standard invariant mass analysis. Charged mesons and nucleons are identified in addition with time-of-flight versus energy analyses. Details are summarized in \cite{8, 13}.

3. Results

Data have been taken for $^2$H, $^3$He, $^4$He, $^{12}$C, $^{40}$Ca, $^{93}$Nb and $^{208}$Pb targets. The data from the deuteron were used as a reference point for the elementary cross sections from the quasifree nucleon.

3.1. The $\Delta(1232)$ resonance

A detailed understanding of the in-medium properties of this state is necessary for any interpretation of pion photoproduction reactions from nuclei. It dominates single pion production in the low energy region up to 500 MeV incident photon energies, but it also contributes at higher energies via multiple pion production processes and through re-absorption of pions. An in-medium broadening at normal nuclear matter density of roughly 100 MeV has been previously extracted from pion-nucleus scattering experiments (see e.g. \cite{19}).

In photon induced reactions on the free proton, single $\pi^o$ photoproduction is best suited to study this state \cite{20} since the background from non-resonant contributions like pion-pole and Kroll-Rudermann terms is suppressed for neutral pions. However, for nuclei a further complication arises. Neutral pions can be produced in (quasifree) breakup reactions, where in simplest plane wave approximation, the pion is produced from a single nucleon, which in the process is knocked out of the nucleus. However, as long as the momentum transfer is small, this process competes with coherent $\pi^o$ production where the amplitudes from all nucleons add coherently, the momentum transfer is taken by the entire nucleus, and no nucleons are removed.
The two reaction mechanisms can be separated via their different kinematics. The total cross sections for the deuteron and the heavy nuclei are summarized for both reaction mechanisms \[8, 21, 13\] in fig. 2. Their behavior is quite different. The coherent reaction can be approximated for spin \(J = 0\) nuclei in plane wave by:

\[
\frac{d\sigma_A}{d\Omega} \propto \frac{d\sigma_N}{d\Omega} A^2 F^2(q) \sin^2(\Theta^*)
\]

where \(d\sigma_A\) is the nuclear cross section, \(d\sigma_N\) the elementary cross section on the free nucleon, \(A\) the atomic mass number, \(F^2(q)\) the nuclear form factor depending on the momentum transfer \(q\), and \(\Theta^*\) the cm polar angle of the pion (for details see \[21\]). The observed shift of the peak cross section to low photon energies for heavy nuclei is not related to in-medium effects of the \(\Delta\) but is a simple consequence of the interplay between the \(F^2(q)\) and \(\sin^2(\Theta^*)\) factors.
It is tempting to argue, that the quasifree breakup process is best suited to study the $\Delta$ in the medium. However, quasifree and coherent contributions are not independent. They are connected via final state interaction (FSI), which was discussed in detail in [8] [22]. Siodlaczek et al. [22] have even argued that for the deuteron the effect of FSI in the breakup process is counterbalanced by the coherent process so that the sum of the cross sections for the coherent and the breakup part with FSI equals the cross section of the pure quasifree process without FSI. A similar effect is visible in the angular distributions of single pion photoproduction from heavy nuclei [13]. The breakup cross section is depleted at forward angles where the coherent cross section peaks. The cross section for inclusive single $\pi^0$ photoproduction, i.e. the sum of breakup and quasifree parts can thus serve as a first approximation. It scales with $A^{2/3}$, which indicates strong FSI effects. The average over the heavy nuclei is compared in fig. 3 to the cross section from the free proton. The $\Delta$-resonance peak for the nuclei is significantly broadened with respect to the free nucleon from 100 MeV to 190 MeV. This is in nice agreement with the prediction for the in-medium spectral function of the $\Delta$ [5] (see fig. 4, right hand side), which corresponds to exactly the same broadening.

The breakup process is mostly treated in the framework of nuclear cascade models or transport models. The data are compared in fig. 4 to calculations in the framework of the Boltzmann-Uehling-Uhlenbeck transport model [23] [13]. The model includes an additional in-medium width of the $\Delta$ of roughly 80 MeV at normal nuclear matter density. The calculations reproduce the shift of the rising slope of the $\Delta$ to lower incident photon energies, but underestimate the falling slope and show a somewhat different mass number dependence of the peak cross section.

The results from coherent $\pi^0$ photoproduction from nuclei have been analyzed in [24] [21] in the framework of the DWIA calculations of Drechsel et al. [25] which include a phenomenological $\Delta$ self-energy. The main finding was, that the model with the self-energy fitted to $^4$He reproduces the data for carbon and calcium so that no significant mass dependence of the self-energy was found. The self-energy
itself corresponds to an increase of the width at resonance position \( (E_\gamma \approx 330 \text{ MeV}) \) of roughly 110 MeV in agreement with the results discussed above. The resonance position is slightly upward shifted (by 20 MeV). This is no contradiction to the excitation functions in figs. \( 6 \). The width increase is energy dependent (only \( \approx 40 \) MeV at \( E_\gamma \approx 250 \) MeV) so that the net effect in the excitation functions in figs. \( 6 \) is a small downward shift of the peak position.

3.2. The second resonance region

Among the clearest experimental observations of in-medium effects is the suppression of the second resonance peak in total photoabsorption (TPA) \( [26, 27] \). 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 \( \text{P}_{11}(1440) \), \( \text{D}_{13}(1520) \), and \( \text{S}_{11}(1535) \) resonances. This structure is not visible for nuclei over a wide range of mass numbers from lithium to uranium (see fig. 5 left hand side).

The resonance bump on the free proton consists of a superposition of reaction channels with different energy dependencies (see fig. 5 right hand side) which complicates the situation \( [20] \). 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. A study of the partial reaction channels is thus desirable. However, the experimental identification of exclusive final states is more involved and FSI effects must be accounted for. The interpretation of exclusive measurements therefore always needs models which account for the trivial in-medium and FSI effects like absorption of mesons and propagation of mesons and resonances through nuclear matter.

The results for meson photoproduction off the free proton suggest, that pion and \( \eta \) photoproduction are best suited for a comparison of the in-medium properties of the \( \text{D}_{13} \) and \( \text{S}_{11} \) resonances \( [20] \). The total cross section for \( \eta \) photoproduction is completely dominated in the second resonance region by the \( \text{S}_{11}(1535) \) resonance.
On the other hand, the resonance structure in $\pi^0$ photoproduction is strongly dominated by the $D_{13}(1520)$ resonance. Furthermore, the analysis of double pion production from the free nucleon has shown that a significant contribution to the decay strength of the $D_{13}$ resonance comes from the $D_{13} \rightarrow N\rho$ decay. The large broadening of the $D_{13}$ in-matter spectral function predicted in [35] is related to this channel. In double pion production reactions the $\rho$ contributes to the $\pi^0\pi^\pm$ and $\pi^+\pi^-$ final states, but not to $\pi^0\pi^0$ since $\rho^0 \rightarrow \pi^0\pi^0$ is forbidden.

The measured excitation functions for quasifree single $\pi^0$, $\eta$, $\pi^0\pi^0$, and $\pi^0\pi^\pm$ photoproduction from nuclei compared to the deuteron response folded with the nucleon momentum distribution of Ca.

\[ \frac{\sigma_{\text{eff}}(A)}{A^{2/3}} \approx \frac{\sigma_{\text{eff}}(d)}{2} \] (2)

The scaling among the heavier nuclei holds even when the comparison to the deuteron is disturbed, e.g. by the effects of coherent single $\pi^0$ production at low photon energies and or by effects of Fermi smearing close to the $\eta$ threshold. The $A^{2/3}$ scaling is the limiting case of strong FSI effects due to the short pion mean free path. This means that the quasifree exclusive reactions probe only the nuclear surface region. Since the properly scaled nuclear cross sections agree with the deuteron cross section no significant in-medium effects are observed for the low density surface zone of the nuclei. Consequently, as already discussed in [7, 37] no direct indications for a broadening of the $S_{11}$ or $D_{13}$ resonance have been found in the exclusive quasifree reactions. This is particularly obvious for the cross section.

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**Fig. 6.** Total cross sections of quasifree meson photoproduction from nuclei compared to the respective cross sections from the deuteron. All data are normalized to $A_{\text{eff}}$, where $A_{\text{eff}} = A$ for the nucleon and the deuteron and $A_{\text{eff}} = A^{2/3}$ for heavier nuclei. The insert for single pion production compares the $^{40}\text{Ca}$ data with (filled symbols) and without (open symbols) the coherent component to the deuteron response folded with the nucleon momentum distribution of Ca.

The measured excitation functions for quasifree single $\pi^0$, $\eta$, $\pi^0\pi^0$, and $\pi^0\pi^\pm$ photoproduction from nuclei compared to the deuteron response folded with the nucleon momentum distribution of Ca.
Fig. 7. Left hand side: sum of exclusive quasifree and coherent channels $\sigma_S$, middle: total inclusive cross section $\sigma_{nm}$ for neutral meson production ($A_{eff}=2$ for the deuteron and $A_{eff}=A^{2/3}$ for $A > 2$), right hand side: non-quasifree components $\sigma_V$. 

The mass number scaling of the different components of the total neutral meson production cross section was analyzed in \cite{Krusche} with the simple ansatz $\sigma(A) \propto A^\alpha$. In case of the quasifree component $\sigma_S$ the exponent $\alpha$ was found to be close to $2/3$ over the whole energy range. This is the expected behavior of surface dominated meson production. However, $\alpha$ is significantly larger for the non-quasifree components, which indicates that this contribution probes to some extent the nuclear volume. In this case, the appearance of the second resonance peak in $\sigma_S$ and its complete suppression in $\sigma_V$ could indicate a strong density dependence of the effect.

sum $\sigma_S$ of these reactions:

$$\sigma_S = \sigma_{\pi^o}^{qf} + \sigma_{\eta}^{qf} + \sigma_{2\pi^o}^{qf} + \sigma_{\pi^o \pi^\pm}^{qf}$$

which is shown in fig. 7 (left hand side). The behavior of $\sigma_S$ throughout the second resonance is very similar for the deuteron and the heavy nuclei. The resonance structure is almost identical, no in-medium effects are visible, and the scaling indicates the dominance of FSI effects.

The total inclusive cross section of $\pi^o$ and $\eta$ photoproduction $\sigma_{nm}$ (see fig. 7 middle) was also extracted in \cite{Krusche}. It includes reactions where a single neutral pion is observed which does not fulfill the kinematic constraints of quasifree or coherent reactions. These are mainly reactions with strong FSI, e.g. double pion production with one pion re-absorbed in the nucleus. The behavior is somewhere in between total photoabsorption and the quasifree component. The resonance structure is still visible for heavy nuclei, but it is much less pronounced than for the deuteron. The difference $\sigma_V = \sigma_{nm} - \sigma_S$ between the inclusive cross section and the quasifree components (see fig. 7 right hand side) has a completely different energy dependence. It does not show any indication of the second resonance bump.
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