In-Medium Properties of the $D_{13}(1520)$ Nucleon Resonance

B. Krusche,[1] J. Ahrens,[2] R. Beck,[2] I. J. D. MacGregor,[3] J. C. McGeorge,[3] V. Metag,[4] and H. Ströher[5]
[1]*Department of Physics and Astronomy, University of Basel, Ch-4056 Basel, Switzerland*
[2]*Institut für Kernphysik, Johannes-Gutenberg-Universität Mainz, D-55099 Mainz, Germany*
[3]*Department of Physics and Astronomy, University of Glasgow, Glasgow G128QQ, United Kingdom*
[4]*II. Physikalisches Institut, Universität Giessen, D-35392 Giessen, Germany*
[5]*Institut für Kernphysik, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
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The in-medium properties of the $D_{13}(1520)$ nucleon resonance were studied via photoproduction of π^0 mesons from nuclei (C, Ca, Nb, Pb) with the TAPS detector at the Mainz Microton accelerator. The inclusive (single and multiple pion production) data disagree with model predictions which explain the disappearance of the second resonance bump in total photoabsorption via a medium modification of the $D_{13} \to N\rho$ decay. The exclusive single π^0 production data show no broadening of the resonance structure beyond Fermi smearing. Both results together cast doubt on attempts to explain the vanishing of the second resonance bump for nuclei by a broadening of the D_{13} resonance.

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The low lying $N^\star$ resonances, excited states of the nucleon with isospin $I = 1/2$, comprise the states $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$ in the well known nomenclature [1]. They are, for example, excited by photons with energies between 600 and 900 MeV. Since their decay widths are large compared to their spacing they overlap and form one single enhancement usually called the second resonance region. Because of their different couplings to the initial photon—nucleon and the final meson—nucleon states they can nevertheless be separated to a large extent: The production of η mesons proceeds almost exclusively via the excitation of the S_{11} resonance, while the largest resonance contributions to single and double pion production come from the D_{13} resonance. Using this selectivity, the properties of the resonances, when excited on the free proton or quasifree neutron, have been studied in much detail during the last few years via η photoproduction [2–8] and single and double pion photoproduction reactions [9–15]. The excellent quality of the recent data sets allowed precise determinations of the resonance properties, e.g., the extraction of a 0.05%–0.08% branching ratio for the $D_{13} \to N\eta$ decay [16].

However, much less is yet known about the behavior of the isobars inside the nuclear medium, where a number of modifications may arise. The most trivial is the broadening of the excitation functions due to Fermi motion. The decay of the resonances is modified by Pauli blocking of final states, which reduces the resonance widths, and by additional decay channels like $N^\star N \to NN$ which cause the so-called collisional broadening. Both effects cancel to some extent and it is *a priori* not clear which one will dominate. A very exciting possibility is that the resonance widths could be sensitive to in-medium mass modifications of mesons arising from chiral restoration effects [17,18]. The D_{13} resonance for example has a 15%–25% decay branch to the $N\rho$ channel [1], which is fed only from the low energy tail of the ρ mass distribution. This means that a broadening or a downward shift of the ρ mass distribution inside the nuclear medium could have significant effects on the D_{13} width.

The first experimental investigation of the second resonance region for nuclei was done with total photoabsorption. The surprising results showed an almost complete absence of the resonance bump for ^{4}He and heavier nuclei [19–21], which up to now has not been understood.

The problem is illustrated in Fig. 1 where the total inclusive π^0 production cross section from Ca from the present experiment is compared to the reaction on the deuteron and to model predictions. The deuteron data show a clear bump around 800 MeV, but the calcium data are rather flat. However, the predictions for Ca from a transport model of the Boltzmann-Uehling-Uhlenbeck (BUU) type [22], which takes into account Fermi smearing, Pauli blocking,

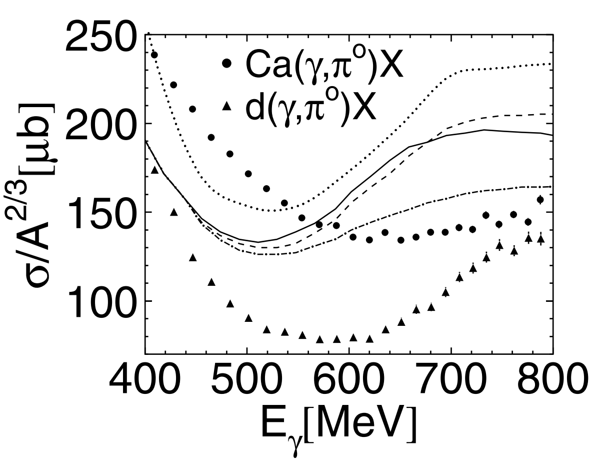

FIG. 1. Total inclusive π^0 photoproduction cross section from ^{2}H [13] and Ca scaled by $A^{2/3}$ compared to model calculations [22] for Ca$(\gamma, \pi^0)X$. Dotted curve: BUU; dashed curve: BUU with Δ collision width from Δ-hole model; solid curve: like dashed curve but modified $D_{13}(1520) \to N\rho$ width; dash-dotted curve: like dashed curve but additional 300 MeV collision width of D_{13}.

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and collisional broadening still exhibit the bump structure. Not even the modification of the D_{13} decay by medium effects of the ρ meson (solid curve) improves the situation. Only an arbitrary and probably unrealistic broadening [22] of the D_{13} resonance by 300 MeV produces a significant suppression. Note that the underestimation of the cross section at low incident photon energies is attributed in [22] to many-body absorption processes of the photon which are not included in the model.

Total photoabsorption has the advantage that no final state interaction effects (FSI) must be accounted for so that the entire nuclear volume is tested. However, many different reaction channels do contribute to this reaction so that it is impossible to test the behavior of individual resonances. Even worse, some of the reaction channels responsible for the structure are not strongly related to the excitation of states from the second resonance region.

Part of the problem is that most of the rise of the cross section towards the resonance bump stems from the opening of the double pion production channels [23]. The largest contribution is due to the $\pi^+\pi^-$ final state. It is well known [10] that this reaction is dominated by Δ-Kroll-Rudermann and Δ-pion-pole terms; i.e., it mainly involves the excitation of the $P_{33}(1232)$ Δ resonance rather than the states from the second resonance region.

It is therefore desirable to study this region with exclusive reactions which allow the investigation of individual resonances, even at the expense that FSI effects complicate the interpretation. In a recent study [24] we used η photoproduction for an investigation of the in-medium properties of the $S_{11}(1535)$. In this case we did not find any unexplained depletion of the in-medium resonance strength. The data were in excellent agreement with predictions from the BUU model [25] and other models (e.g., [26]), taking into account Fermi smearing, Pauli blocking, collisional broadening, and FSI effects. Since the energy range extended just up to the resonance maximum, it was not possible to deduce the in-medium width of the resonance. In the meantime, Yorita *et al.* [27] have studied quasifree η photoproduction from carbon over a larger energy range and also found no significant broadening of the S_{11} resonance. Again the data are in fairly good agreement with model expectations.

The above results do not preclude broadening as the explanation for the absence of the second resonance bump because the total contribution of the S_{11} resonance to the bump structure is quite small. Furthermore, due to the location of the η-production threshold in the low energy tail of the resonance, the effects of nuclear Fermi motion have a drastic influence on the excitation curve so that any extraction of the in-medium width requires a lot of modeling. In the present work we have therefore investigated the dominant $D_{13}(1520)$ resonance in the nuclear medium via quasifree single π^0 photoproduction.

The experiments using C, Ca, Nb, and Pb targets were carried out at the Glasgow tagged photon facility installed at the Mainz Microton (MAMI) with the TAPS detector. Details of the experimental setup and the data analysis are summarized in [13]. The neutral pions were identified via an invariant mass analysis and quasifree single π^0 production was selected by a missing energy analysis as in [13]. The stronger broadening of the structures in the missing energy spectra for nuclei heavier than deuterium was compensated by more restrictive cuts, so that contamination from multiple meson production was excluded.

The total single π^0 production cross section for the proton and the deuteron [13] are shown in Fig. 2. The inset shows for the deuteron the separation of quasifree single π^0 production in missing energy from multiple pion production processes ($\pi^0\pi^0, \pi^\pm\pi^0, \eta \rightarrow 3\pi^0, \eta \rightarrow \pi^0\pi^+\pi^-$), which contribute to the inclusive cross section. In the main part of the figure the proton and deuteron cross sections are compared to the expectation from a unitary isobar analysis of pion photoproduction (MAID) [28]. The data for the proton are very well reproduced. For the deuteron, we have taken the sum of the proton and neutron cross sections from MAID (full curve in Fig. 2) and folded this cross section with the momentum distribution of the nucleons bound in the deuteron (dashed curve). The momentum distribution was derived from a parametrization of the deuteron wave function [29]. The prediction for the deuteron cross section agrees very well with the data in the tail of the Δ resonance, but it significantly overestimates the cross section in the D_{13} region. This result is very surprising since we are dealing with *quasifree* pion production, for which the large momentum mismatch between participant and spectator nucleon is expected to suppress any interference terms between the two nucleons. At present it is not clear if this problem is related to the input

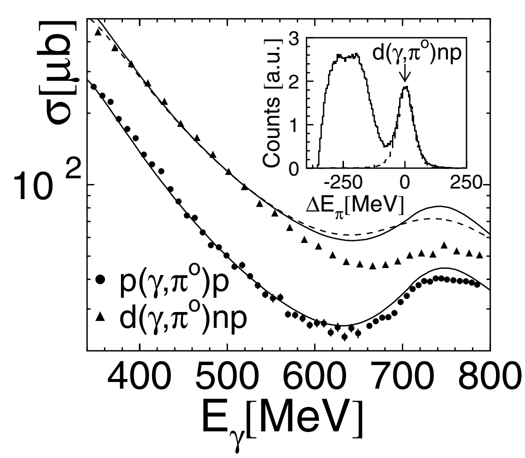

FIG. 2. Comparison of the measured total cross sections for $p(\gamma,\pi^0)p$ and $d(\gamma,\pi^0)np$ to the MAID analysis [28]. Proton case, solid line: MAID analysis. Deuteron case, solid curve: sum of proton and neutron MAID cross section; dashed curve: folded with momentum distribution of bound nucleons. Inset: missing energy spectrum of the reaction $d(\gamma,\pi^0)X$ for incident photon energies 600–800 MeV used to separate single π^0 production from multiple pion production reactions. Dashed line: Monte Carlo simulation for single π^0 production (see [13]).

used for the elementary cross section of the $n(\gamma,\pi^0)n$ reaction or if the incoherent addition of the Fermi smeared elementary cross sections, which in the same energy region works excellently, e.g., for η photoproduction [6,8], is not a good approximation. Precise measurements of π^0 photoproduction from the deuteron with coincident detection of the recoil nucleons and more refined model calculations are necessary to solve this problem. However, no matter what the nature of the problem is, we stress that this finding has important consequences for the extraction of resonance in-medium properties from a comparison to model predictions. Models like the BUU [22] must rely on the assumption that the total cross section from nuclei before taking into account in-medium and FSI effects is the incoherent sum of the known proton and neutron cross sections, which in this case is not even true for the deuteron.

For a more quantitative analysis of the D_{13} excitation in nuclei we have decomposed the cross sections into a resonance and a background part. In principle, such a decomposition requires a multipole analysis that takes into account resonance-background interference terms. However, interference terms are small in this case as demonstrated in Fig. 3, which shows the proton and neutron cross sections calculated with MAID [28].

The single π^0 production cross sections taking into account all resonances and background terms (σ_{π^0}) are very similar to the sum of the separate cross sections σ_r (excitation of the S_{11} and D_{13} resonances only) and σ_{nr} (everything except S_{11} and D_{13} excitation). In the following we do not attempt to separate the contribution from the two resonances, but one should keep in mind that the resonance part is dominated by the excitation of the D_{13} (see Fig. 3). The decomposition of the measured cross sections is shown in Fig. 4. The background part coming from the tail of the Δ resonance, the contribution of the P_{11} resonance, nucleon Born terms, and vector meson exchange, was fitted with a function of the type

$$\sigma \propto e^{(aE_\gamma^2 + bE_\gamma)} \tag{1}$$

with a and b as free parameters. It is obvious from the figure that the resonance contribution for the data for heavier nuclei is not qualitatively different from the deuteron case.

The differences between measured cross sections and fits are shown in Fig. 5. In the main figure the resonance contributions for the proton, the deuteron, and the average for the heavier nuclei are compared to the MAID predictions for the D_{13} and S_{11} contributions. For the deuteron and the heavier nuclei the MAID average of proton and neutron cross sections folded with the proper momentum distributions is scaled to the data. Obviously no broadening of the resonance structure beyond Fermi smearing is observed. A D_{13} resonance broadened to 300 MeV as used in the BUU calculations [22] for the inclusive data (see Fig. 1) is clearly ruled out; the data correspond rather to BW curves with a width around 100 MeV.

Finally, we have investigated if the strength of the resonance signal for the nuclei is consistent with the deuteron case. For this purpose we have folded the MAID proton cross section for resonance excitation with the deuteron Fermi motion and compared the result to the measured deuteron cross section. Agreement is obtained for $\sigma_n(D_{13})/\sigma_p(D_{13}) \approx 1/3$, while the ratio obtained from a direct comparison of MAID proton and neutron cross sections is 2/3. We have then adopted the 1/3 ratio, folded $(1 + 1/3)\sigma_p/2$ with a typical nuclear momentum distribution, and compared the result to the nuclear data scaled to $A^{2/3}$, which in the simplest approximation

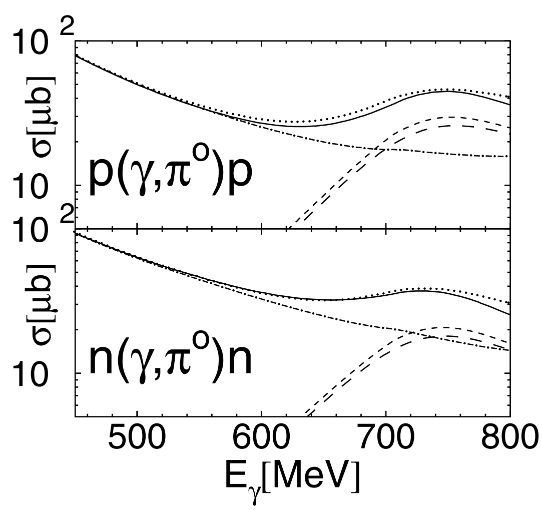

FIG. 3. Decomposition of single π^0 photoproduction in the second resonance region from MAID2000 [28]. Full lines: cross section σ_{π^0} for full model; dash-dotted curves: cross section σ_{nr} without contribution from D_{13} and S_{11} resonances; short-dashed curves: cross section σ_r for excitation of D_{13} and S_{11} only; long-dashed curves: D_{13} only, dotted curves: $\sigma_{nr} + \sigma_r$.

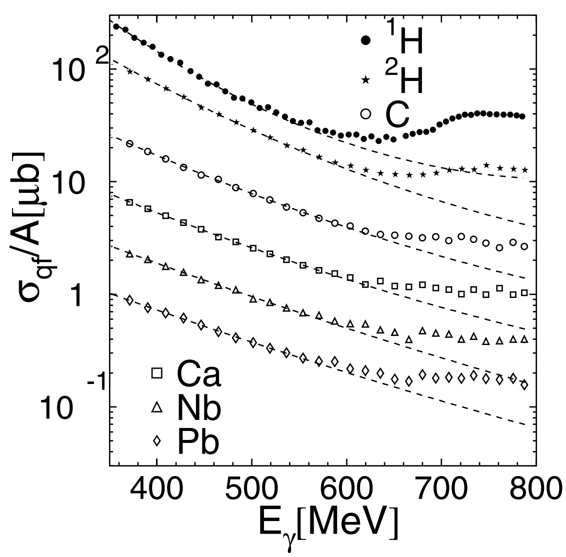

FIG. 4. Total cross section per nucleon for single π^0 photoproduction in the second resonance region for the nucleon and for nuclei. The scale corresponds to the proton data; the other data are scaled down by factors 2, 4, 8, 16, and 32. The dashed curves are fits to the data in the energy range 350–550 MeV.

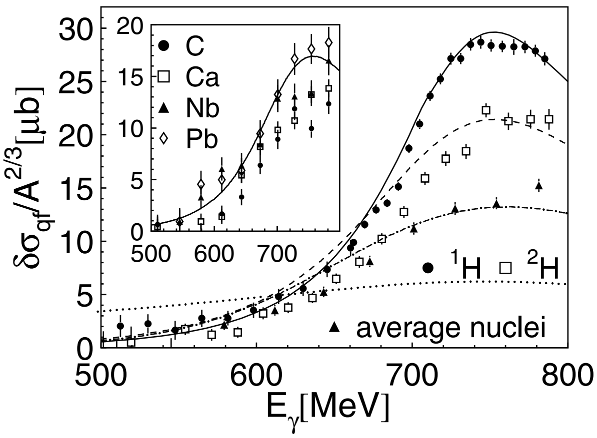

FIG. 5. Main figure: differences between measured cross sections and fits shown in Fig. 4 scaled by $A^{2/3}$. Full curve: MAID prediction for excitation of the D_{13} and S_{11} resonances on the proton; dashed curve: MAID proton-neutron average folded with momentum distribution for deuteron; dash-dotted curve: curve folded with momentum distribution for medium weight nuclei (both scaled to the data). Dotted curve: Breit-Wigner curve for the D_{13} resonance with 300 MeV width. Inset: individual nuclear data and prediction from deuteron cross section (solid curve; see text).

accounts for the FSI effects (see Fig. 5 inset). The agreement of this approximation with the data is quite good.

At this point we must clarify a crucial aspect of our results. The approximate scaling of the cross sections with $A^{2/3}$ indicates FSI effects. This means that in contrast to total photoabsorption not the entire nuclear volume is probed. BUU-model calculations [30] indicate that, e.g., for ^{208}Pb in the Δ-resonance region *observed* pions are predominantly produced in a surface region where the nuclear density drops from $0.8\rho_0$ to $0.4\rho_0$ (ρ_0: normal nuclear density). However, suppression of the resonance bump in total photoabsorption reactions occurs already for ^{4}He [21] and does not change from very light nuclei like lithium and beryllium up to very heavy ones like uranium. This excludes a strong density dependence of the effect.

Furthermore, it is clear that the models without a strong broadening of the D_{13} resonance overestimate our inclusive pion data (see Fig. 1). However, these data are subject to FSI in the same way as the exclusive data. This can be shown by fitting the mass dependence of the cross section from carbon to lead with a simple $\propto A^\alpha$ law. The results in the energy range 720–790 MeV are $\alpha = 0.791 \pm 0.005$ (inclusive pion data), $\alpha = 0.74 \pm 0.01$ (exclusive pion data; Fig. 4), and $\alpha = 0.81 \pm 0.05$ (D_{13} part only, Fig. 5 inset). This means that the inclusive and exclusive data probe the nuclei at comparable densities and consequently a broadening of the D_{13} resonance is ruled out as an explanation for the overestimation. It is thus evident that the models miss some other effect which must be understood before the results from total photoabsorption can be used as evidence for an in-medium resonance broadening.

In summary, investigating quasifree π^0 photoproduction we have found a strong quenching but no broadening of the D_{13}-resonance structure for the deuteron with respect to the proton. However, for heavy nuclei we found no indication of a broadening or a suppression of the D_{13} structure with respect to the deuteron. Since so far model predictions agree with the pion photoproduction data only under the assumption of a strong broadening of the resonance, other effects seem to be missing in the models. This also casts doubt on the interpretation of the total photoabsorption data via resonance broadening in the framework of the same models.

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