Photoexcitation of Baryon Resonances - News from the $D_{13}(1520)$

B. Krusche

Department of Physics and Astronomy, University of Basel
CH-4056 Basel, Klingelberstr. 82, Switzerland

Abstract

The so-called second resonance region of the nucleon comprises the states $P_{11}(1440)$, $D_{13}(1520)$ and $S_{11}(1535)$. During the last few years photoproduction experiments have largely contributed to a better understanding of these states, but the strong suppression of the resonance structure in total photoabsorption experiments from nuclei is still not understood. The $D_{13}$-resonance dominates the resonance structure due to its large photon coupling. In this contribution new results for the excitation and decay modes of the $D_{13}$ on the free nucleon and first results for the in-medium behavior of the resonance are summarised.

1 Introduction

Due to their different couplings to the initial photon - nucleon and the final meson - nucleon states the low lying nucleon resonances $D_{13}(1520)$ and $S_{11}(1535)$ can be separated to a large extent: The production of $\eta$-mesons proceeds almost exclusively via the excitation of the $S_{11}$, while the largest resonance contributions to single and double pion production come from the $D_{13}$. 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 $\eta$-photoproduction [1, 2, 3, 4, 5, 6, 7] and single and double pion photoproduction reactions [8, 9, 10, 11, 12, 13, 14]. The excellent quality of the data allowed precise determinations of the resonance properties, like the extraction of a $0.05\% - 0.08\%$ branching ratio for the $D_{13} \to N\eta$ decay [15].

Much less is known about the behavior of the isobars inside the nuclear medium, where a number of modifications 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 $N^*N \to NN$ which cause the 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. The $D_{13}$-resonance for example has a 15 - 25% decay branch to the $N\rho$-channel \cite{16}, which is only fed from the low energy tail of the $\rho$ mass distribution. This means that the resonance width is very sensitive to the $\rho$ mass distribution. The first experimental investigation of the second resonance region for nuclei was done with total photoabsorption. The results showed an almost complete absence of the resonance bump for $^4\text{He}$ and heavier nuclei \cite{17,18,19}, which up to now has not been understood.

In this talk new experimental results are presented which shed light on the contribution of the $D_{13}$ resonance to the second resonance bump via the double pion decay channels and on the in-medium behavior of the resonance.

2 Double pion production and the $D_{13}(1520)$

The cross sections for single meson photoproduction (pions and $\eta$-mesons) and double pion photoproduction are almost equal at incident photon energies between 600 and 800 MeV. Moreover, most of the rise of the total photoabsorption cross section from the dip above the $\Delta$-resonance to the peak of the second resonance bump is due to double pion production (see fig.1 left hand side). Any detailed interpretation of the second resonance bump therefore requires the understanding of double pion production. Previously it was not

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Left hand side: decomposition of the total photoabsorption cross section of the proton into single and double meson production. Right hand side: total cross section for $\gamma p \rightarrow p\pi^+\pi^-$ \cite{8} compared to models \cite{20,21,22}.}
\end{figure}
even clear which role the $P_{11}$-, $D_{13}$- and $S_{11}$-resonances play for double pion production. Background terms like the $\Delta$-Kroll-Rudermann (KR) and the $\Delta$-pion-pole term, which instead involve the excitation of the $\Delta$, are important at least for the charged double pion channels.

Among the possible double pion production reactions previously only $\gamma p \to p\pi^+\pi^-$ was measured with good precision. The total cross section, which is in reasonable agreement with model calculations (see fig.1 right hand side), is very small between threshold at $\approx 310$ MeV and $\approx 400$ MeV. It rises sharply from $\approx 400$ MeV to a maximum at $\approx 650$ MeV. This rise is accompanied by a strong peak at the mass of the $\Delta$-resonance in the invariant mass distribution of the $p\pi^+$-pair. This peak is absent in the $p\pi^-$ invariant mass. A large contribution to the cross section is therefore assigned in all models to the $\gamma p \to \Delta^{++}\pi^-$-reaction via the $\Delta$-KR and the $\Delta$-pion pole terms.

![Figure 2](image)

Figure 2: Total cross sections of the $\gamma p \to p\pi^0\pi^0$ reaction (left hand side) and the $\gamma p \to n\pi^+\pi^0$-reactions compared to model predictions [20, 21, 22].

The situation is very different for the final states involving neutral pions. The total cross sections for $\gamma p \to p\pi^0\pi^0$ and $\gamma p \to n\pi^+\pi^0$ measured in Mainz with the TAPS [10, 14, 23] and DAPHNE [8] detectors are compared in fig.2 to the model calculations of Gomez-Tejedor et al. [20], Murphy et al. [21] and Ochi et al. [22]. None of the models agrees with both data sets. The calculation by Ochi et al. [22], was developed later with special emphasis on the $\pi^+\pi^0$ final state.
In case of the \( \pi^0\pi^0 \) final state the two models from refs. [20, 21] made very different predictions. One of them [20] predicted as dominant process the sequential decay of the \( D_{13}(1520) \) resonance via a \( \Delta\pi \) intermediate state, the other [21] the decay of the \( P_{11}(1440) \) resonance via a correlated pair of pions in a relative s-wave. The total cross section (see fig.2) is in better agreement with the prediction from ref. [20], but the problem was finally solved by the study of the the invariant mass distributions [10, 14]. The pion - pion invariant mass distributions are similar to phase space behavior, while a strong deviation from phase space was predicted for the correlated two pion decay of the \( P_{11} \) in [21]. The pion - proton invariant mass deviates from phase space and peaks at the \( \Delta \) mass as expected for a sequential \( N^* \to \Delta\pi^0 \to N\pi^0\pi^0 \) decay and as predicted in [20]. The high quality invariant mass distributions available now [13], will certainly allow a more detailed analysis.

The first measurement of the \( \gamma p \to \pi^0\pi^+ \) reaction [8] came up with a total cross section that was strongly underestimated by the predictions from the then available models [20, 21] (see fig.2 right hand side). This experimental result was confirmed by a measurement with the TAPS detector [23] and a similar situation was found for the \( \gamma n \to p\pi^-\pi^0 \) reaction [11]. Obviously an important contribution was missing in the models.

Ochi et al. [22] suggested that a contribution of the \( \rho \)-Kroll-Ruderman term, which is negligible for the other isospin channels, might solve the problem. This suggestion motivated a careful study of the invariant mass distributions of the pion - pion and the pion - nucleon pairs, which are again the most sensitive observables [23]. Contributions from \( \rho^+ \)-meson production should result in an enhancement of high pion - pion invariant masses.

The DAPHNE collaboration [11] has searched for such enhancements in the \( d(\gamma, \pi^0\pi^-)pp \) reaction and found some indication of the effect. However, their analysis is largely complicated by effects from the bound nucleons. The pion - pion invariant masses for the \( \pi^0\pi^0 \) and \( \pi^0\pi^+ \) pairs from the free proton measured with TAPS [14, 23] are compared at the left hand side of fig.3. This comparison is particularly instructive since the \( \rho^0 \to \pi^0\pi^0 \) decay is forbidden so that the \( \rho \)-meson cannot contribute to the double \( \pi^0 \) channel. The \( \pi^0\pi^0 \) invariant mass is similar to phase space behavior, but at the higher incident photon energies the \( \pi^0\pi^+ \) invariant mass has an excess at large values. The \( \pi^0\pi^+ \)-data were fitted with a simple model assuming only phase space and \( \rho \)-decay contributions [23]. The result for the ratio of the matrix elements without phase space factors is shown at the right hand side of fig.3. The relative contribution of the \( \rho \)-decay matrix element peaks close to the position of the \( D_{13} \) resonance which is a hint at a \( D_{13} \to N\rho \) contribution. In view of
the new experimental results the group of E. Oset has updated their model \[24\] and now correctly included the possible $\rho$ diagrams. They found indeed a significant contribution of the $D_{13} \rightarrow N\rho$ decay.

The final results are summarized in fig.4 where the measured total cross sections are compared to the latest model results. The prominent role of the sequential decay of the $D_{13}$ resonance via $D_{13} \rightarrow \Delta \pi \rightarrow N\pi^0\pi^0$ to the $\pi^0\pi^0$ final state explains the peak at roughly 700 MeV incident photon energy. The peak like structure for the $\pi^0\pi^+$ final state is mainly caused by the $D_{13} \rightarrow N\rho$ decay which is enhanced via interference effects with other diagrams. It was shown earlier \[20\] that the peaking of the $\pi^+\pi^-$ final state comes from an interference of the $D_{13} \rightarrow \Delta \pi \rightarrow N\pi^+\pi^-$ with the leading $\Delta$-KR term. These results taken
The in-medium properties of mesons and nucleon resonances are a very hotly debated subject, however with the exception of the Δ-isobar experimental results are still very scarce and partly contradicting. We have therefore now investigated the $D_{13}(1520)$ resonance in the nuclear medium via quasi-free single $\pi^0$-photoproduction.

For the discussion of possible medium modifications of the $D_{13}$ resonance we compare first the inclusive data to predictions in the framework of a transport model (BUU) \cite{25}. Here, inclusive means that all events with at least one $\pi^o$ are included. The total cross section (left hand side of fig.4) predicted by the standard BUU calculation largely overestimates the data. Some improvement is achieved when the spreading width of the $\Delta$ is taken from $\Delta$-hole models. However, even the calculation taking into account the in-medium modification of the $D_{13} \rightarrow N\rho$ decay shows a much larger resonance bump than is observed in the data. Only an arbitrary and probably unrealistic broadening \cite{25} of the $D_{13}$-resonance by 300 MeV produces a significant suppression.

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**Figure 4:** Left side: total cross section for the $\gamma p \rightarrow p\pi^o\pi^o$ reaction compared to the results of the model from ref. \cite{20}. Right side: total cross section for the $\gamma p \rightarrow p\pi^o\pi^+\pi^-$ reaction compared to the results with and without $\rho$-contributions \cite{20,24}.

together show that the resonance bump in double pion production is mainly due to the excitation of the $D_{13}$ resonance.

3 The $D_{13}(1520)$ excited in nuclei

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Figure 5: Left hand side: total inclusive cross section for Ca(γ, π^0)X compared to BUU-model predictions [25]. Curves: standard BUU (dotted); BUU, Δ-collisional width from Δ-hole model (dashed); like dashed but modified D_{13} → Nρ-decay (solid), like dashed but 300 MeV collisional width of D_{13} (dash-dotted). Right hand side: quasifree single π^0-production from proton and deuteron. Open symbols: proton data, solid curve: MAID proton cross section; filled triangles: deuteron data, solid curve: incoherent sum of MAID proton, neutron cross sections, dashed: like solid but Fermi smeared.

missing energy analysis as in [12]. The result for the deuteron is compared at the right hand side of fig.5 to the proton data and to the expectation from a unitary isobar analysis of pion photoproduction (MAID) [26].

The data for the proton are well reproduced. The deuteron data are compared to the sum of the proton and neutron cross sections from MAID folded with the momentum distribution of the bound nucleons (see fig.5 right side). The result agrees very well with the data in the tail of the Δ-resonance, but it largely overestimates the data in the D_{13} region. This result is 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. This finding could be part of the explanation why the BUU results overestimate the inclusive data. Such calculations 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 proton and neutron cross sections.

For a more quantitative analysis of the $D_{13}$-excitation in nuclei the cross sections were decomposed into a resonance and a background part. In principle, such a decomposition requires a multipole analysis which takes into account resonance - background interference terms. However, interference terms are small in this case [27]. The result is shown in fig.6 (left hand side). The
background part was fitted with a function of the type:

\[ \sigma \propto e^{(aE^2+bE^\gamma)} \]  

with \( a \) and \( b \) as free parameters. The resonance contribution for heavier nuclei is not qualitatively different from the deuteron case. The differences between measured cross sections and fits are shown in fig. (right hand side). In the upper part of the figure the resonance contributions for the proton, the deuteron and the average for the nuclei are compared to the MAID predictions for the \( D_{13} \) and \( S_{11} \) contributions folded with the Fermi momentum distributions and scaled to the data. 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 \[25\] for the inclusive data (see fig.5) is clearly ruled out, the data correspond rather to BW-curves with a width around 100 MeV.

Finally, it was investigated if the strength of the resonance signal for the nuclei is consistent with the deuteron case. The MAID proton cross section for resonance excitation was folded with the nucleon momentum distribution and compared to the measured deuteron cross section. Agreement is obtained for \( \sigma_n(D_{13})/\sigma_p(D_{13}) \approx 1/3 \). 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 first approximation accounts for the FSI effects (see fig. lower part). The agreement of this approximation with the data is quite good.

The approximate scaling of the cross sections with \(A^{2/3} \) indicates of course FSI effects. This means that in contrast to total photoabsorption not the entire nuclear volume is probed. However, suppression of the resonance bump in total photoabsorption reactions occurs already for \(^4\text{He} \[19\] 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, the models without a strong broadening of the \( D_{13} \) resonance overestimate our inclusive pion data (see fig.5) which are subject to FSI in a similar way as the exclusive data. It thus seems 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 \( \pi^0 \) photoproduction from nuclei we have found no indication of a broadening or a depletion of the excitation strength of the \( D_{13}(1520) \) resonance compared to the deuteron. On the other hand, in comparison to the free proton, the resonance structure for the deuteron in the \( D_{13} \)-region is much reduced, but not broadened.
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