Direct observation of a $\rho$ decay of the $D_{13}(1520)$ baryon resonance

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The reaction $\gamma p \to \pi^+\pi^- n$ has been measured at MAMI for photon energies up to 820 MeV. Invariant mass spectra of the particles in the final state ($\pi^+ n$, $\pi^- n$, $\pi^+\pi^- n$) have been determined for seven bins of incident photon energy. Differences in $\pi^+\pi^-$ and simultaneously measured $\pi^+\pi^-\pi^0$ invariant mass distributions are assigned to a $\rho$ branch of the $D_{13}(1520)$ nucleon resonance.

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The complex structure of the nucleon is reflected in a rich excitation energy spectrum. The electromagnetic excitation of the nucleon with real photons and the subsequent decay via mesons allow insight into its structure and couplings. With the advent of continuous wave electron accelerators which provide intense electron beams and tagged photon beams, high quality measurements have been performed using electromagnetic probes. Although studied for a long time with hadron beams, the properties of many baryon resonances are not sufficiently well known to provide a crucial test for quark models and other descriptions of nucleon resonances as bound baryon-meson molecules [1].

This letter presents new information on one such resonance, the $D_{13}(1520)$. A comparison of photoabsorption cross sections on the proton and on nuclei shows strong differences in the second resonance region ($E_{\gamma} \sim 500 - 800$ MeV) [2,3]. In this region the $D_{13}(1520)$ has the largest coupling to the incident photon. It is strongly excited in photoabsorption on the free proton but it appears to be smeared out in the nuclear medium. It has been argued that this broadening of the $D_{13}$ resonance is due to its $p$ meson decay [4,5], since the $p$ meson is appreciably broadened in the nuclear medium [6]. This would cause a corresponding broadening of the decaying resonance and may explain the observed depletion of the photoabsorption cross section on nuclei [5].

For this interpretation, it is of vital importance to show that the free $D_{13}(1520)$ resonance has a sizable $p$ meson decay strength. The $\rho$ decay width of this nucleon state quoted by the PDG [7] is based on coupled channel analyses of pion induced reactions not on a direct observation of this decay channel. Indications for $\rho$ strength in photoabsorption experiments have been deduced by the DAPHNE group in the $\gamma n \to \pi^-\pi^0 p$ reaction on a deuteron target [8] by comparison to model calculations of Ochi et al. [9]. In the experimental analysis effects stemming from the fact that the neutron is bound in the deuteron target had to be accounted for. Meanwhile, none of the presently available models describe all two-pion channels consistently. This situation calls for a direct experimental and model independent extraction of the $\rho$ strength.

In this letter, direct evidence for $\rho$ strength is provided for the first time by a comparison of $\pi\pi$ invariant mass distributions from the reactions $\gamma p \to \pi^+\pi^- n$ and $\gamma p \to \pi^+\pi^- p$ [10]. Since the $\rho \to \pi\pi$ contribution can be observed in the $\pi^+\pi^-$ invariant mass distributions while the $p$ meson decay into $2\pi^-$ is forbidden, deviations of $\pi^+\pi^-$ from $\pi^+\pi^-\pi^0$ invariant mass distributions can be used as a measure of the $\rho$ contribution.

The data reported here stem from a simultaneous measurement of $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ photoproduction from the proton for photon energies up to 820 MeV. The measurement was performed at the electron accelerator MAMI in Mainz [11] with the Glasgow tagged photon facility [12] and the photon spectrometer TAPS [13].

Quasimonochromatic photons were generated from the 880 MeV electron beam by means of bremsstrahlung tagging. The tagger covered the photon energy range from 300 to 820 MeV with an average resolution of about 2 MeV at a flux of $5 \cdot 10^7$ s$^{-1}$ p$^{-1}$ MeV incident photon energy bin. Mesons were produced in a 10 cm long, liquid hydrogen target. Neutral mesons were detected with the TAPS detection system via their 2 photon decay. All BaF$_2$ modules were equipped with individual 5 mm thick plastic detectors for the identification of charged particles. Energy loss and time of flight information allowed for the identification of positive pions. In this experiment, the TAPS detector consisted of 384 hexagonally shaped BaF$_2$ scintillators and 120 BaF$_2$-plastic phoswich modules [14]. 64 of these crystals, arranged in an 8 x 8
matrix, formed a single TAPS block. Six blocks were mounted in a plane around the target at a distance of 57 cm and polar angles of ±50°, ±100°, and ±150° with respect to the photon beam direction. The 120 BaF2 plastic phoswich detectors were arranged in a hexagonally shaped forward wall which covered polar angles between 5 and 20 degrees with respect to the beam axis.

The $\pi^-\pi^2$ and $\pi^+\pi^2$ data were simultaneously measured with the same detection system using a similar analysis to reduce systematic errors. $\pi^2$ mesons were identified via their 2 photon decay using an invariant mass analysis. A detailed description of the observation of the reaction $\gamma p \to \pi^2\pi^2 p$ is given in refs. [10,15]. The plastic detector information, the pulse shape analysis, and the time-of-flight measurement were employed in the separation of $\pi^\pm\pi^\mp$ production from background events. Kinematic overdetermination allowed the reconstruction of energy and momentum of the neutron whereby a missing mass analysis enabled the selection of the reaction channel. In the $\Delta$ resonance energy regime the $\gamma p \to \pi^\pm\pi^\mp$ reaction dominates the photoproduction with a cross section of about 310 mb. These background events were identified and suppressed by a missing mass cut on the reconstructed proton. This led to an unambiguous identification of the $\pi^\pm\pi^\mp$ channel.

The cross section was deduced from the rate of the $\pi^\pm\pi^\mp$ events divided by the thickness of the hydrogen target, the photon flux, the detector and analysis efficiency, and the branching ratio of the $\pi^\pm$ into two photons. The intensity of the photon beam was determined by counting the scattered electrons in the tagger focal plane and measuring the tagging efficiency with a lead glass detector which was moved into the photon beam at low intensity. The average efficiency of the TAPS detector and the analysis is about 0.1%. This has been calculated with Monte Carlo simulations using the GEANT code [16].

Figure 1 shows the total cross section of the reaction $\gamma p \to \pi^\pm\pi^\mp n$ as a function of the incident photon energy. The result is consistent with a previous measurement performed with the DAPHINE detector [19]. The improved statistics of this work corroborates the resonance structure at the $D_{13}(1520)$ resonance ($E_\gamma=760$ MeV). Recently, Ochi et al. [9] proposed that the experimental data can be explained by introducing a dominant contribution from a $\rho$-Kroll-Ruderman term ($\gamma p \to \rho^+ n \to \pi^+\pi^0 n$) which cannot affect the double $\pi^0$ production and is negligible for the $\pi^\pm\pi^\mp$ channel. However, this model fails to describe the neutral double pion reaction channel. Other models [17,18] describe the neutral channel but strongly underestimate the $\pi^+\pi^0$ cross section. Although the $\Delta$-Kroll-Ruderman and the $\Delta$-pion-pole terms are considered in calculating the $\gamma p \to \pi^\pm\Delta^0 \to \pi^\pm\pi^\mp n$ reaction an important contribution is obviously missing in these models.

The experiment described here allows an invariant mass analysis of all particles in the final state providing detailed insight in the reaction mechanism. Figures 2 and 3 show invariant mass distributions of the particles in the final state for seven bins of the incident photon energy. A phase space distribution is represented by a dashed line. Deviations of the experimental data from the phase space distribution are evident for resonant or meson intermediate states in the $\pi^\pm\pi^\mp$ photoproduction.

Before presenting the $\pi\pi$ invariant mass spectra and the investigation of the $\rho$ strength, the $N\pi$ distributions in figure 2 are discussed. For the lowest photon energies a distinct peak in the $\pi^\pm n$ invariant mass near the mass pole of the $\Delta(1232)$ resonance ($E_\gamma=340$ MeV) is observed, whereas the $\pi^\pm n$ system hardly shows such a correlation. This is in accordance with the assumption of refs. [17,18] where the $\Delta$-Kroll-Ruderman and $\Delta$-pion-pole terms are the most important mechanisms for this isospin channel. Since terms involving $\Delta$-Kroll-Ruderman and the $\Delta$-pion-pole terms are strongly suppressed in the neutral channel the first emitted pion has to be charged. Therefore, the reaction sequence is $\gamma p \to \pi^\pm\Delta^0 \to \pi^\pm\pi^\mp n$ and not $\gamma p \to \pi^\pm\Delta^+ \to \pi^\mp\pi^\mp n$. Hence, the peak of the $\pi^\pm n$ invariant mass in the $D_{13}(1232)$ region reflects the decay of the neutral $\Delta$ resonance. Due to the fact that both pions are neutral in the $\pi^\pm\pi^\mp$ photo-production all background terms including the $\Delta$-Kroll-Ruderman and the $\Delta$-pion-pole term are strongly suppressed. In fact, this correlation in the pion-nucleon system has not been observed at low energies of the incident photon beam (see ref. [10]). At higher excitation energies the $\Delta$ resonance is still present in the $N\pi$ invariant mass spectra of both double pion channels. For the $\pi^\pm$ production this behavior has been assigned to the sequential decay of the $D_{13}(1520)$ ($E_\gamma=760$ MeV) via the $\Delta(1232)$ resonance [15,17], suggesting that a sequential decay is also important in the $\pi^\pm\pi^\mp$ channel.

Figure 3 depicts the $\pi\pi$ invariant mass for the $2\pi^0$ and $\pi^+\pi^-\pi^0$ reaction. At low excitation energies both experimental distributions agree within the error bars with phase space, whereas in the second resonance energy region the $\pi^\pm\pi^0$ system shows a pronounced shift to higher masses. As pointed out before, the decay of a $\rho^0$ meson into a neutral pion pair is forbidden. Therefore, the $\rho$ cannot lead to a correlation of the pions in the double $\pi^0$ photoproduction. The deviation towards higher invariant masses in the charged channel is thus attributed to an intermediate $\rho^0$ meson. In this case, the shift in figure 3 is due to the population of the low energy tail of the broad $\rho$ meson of mass 770 MeV and full width 150 MeV. These deviations are assigned to a $\rho$ branch of the $D_{13}(1520)$ resonance since this state is predominantly excited in the second resonance region and the $\pi^\pm\pi^0$ cross section shows a broad peak at the $D_{13}(1520)$ resonance ($E_\gamma=760$ MeV). This conclusion is supported by a simplified fit to the data considering a phase space contribution (including sequential decays in approximation) and a $\rho$ contribution as in $\gamma p \to \rho^0 n \to \pi^+\pi^- n$. 

2
\[
\frac{d\sigma}{dm} \sim a(\sqrt{s}) + b(\sqrt{s}) p_{\pi} m_{\pi \pi} \cdot D_{\rho}(m_{\pi \pi})^2 P_{\sqrt{s} \pi \pi N}
\]  
(1)

where \(a(\sqrt{s})\) and \(b(\sqrt{s})\) are the fit parameters. \(p_{\pi}(m_{\pi \pi})\)
is the momentum of the \(\pi\) in the \(\rho\) rest frame introduced to
account for the known energy dependence of the \(\rho\pi\pi\) vertex. \(P_{\sqrt{s} \pi \pi N}\) is the three-body phase space factor and \(D_{\rho}\) represents the \(\rho\) meson propagator. In figure 4, the
two of the resulting squared amplitudes of the phase space
\((A_{\rho})\) and \(\rho\) \((A_{\rho})\) contributions is presented as a function
of the energy \(\sqrt{s}\) in the center-of-mass system. A
prominent maximum near the \(D_{13}(1520)\) resonance is observed.
This results is corroborated in a rigorous theoretical treatment of double pion photoproduction [20] which has been motivated by the present experiment. The right hand side of Figure 3 shows a comparison of our data
to these calculations with and without the inclusion of the \(D_{13} \rightarrow N\rho\) and \(\rho\)-Kroll-Rudermann decays. For a
branching ratio of 20% for this channel also the total cross section is reproduced as shown in the left hand side of Figure 4. This figure also displays separately the contribution of the \(D_{13} \rightarrow N\rho\) and the \(\rho\)-Kroll-Rudermann terms.

In conclusion, the \(\pi^+\pi^0\) photoproduction from the proton
up to 820 MeV excitation energy has been measured. The total cross section is consistent with a previous measurement performed with the DAPHNE detector [19]. A population of an intermediate \(\Delta(1232)\) resonance most likely via the \(\Delta\)-Kroll-Ruderman and the \(\Delta\)-pion-pole term is deduced from \(N\pi\) invariant mass distributions at low incident energies. This is in accordance with the assumption of refs. [17,18].

The \(\pi^+\pi^0\) system has been compared to simultaneously measured \(\pi^+\pi^0\) data showing an invariant mass distribution which is shifted towards higher masses. This behavior of the \(\pi^+\pi^0\) mass distribution provides first experimental evidence for a contribution of an intermediate \(\rho^+\) meson with a subsequent decay into two pions in the reaction \(\gamma p \rightarrow \rho^+ n \rightarrow \pi^+\pi^0 n\). Because of the resonant behavior this \(\rho^+\) strength is assigned to the decay of the \(D_{13}(1520)\) resonance as also found in recent calculations by J.C. Nacher et al. [20]. The \(\rho\) decay branch of the \(D_{13}(1520)\) is of great interest for the understanding of medium modifications in nuclear reactions as a strong broadening of the \(\rho\) spectral function might play a role in the depletion of the photoabsorption cross section in the second resonance region [5].

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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Graph showing the relationship between \(E_{\gamma}\) and \(\sigma\) with various contributions indicated.}
\end{figure}

\begin{thebibliography}{9}
\bibitem{3} C. Amshler et al., Nucl. Phys. A 622 (1997) 315c
\bibitem{5} U. Mosel et al., Prog. Part. Nucl. Phys. 42 (1999) 163
\bibitem{6} F. Klingl et al., Nucl. Phys. A 624 (1997) 527
\bibitem{8} A. Zabrodin et al., Phys. Rev. C 60 (1999) 055201
\bibitem{9} K. Ochi et al., Phys. Rev. C 56 (1997) 1472 and
\bibitem{10} K. Ochi et al., nucl-th/9711031
\bibitem{12} Th. Walcher, Prog. Part. Nucl. Phys. 24 (1990) 189
\bibitem{13} I. Anthony et al., Nucl. Inst. Meth. A 301 (1991) 230
\bibitem{17} R. Brun et al., CERN Report No. GEANT3 Cern/DD/ee/84-1, 1986
\bibitem{18} J.A. Gómez Tejedor, E. Oset, Nucl. Phys. A 600 (1996) 413
\bibitem{19} L.Y. Murphy, J.M. Laget, DAPNIA/SPhN 96-10 (1996)
\bibitem{21} J.C. Nacher et al., nucl-th/0012065 and private communication
\end{thebibliography}
FIG. 1. Total cross section of the $\pi^+\pi^-$ photoproduction from the proton as a function of the incident photon energy. The result of this work (filled circles) is compared to the three theoretical predictions of [17] (dashed line), [18] (dotted line), and [9] (dash-dotted line). The open circles are from a previous measurement with the DAPHNE detector [19].

FIG. 2. Invariant mass distribution of the $\pi^+n$ and $\pi^+n$ system for seven bins of incident photon energy. The dashed line represents a phase space distribution. The resonance names mark the bins containing their mass pole.

FIG. 3. Invariant mass distributions of the two pions for three bins of incident photon energy. The solid and open circles are the result of our measurement for the reactions $\gamma p \rightarrow \pi^+\pi^+ n$ (left) and $\gamma p \rightarrow \pi^+\pi^+ p$ (right) [10], respectively. They have been adjusted such that the respective phase space distributions (dashed line, left panel) coincide. The solid curves in the left panels represent a fit to the $\pi^+\pi^-$ data, as explained in the text. The curves in the right panels correspond to calculations from [20] with (solid) and [17] without (dashed) $\rho$ contributions.

FIG. 4. Left Panel: Total cross section of the $\pi^+\pi^-$ photoproduction from the proton as a function of incident photon energy. The result of this work (filled circles) is compared to the theoretical predictions of [20] (solid line). The contribution of the $D_{13} \rightarrow \rho$ (dashed) and the $\rho$-Kroll-Rudermann (dotted) terms are separately displayed. The open circles are from a previous measurement with the DAPHNE detector [19]. Right panel: Ratio of squared $\rho$ channel and phase space amplitudes deduced from a fit data of figure 3 plotted as a function of the center of mass energy $\sqrt{s}$. 

FIG. 5. Invariant mass distributions of the two pions for three bins of incident photon energy. The solid and open circles are the result of our measurement for the reactions $\gamma p \rightarrow \pi^+\pi^+ n$ (left) and $\gamma p \rightarrow \pi^+\pi^+ p$ (right) [10], respectively. They have been adjusted such that the respective phase space distributions (dashed line, left panel) coincide. The solid curves in the left panels represent a fit to the $\pi^+\pi^-$ data, as explained in the text. The curves in the right panels correspond to calculations from [20] with (solid) and [17] without (dashed) $\rho$ contributions.