Direct Observation of a ρ Decay of the $D_{13}(1520)$ Baryon Resonance

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The reaction $\gamma p \to \pi^+\pi^0 n$ has been measured at MAMI for photon energies up to 820 MeV. Invariant mass spectra of the particles in the final state $(\pi^+ n)$, $(\pi^0 n)$, $(\pi^+\pi^0)$ have been determined for several bins of incident photon energy. Differences in $\pi^+\pi^0$ and simultaneously measured $\pi^0\pi^0$ invariant mass distributions are assigned to a ρ 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 such 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 [2,3] shows strong differences in the mass region $M_{N^*} =$ 1400–1600 MeV which is called the second resonance region. The resonance structure of the nucleon is formed by the three overlapping states, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$, and is excited by photons in the energy range 500–900 MeV. The structure is prominent in photoabsorption on the free nucleon but it appears strongly suppressed for photoabsorption from nuclei. In this region, the D_{13} resonance has the largest coupling to the initial photon-nucleon state and it has been argued that an in-medium broadening of this resonance is a likely cause of the observations [4,5]. The broadening could arise from a coupling of the resonance to the $N\rho$ final state since the ρ meson itself is appreciably broadened in the nuclear medium [6].

For this interpretation, it is of vital importance to show that the free $D_{13}(1520)$ resonance has a sizable ρ meson decay strength. The ρ decay width of this nucleon state is quoted by the Particle Data Group (PDG) Booklet [7] and Manley [8]. Here, the extraction of the parameters is based on coupled channel analyses of pion induced reactions rather than a direct observation of the decay channel. Indications for ρ strength in photoabsorption experiments were deduced by the DAPHNE group in the $\gamma n \to \pi^-\pi^0 p$ reaction on a deuteron target [9] by comparison to model calculations of Ochi *et al.* [10]. In the experimental analysis, effects stemming from the fact that the neutron is bound in the deuteron target had to be accounted for. Furthermore, none of the models available so far describes all two-pion channels consistently. This situation calls for a direct experimental and model independent extraction of the ρ strength.

In this Letter, direct evidence for ρ strength is provided for the first time by a comparison of $\pi\pi$ invariant mass distributions from the reactions $\gamma p \to \pi^+\pi^0 n$ and $\gamma p \to \pi^0\pi^0 p$ [11]. Since the $\rho \to \pi\pi$ contribution can be observed in the $\pi^+\pi^0$ invariant mass distributions while the ρ meson decay into $2\pi^0$ is forbidden due to isospin conservation in the strong interaction, deviations of $\pi^+\pi^0$ from $\pi^0\pi^0$ invariant mass distributions can be used as a measure of the ρ contribution.

The data reported here stem from a simultaneous measurement of $\pi^+\pi^0$ and $\pi^0\pi^0$ photoproduction from the proton for photon energies up to 820 MeV. The data on the $\pi^0\pi^0$ exit channel have meanwhile been published [11]. The measurement was performed at the electron accelerator MAMI in Mainz [12] with the Glasgow tagged photon facility [13] and the photon spectrometer TAPS [14].

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 5×10^5 s^{-1} per 2 MeV incident photon energy bins. Mesons were produced in a 10-cm-long, liquid hydrogen target. Neutral mesons were detected with the TAPS detection system via their two-photon decay. All BaF_2 modules were equipped with individual 5-mm-thick plastic detectors for the identification of charged particles.

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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 [15]. Sixty-four of these crystals, arranged in an 8×8 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 $\pm 50°$, $\pm 100°$, and $\pm 150°$ with respect to the photon beam direction. The 120 BaF_2 plastic phoswich detectors were arranged in a hexagonally shaped forward wall which covered polar angles between 5° and 20° with respect to the beam axis.

The $\pi^0\pi^0$ and $\pi^+\pi^0$ data were simultaneously measured with the same detection system using a similar analysis to reduce systematic errors. π^0 mesons were identified via their two-photon decay using an invariant mass analysis. The plastic detector information, the pulse shape analysis, and the time-of-flight measurement were employed in the separation of $\pi^+\pi^0$ 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 Δ resonance energy regime the $\gamma p \to \pi^0 p$ reaction dominates the photoabsorption with a cross section of about 310 μb. These background events were identified and suppressed by a missing mass cut on the reconstructed proton. This led to an unambiguous identification of the $\pi^+\pi^0$ channel.

The cross section was deduced from the rate of the $\pi^+\pi^0$ events divided by the thickness of the hydrogen target, the photon flux, the detector and analysis efficiency, and the branching ratio of the π^0 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 GEANT3 code [16].

Figure 1 shows the total cross section of the reaction $\gamma p \to \pi^+\pi^0 n$ as a function of the incident photon energy. The result is consistent with a previous measurement performed with the DAPHNE detector [17]. The improved statistics of this work corroborates the resonance structure at the $D_{13}(1520)$ resonance ($E_\gamma = 760$ MeV). Recently, Ochi *et al.* [10] proposed that the experimental data can be explained by introducing a dominant contribution from a ρ-Kroll-Ruderman term ($\gamma p \to \rho^+ n \to \pi^+\pi^0 n$) which cannot affect the double π^0 production and is negligible for the $\pi^+\pi^-$ channel. However, this model fails to describe the neutral double pion reaction channel. Other models [18,19] describe the neutral channel but strongly underestimate the $\pi^+\pi^0$ cross section. Although the Δ-Kroll-Ruderman and the Δ-pion-pole terms are considered in calculating the $\gamma p \to \pi^+\Delta^0 \to \pi^+\pi^0 n$ reaction, an important contribution is obviously missing in these models.

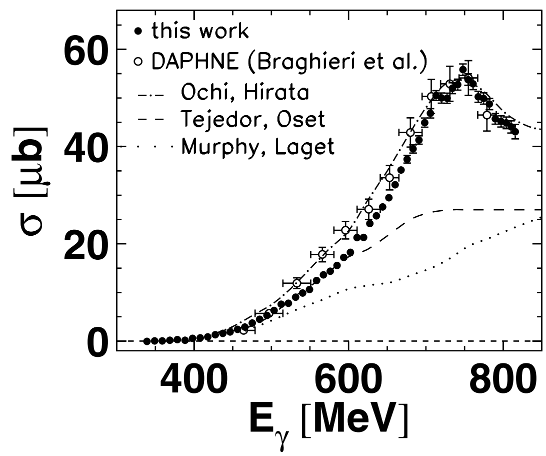

FIG. 1. Total cross section of the $\pi^+\pi^0$ photoproduction from the proton as a function of the incident photon energy. The result of this paper (filled circles) is compared to the three theoretical predictions of [18] (dashed curve), [19] (dotted curve), and [10] (dash-dotted curve). The open circles are from a previous measurement with the DAPHNE detector [17].

The experiment described here allows an invariant mass analysis of all particles in the final state providing detailed insight into the reaction mechanism. Figures 2 and 3 show invariant mass distributions of the particles in the final state for several bins of the incident photon energy. Phase space distributions are represented by dashed curves. Deviations of the experimental data from the phase space distribution are evidence for resonant or meson intermediate states in the $\pi^+\pi^0$ photoproduction.

Before presenting the $\pi\pi$ invariant mass spectra and the investigation of the ρ strength, the $N\pi$ distributions in Fig. 2 are discussed. For the lowest photon energies a distinct peak in the $\pi^0 n$ invariant mass near the mass pole of the $\Delta(1232)$ resonance ($E_\gamma = 340$ MeV) is observed, whereas the $\pi^+ n$ system hardly shows such a correlation. This is in accordance with the assumption of Refs. [18,19], where the Δ-Kroll-Ruderman and Δ-pion-pole terms are the most important mechanisms for this isospin channel. Since terms involving Δ-Kroll-Ruderman and the Δ-pion-pole terms are strongly suppressed in the neutral channel, the first emitted pion has to be charged. Therefore, the reaction sequence is $\gamma p \to \pi^+\Delta^0 \to \pi^+\pi^0 n$ and not $\gamma p \to \pi^0\Delta^+ \to \pi^0\pi^+ n$. Hence, the peak of the $\pi^0 n$ invariant mass in the $\Delta(1232)$ region reflects the decay of the neutral Δ resonance. Because of the fact that both pions are neutral in the $2\pi^0$ photoproduction, all background terms including the Δ-Kroll-Ruderman and the Δ-pion-pole terms are strongly suppressed. In fact, this correlation in the pion-nucleon system was not observed at low energies of the incident photon beam (see Ref. [11]). At higher excitation energies the Δ resonance is still present in the $N\pi$ invariant mass spectra of both double pion channels. For the $2\pi^0$ production this behavior was assigned to the

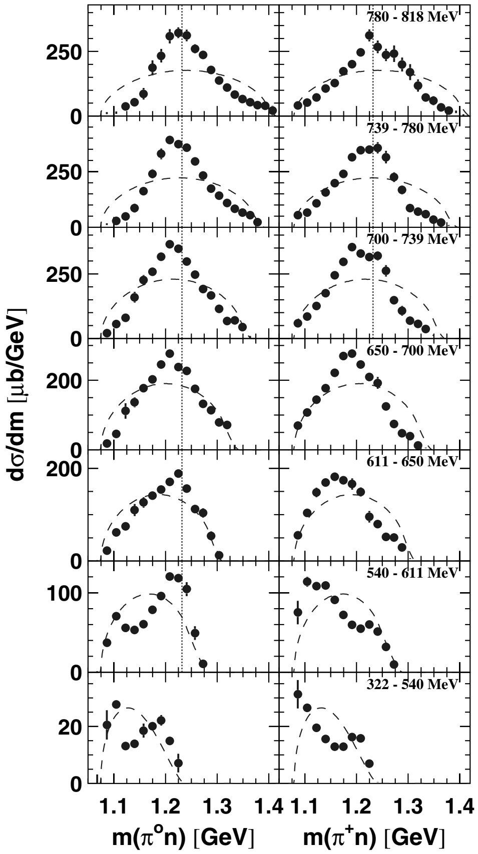

FIG. 2. Invariant mass distribution of the $\pi^0 n$ and $\pi^+ n$ system for seven bins of incident photon energy. The dashed curve represents a phase space distribution. The position of the Δ resonance is marked by dotted lines.

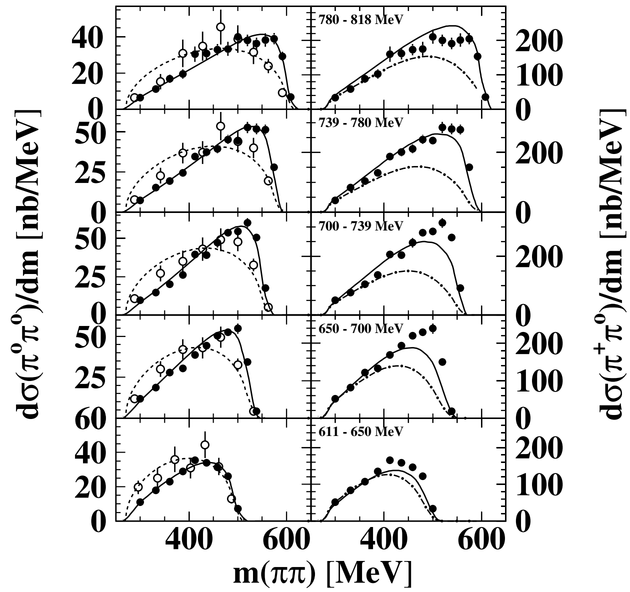

FIG. 3. Invariant mass distributions of the pion pairs for five bins of incident photon energy. Left side: comparison of the shape of the distributions for $\gamma p \to \pi^+\pi^0 n$ (solid circles) and $\gamma p \to \pi^0\pi^0 p$ (open circles). Dashed curve: phase space expectation; solid curve: fit to the $\pi^+\pi^0$ data, as explained in the text. The vertical scale corresponds to the $\pi^0\pi^0$ data, the $\pi^+\pi^0$ data, and the curves are normalized to the same area. Right side: comparison of the $\pi^+\pi^0$ distributions to the calculations with (solid lines) [20] and without (dash-dotted lines) [18] ρ contributions.

sequential decay of the $D_{13}(1520)$ ($E_\gamma = 760$ MeV) via the $\Delta(1232)$ resonance [11,18], suggesting that a sequential decay is also important in the $\pi^+\pi^0$ channel.

Figure 3 depicts the $\pi\pi$ invariant mass for the $2\pi^0$ and $\pi^+\pi^0$ reaction. At low excitation energies both experimental distributions agree within the error bars with phase space, whereas in the second resonance energy region the $\pi^+\pi^0$ system shows a pronounced shift to higher masses. As pointed out earlier, the decay of a ρ^0 meson into a neutral pion pair is forbidden. Therefore, the ρ cannot lead to a correlation of the pions in the double π^0 photoproduction. The deviation towards higher invariant masses in the charged channel is thus attributed to an intermediate ρ^+ meson. In this case, the shift in Fig. 3 is due to the population of the low energy tail of the broad ρ meson of mass 770 MeV and full width 150 MeV. These deviations are assigned to a ρ branch of the $D_{13}(1520)$ resonance since this state is predominantly excited in the second resonance region and the $\pi^+\pi^0$ cross section shows a broad peak at the $D_{13}(1520)$ resonance ($E_\gamma =$ 760 MeV, $\Gamma_{D_{13}} = 120$ MeV). This conclusion is supported by a simplified fit to the data considering a phase space contribution (including sequential decays in approximation) and a ρ contribution as in $\gamma p \to \rho^+ n \to \pi^+\pi^0 n$,

$$\frac{d\sigma}{dm} \sim |a(\sqrt{s}) + b(\sqrt{s}) p_\pi(m_{\pi\pi}) \cdot D_\rho(m_{\pi\pi})|^2 P_{\sqrt{s}\to\pi\pi N}\,, \qquad (1)$$

where $a(\sqrt{s})$ and $b(\sqrt{s})$ are the fit parameters. $P_\pi(m_{\pi\pi})$ is the momentum of the π in the ρ rest frame introduced to account for the known energy dependence of the $\rho\pi\pi$ vertex. $P_{\sqrt{s}\to\pi\pi N}$ is the three-body phase space factor and D_ρ represents the ρ meson propagator. In Fig. 4, the ratio

$$\frac{|A_\rho|^2}{|A_{ps}|^2} = \frac{\int |b(\sqrt{s}) p_\pi(m_{\pi\pi}) \cdot D_\rho(m_{\pi\pi})|^2 dm_{\pi\pi}}{\int |a(\sqrt{s})|^2 dm_{\pi\pi}} \qquad (2)$$

of the resulting squared amplitudes of the phase space (A_{ps}) and ρ (A_ρ) 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 result 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 Fig. 3 shows a comparison of the relevant mass distributions to these calculations with and without the inclusion of the $D_{13} \to N\rho$ and ρ-Kroll-Ruderman decays, using the PDG values for masses and widths [7]. For a branching ratio of 20% for the $D_{13} \to N\rho$ channel also the total cross section is reproduced, as shown in the right-hand side of

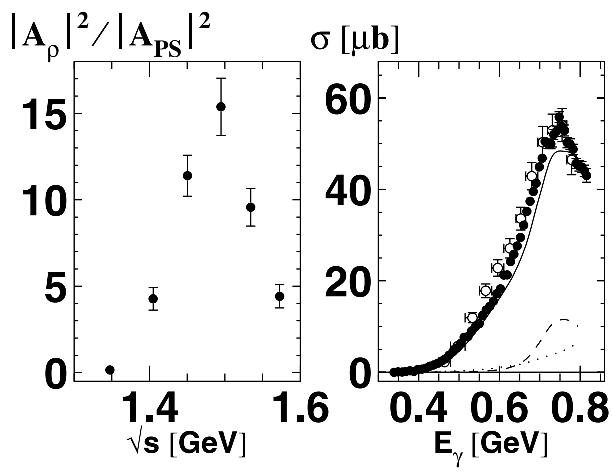

FIG. 4. Left panel: ratio of squared ρ channel and phase space amplitudes deduced from a fit to the $\pi^+\pi^0$ data of Fig. 3 plotted as a function of the center-of-mass energy $\sqrt{s}$. Right panel: total cross section of the $\pi^+\pi^0$ photoproduction from the proton as a function of incident photon energy. The result of this paper (filled circles) is compared to the recent theoretical predictions of [20] (solid curve), including the $D_{13} \rightarrow N\rho$ branch. The contribution of the $D_{13} \rightarrow N\rho$ (dashed curve) and the ρ-Kroll-Ruderman (dotted curve) terms are separately displayed. The open circles are from a previous measurement with the DAPHNE detector [17].

Fig. 4. This figure also displays separately the contribution of the $D_{13} \rightarrow N\rho$ and the ρ-Kroll-Ruderman 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 [17]. A population of an intermediate $\Delta(1232)$ resonance, most likely via the Δ-Kroll-Ruderman and the Δ-pion-pole terms, is deduced from $N\pi$ invariant mass distributions at low incident energies. This is in accordance with the assumption of Refs. [18,19].

The $\pi^+\pi^0$ system has been compared to simultaneously measured $\pi^0\pi^0$ 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 ρ^+ 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 ρ strength is assigned to the decay of the $D_{13}(1520)$ resonance, as also found in recent calculations by Nacher *et al.* [20]. The ρ decay branch of the $D_{13}(1520)$ is of great interest for the understanding of medium modifications in nuclear reactions. A strong broadening of the ρ spectral function should have an impact on the decaying resonance and might play a role in the depletion of the photoabsorption cross section in the second resonance region [5].

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