Search for Narrow Nucleon Resonances below Pion Threshold in the $H(e,e'\pi^+)X$ and $D(e,e'p)X$ Reactions

M. Kohl,1,* M. Ases Antelo,2 C. Ayerbe,2 D. Baumann,2 R. Böhm,2 D. Bosnar,3 M. Ding,2 M.O. Distler,2 J. Friedrich,2 J. García Longo,2 P. Jenessen,2 G. Jover Mañes,2 H. Merkel,2 P. Merle,2 U. Müller,2 R. Neuhausen,2 L. Nungesser,2 R. Pérez Benito,2 J. Pochodzalla,2 M. Potokar,4 C. Rangacharyulu,5 A. Richter,1,† G. Schrieder,1 M. Seimetz,3 Th. Walcher,2 and M. Weis2

1 Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany
2 Institut für Kernphysik, Universität Mainz, D-55099 Mainz, Germany
3 Department of Physics, University of Zagreb, HR-10002 Zagreb, Croatia
4 Institute “Jožef Stefan”, University of Ljubljana, SI-1001 Ljubljana, Slovenia
5 Department of Physics, University of Saskatchewan, Saskatoon, SK, S7N 5E2, Canada

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I. INTRODUCTION

It is an important issue of modern experiments in hadron physics to provide significant information on manifestations of QCD. As is well known (see e.g. [1]), the description of the experimentally observed baryon excitation spectrum in terms of the colorless three-quark ($q^3$) configuration within the various quark models has been quite successful. Moreover, QCD allows for exotic structures like multi-quark configurations, glueballs and hybrids. Such states are mainly expected in the mass region above 1.5 GeV/c$^2$. It is one of the irritating facts, however, that already the description predicts far more resonance states than experimentally observed. Thus, the search for missing resonances is one of the major concerns of hadron experiments. On the other hand, the existing low-lying states (nucleon, $\Delta$, $N^*$) are well accounted for within the three-quark picture and neither QCD-inspired calculations at low momentum and close to the chiral limit (i.e. Chiral Perturbation Theory) nor perturbative QCD in the high-momentum regime predict states below or close to pion threshold. If such low-lying states did exist, configurations beyond the naive $q^3$ picture would be required for an explanation.

Since the strong decay via pion emission is energetically forbidden for states below pion threshold, these states would necessarily be narrow (less than a few keV) with lifetimes typical for electromagnetic or weak decays. A precise examination of the low-lying nucleon excitation spectrum with various probes is thus a powerful tool to test QCD.

Recently, there have been two experiments reported in the literature, one performed at the SATURNE synchrotron in Saclay and the other at the INR in Moscow, which claimed the observation of excited states of the nucleon below pion threshold [2, 3]. Tatischeff et al. utilized the $H(p,p',\pi^+)X$ reaction to measure the invariant-mass spectrum of the missing nucleon [2]. They claimed to have found resonance states at $M_X = 1004, 1044, and 1094$ MeV/c$^2$, with a statistical significance of up to 17 standard deviations. However, the missing-mass resolution of this experiment was limited and ranged from 7 to 25 MeV/c$^2$ (FWHM). Very recently, Tatischeff et al. reported further the observation of additional states at $M_X = 1136, 1173, 1249, 1277, 1384, and possibly 1339$ MeV/c$^2$, from those reported in [2], using the $H(p,p',\pi^+)X$, the $D(p,p',\pi^+)X$, and the $H(p,p'p)$ reactions [4].

Fil’kov et al. [3] found resonance structures in the $D(p,p',p)X$ reaction in the spectra of the invariant masses $M_{pX}$ as well as $M_X$ and claimed the observation of “super-narrow” dibaryons (SND) at $M_{pX} = 1904, 1926, and 1942$ MeV/c$^2$. The additionally observed resonance structures at $M_X = 966, 986, and 1003$ MeV/c$^2$ differ from those reported in $M_{pX}$ by about one nucleon mass. They were interpreted to be either genuine, i.e. SND $\rightarrow p + X$, or to result from the decay SND $\rightarrow p + n + \gamma$ under the restrictions of a small phasespace and experimental acceptance. The significance for the SND peaks was estimated to be 6 to 7 standard deviations, with a moderate missing-mass resolution of about 5 MeV/c$^2$. 

*Present address: MIT-Bates Linear Accelerator, Middleton, MA 01949, U.S.A.
†Corresponding author; email: richter@ikp.tu-darmstadt.de
So far, various attempts for an explanation of the narrow resonances \([2, 3]\) have been offered. Model assumptions beyond the \(q^3\) picture result in mass formula prescriptions based on colored \([5]\) and colorless \([6]\) quark clusters. It has been argued however \([7]\), that narrow nucleon resonances should be completely excluded, since they were not observed in real Compton scattering experiments \([8]\). Another approach describes the narrow resonances as possible members of the SU(6) spin-flavor multiplet, where only the two-photon transition channel is allowed \([9]\). This picture accounts for the fact that narrow resonances were not observed in photon-induced reactions like in real Compton scattering experiments. Recently, it was proposed to interpret the narrow states as collective excitations of the quark condensate through the multiple production of “genuine” Goldstone pions with a light mass of \(m \approx 20\) MeV/\(c^2\) \([10]\). In this model, the narrow states are spatially extended structures and thus they are likely inaccessible to the real photon probe.

Another theoretical interest in the narrow baryons is their influence on astrophysical objects. It was pointed out that the existence of narrow nucleon resonances would drastically affect the structure of neutron stars by lowering their possible maximal mass, which would be inconsistent with the observations \([11]\). However, the existence of light pions would still be compatible with the observed masses of neutron stars.

Meanwhile, there have been reported experiments in direct response to Tatischeff’s and Fil’kov’s findings. In a pilot study of the \(H(e,e'\pi^+)X\) reaction at the Jefferson Laboratory \([12]\), the yield ratio \(H(e,e'\pi^+)X / H(e,e'\pi^+)n\) was measured, which excludes narrow nucleon resonances to a level of \(10^{-3}\). The \(D(p,p'p)X\) reaction has been revisited at the RCNP in Osaka \([13]\), yielding a null result for the above claimed states. However, the significance of the result of the latter experiment has been questioned in Ref. \([14]\). In fact, we have also reanalyzed the data of the virtual Compton scattering experiments at MAMI, but we did not find any signal above a significance of three standard deviations. In a photoproduction experiment at MAMI, the reactions \(H(\gamma, \pi^+\gamma n)\) and \(H(\gamma, \pi^+\gamma\gamma n)\) have been measured with a high luminosity and results are awaited \([15]\).

The issue of the occurrence of resonances below pion threshold is thus unsettled. The observation of such narrow states is always limited by the achievable resolution. Experiments providing highest resolution are therefore best suited to perform such studies. In this paper, we report the results of two series of high-resolution measurements using the \(H(e,e'\pi^+)X\) and \(D(e,e'p)X\) reactions. The first reaction has been chosen as the analogous reaction to the \(H(p,p'\pi^+)X\) process of Tatischeff et al. \([2]\). The energy transfer corresponds to the excitation region of the \(\Delta\) resonance. With the detection of the scattered electron in coincidence with the produced pion the missing mass of the reaction has been reconstructed. The experiment covered the missing-mass region from the neutron mass up to about \(1050\) MeV/\(c^2\). In addition, the second electromagnetic reaction \(D(e,e'p)X\) has been studied as the analog of the strong \(D(p,p'p)X\) experiment by Fil’kov et al. \([3]\). The energy transfer varied from close to the threshold of the deuteron breakup up to the quasielastic region. With the detection of both the scattered electron and the emitted proton, the missing mass of the reaction has been reconstructed. The experiment covered the missing-mass region from the neutron mass up to about \(1100\) MeV/\(c^2\).

II. MEASUREMENTS

The measurements were carried out at the three-spectrometer facility of the A1 collaboration at the Mainz Microtron MAMI \([16]\). The target was a standard liquid hydrogen/deuterium target, which was operated at beam currents of up to \(15\) \(\mu\)A. The target cell has been made of a thin HAVAR foil of \(10.2\) \(\mu\)m thickness (\(8.9\) \(\mu\)m in case of the deuterium target). The cell geometry is stadium-like with a length of \(5\) cm along the beam axis and a width of \(1\) cm in the perpendicular direction. The beam was swept before entering the scattering chamber to fill a square of \(4	imes4\) mm\(^2\) on the target. The three magnetic spectrometers A, B, and C have been used for the detection of the scattered electrons and of the pions or protons of the respective reactions. The spectrometers are equipped with vertical drift chambers for tracking, a thin and a thick layer of plastic scintillators for the trigger and for \(\pi^+\)/\(p\) discrimination, and a large-volume gas Čerenkov counter for \(e^\pm/\pi^\pm\) identification. The setup allows for very clean and high-resolution (\(\Delta p/p \lesssim 10^{-4}\), \(\Delta\theta \lesssim 3\) mrad) coincidence measurements yielding missing-mass resolutions of typically \(1\) MeV/\(c^2\) (FWHM).

A. The \(H(e,e'\pi^+)X\) Reaction

The first pilot measurement in the \(H(e,e'\pi^+)X\) reaction based on our proposal to the Program Advisory Committee at MAMI \([17]\) was carried out in July 2000 with a total runtime of 18 h. The missing-mass spectrum showed a resonance-like structure around \(M_X \approx 1007\) MeV/\(c^2\), with a width of about \(1\) MeV/\(c^2\), i.e. with the resolution of the setup. However, the significance was only \(3\) standard deviations, not warranting an interpretation of this finding as a positive identification.

A dedicated \(H(e,e'\pi^+)X\) experiment was thus performed in February and August 2002 with a total runtime of 257 hours. The parameters of the kinematical settings are listed in Tab. I. The scattered electrons were detected in Spectrometer B at forward angles, and both Spectrometer A and C were used in coincidence with B to detect the pions along the momentum-transfer direction (pion center-of-mass angle \(\theta_\pi' \approx 0^\circ\)), and almost perpendicular to it (\(\theta_\pi' \approx 100^\circ\) and \(110^\circ\)), respectively. Most of the AB and BC measurements were carried out simultaneously,
exploiting the full capabilities of the three-spectrometer facility.

The resolution of the measured coincidence time, after applying corrections due to individual path lengths and detector-related influences on the timing signals, varied from 0.8 to 1.2 ns (FWHM). The true events were selected by a ±1.5 ns cut on the coincidence time spectrum. The shape of the background has been determined by selecting purely random coincidences. Furthermore, the data were normalized to the collected charge and the target thickness and were corrected for deadtime effects. The loss of pions due to their decay in flight from the origin to the detector has been corrected by weighting each pionic event with an individual survival probability, depending on the pion momentum and on the length of the pion track. The acceptance was determined by a simulation code, which accounts for the energy loss in the target and window materials of the scattering chamber and the spectrometer entrance as well as for the Bethe-Heitler radiation of the electrons. After subtraction of the random background and application of the mentioned corrections, normalized yields for the H(e,e′π+)X reaction have been obtained.

Figures 1 and 2 summarize the results of the H(e,e′π+)X measurements. In the upper halves of Figs. 1 and 2, the normalized yields of three kinematical settings are presented as a function of the missing mass. The missing-mass resolution was ≈ 0.6 MeV/c² (FWHM) for the AB runs shown in Fig. 1, and ≈ 1.5 to 1.6 MeV/c² for the BC runs plotted in Fig. 2. The invariant masses of the states claimed by Tatschew et al. [2] and Fil’kov et al. [3] are indicated by the vertical arrows. As is seen from the spectra, no significant narrow structure other than the peak corresponding to the ground state of the neutron is found. The missing-mass region from MX ≈ 950 to 1050 MeV/c² shows a smooth radiation tail. The measurements include a repetition of the kinematics of the pilot run (settings H-2/H-3 in Fig. 1) with about five times the statistics of the first run. In order to quantify the sensitivity of our measurements, we show yield ratios in the lower halves of Figs. 1 and 2. They are obtained by subtracting the radiation tail, modelled by a fifth-order polynomial, and dividing the spectra by the height of the respective neutron peak. The differential cross section for the H(e,e′π+)n channel can be estimated using the Unitary Isobar Model “MAID” [18]. For the three kinematics of Figs. 1, 2(a), and 2(b), one obtains d²σ/(dΩ_e′dE_e′) ≈ 2.6 · 10⁻⁴, 8.2 · 10⁻⁴, and 1.9 · 10⁻⁵ µb/(sr²MeV). As the yield ratios in the lower halves indicate, narrow structures can be excluded to a level of 10⁻⁴ of the height of the neutron peak.

![FIG. 1: Upper half: Missing-mass spectrum of the H(e,e′π+)X reaction, measured with Spectrometer A and B at θ_e′ = 0°. The plot shows the result of setting H-1 (with the neutron peak height set to unity) and the combined settings H-2 and H-3 (at the electron beam energy and spectrometer settings listed in Tab. 1). The achieved missing-mass resolution is 0.6 MeV/c² (FWHM) as given by the width of the neutron peak. A fifth-order polynomial is fit to the data to model the radiation tail. The invariant masses of the states claimed by Refs. [2, 3] are indicated by the arrows. Lower half: Yield ratio of the above spectrum after subtraction of the radiation tail and division by the height of the neutron peak. Narrow structures (see the experiments of [2] and [3]) are excluded to a level of 10⁻⁴ of the height of the neutron peak.](image-url)
\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Upper half: Missing-mass spectra of the $\text{H}(e,e'\pi^+)\text{X}$ reaction, measured with Spectrometer B and C at $\theta^*_e \approx 100^\circ$. Plot (a) shows the settings $H-4$ (with the neutron peak height set to unity) and $H-5$, and (b) setting $H-6$ (at the electron beam energy and spectrometer settings listed in Tab. I). The achieved missing-mass resolution is (a) $\approx 1.6\;\text{MeV/c}^2$ (FWHM) and (b) $\approx 1.5\;\text{MeV/c}^2$, respectively. The vertical arrows are the same as in Fig. 1. The solid curves and the yield ratios in the lower half are obtained in the same way as in Fig. 1. Narrow structures (see the experiments of [2] and [3]) are excluded to a level of (a) $10^{-3}$ and (b) $2 \cdot 10^{-3}$ of the height of the neutron peak, respectively.}
\end{figure}

B. The D(e,e'p)X Reaction

The D(e,e'p)X reaction was studied between May and August 2002 with a total runtime of 632 hours. The measured kinematics can be characterized by the relative energy $E_{pX} = W - M_p - M_X$ of the p-X system, where $W$ is the photon-deuteron invariant mass, $M_p$ the proton mass, and $M_X$ the missing mass of the D(e,e'p)X reaction. The kinematics of the measured settings varied from the threshold region ($E_{pX} \rightarrow 0$) up to the quasielastic region ($E_{pX} \approx 100$ to 150 MeV). The near-threshold kinematics have been chosen in analogy to the experiment by Fil’kov et al. [3], where the relative energy of the two outgoing nucleons pn (or possible pX) is small and a strong final-state interaction is expected. In this case, the detected proton is emitted into a small forward cone around the direction of momentum transfer. The kinematical parameters of the measured settings of the D(e,e'p)X reaction are listed in Tab. II.

The D(e,e'p)X measurements were carried out simultaneously with a dedicated experiment to measure the electric form factor of the neutron $G_{E,n}$ via the D($\vec{e},e'\vec{n}$) reaction [19]. The $G_{E,n}$ experiment utilized Spectrometer A for the scattered electrons and a separate setup to measure the neutron polarization. Spectrometer C (at angles $\geq 90^\circ$ right of the beam) and Spectrometer B (at forward angles left of the beam) were used in coincidence for the detection of electrons and protons, respectively, in a parasitic mode. The electron scattering angle was restricted to large values, which, though not optimal, resulted in quite sizeable four-momentum transfer $Q^2$.

The analysis of the missing-mass spectra has been car-

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Km & $E_0$ [MeV] & $\theta_{e^\prime}$ [Degree] & $\theta_p$ [Degree] & $p_{e^\prime}$ [MeV/c] & $p_p$ [MeV/c] & $Q^2$ [(MeV)^2] & $E_{pX}$ [MeV] & $I$ [µA] & $T$ [h] \\
\hline
D-1 & 659.7 & 110 & 26 & 420 & 444 & 0.8 & 0-6 & 15 & 181.2 \\
D-2 & 659.7 & 110 & 26 & 420 & 444 & 0.8 & 0-6 & 15 & 602.5 \\
D-3 & 659.7 & 110 & 26 & 400 & 500 & 0.7 & 0-10 & 12.5 & 63.9 \\
D-4 & 659.7 & 110 & 26 & 355 & 740 & 0.6 & 0-15 & 12.5 & 29.5 \\
D-5 & 659.7 & 103 & 26 & 400 & 500 & 0.7 & 25-90 & 15 & 14.7 \\
D-6 & 659.7 & 103 & 26 & 355 & 740 & 0.6 & 75-145 & 12.5 & 29.5 \\
D-7 & 883.1 & 107 & 25 & 455 & 570 & 0.1 & 0-14 & 10 & 212.8 \\
D-8 & 883.1 & 107 & 25 & 455 & 570 & 0.1 & 0-14 & 10 & 47.0 \\
D-9 & 883.1 & 92.3 & 30 & 455 & 570 & 0.1 & 0-14 & 10 & 3.7 \\
D-10 & 883.1 & 92.3 & 30 & 455 & 570 & 0.1 & 0-14 & 10 & 13.5 \\
\hline
\end{tabular}
\caption{Kinematics of the D(e,e'p)X reaction. The columns $p_{e^\prime}$ ($\theta_{e^\prime}$) and $p_p$ ($\theta_p$) are the central momenta and angles of the electron spectrometer (C) and the proton spectrometer (B), respectively. Also shown are the four-momentum transfer $Q^2$ and the p-X relative energy $E_{pX}$. The average beam current $I$ and the net runtime $T$ are shown in the rightmost columns.}
\end{table}
FIG. 3: Upper half: Missing-mass spectra of the D(e,e′p)X reaction in the region of the deuteron-breakup threshold at the four-momentum transfer (a) $Q^2 = 0.8$ (GeV/c)$^2$ and (b) $Q^2 = 1.1$ to 1.2 (GeV/c)$^2$ (with the neutron peak height set to unity). The plot shows the combined settings (a) $D_{-1,2,3}$, and (b) $D_{-6,7}$ (cf. Tab. II). The achieved missing-mass resolution is $\approx 1.3$ MeV/c$^2$. The solid curves and the yield ratios in the lower half are obtained in the same way as in Fig. 1. Significant structures are excluded to a level of (a) $10^{-2}$ and (b) $5 \cdot 10^{-2}$ of the height of the neutron peak, respectively.

The plot shows the combined settings (a) $D_{-1,2,3}$, and (b) $D_{-6,7}$ (cf. Tab. II). The achieved missing-mass resolution is $\approx 1.3$ MeV/c$^2$. The solid curves and the yield ratios in the lower half are obtained in the same way as in Fig. 1. Significant structures are excluded to a level of (a) $10^{-2}$ and (b) $5 \cdot 10^{-2}$ of the height of the neutron peak, respectively.

The resulting normalized yields and yield ratios of the D(e,e′p)X reaction are presented in Figs. 3 and 4. Figure 3 shows the results of the near-threshold settings, while the results of the quasielastic settings are depicted in Fig. 4. The missing-mass resolution was $\approx 1.3$ MeV/c$^2$ (FWHM) for the near-threshold runs, and $\approx 0.9$ (1.3) MeV/c$^2$ for the runs near the quasielastic maximum. The continuous part of the missing-mass distribution is mainly due to the radiation tail, with the above mentioned $\pi^-p$ background giving a small contribution in the higher missing-mass region. In Fig. 4(b), the pion threshold is open above $M_X > 1070$ MeV/c$^2$, yielding additional strength. The invariant masses of the states claimed by Tatischeff et al. [2] and Fil’kov et al. [3] are indicated by the vertical arrows. Here again, as in the case of the hydrogen experiment described above, no significant peak structure other than the one corresponding to the ground state of the neutron is found. Though the measurements in the threshold region took most of the beamtime (see Tab. II), the statistics is quite poor even for the ground-state breakup of the deuteron. This is due to the fact that this kinematics maps out very high missing momenta of the proton in the order of 450 MeV/c. In the quasielastic settings (Fig. 4), the cross section is much larger. The differential cross section for the D(e,e′p)n channel can be estimated using the deuteron electrodisintegration model of Arenhövel et al. [20]. For the threshold settings of Fig. 3(a) and 3(b), one obtains an average of $d^3\sigma/(d\Omega_e dE_e d\Omega_p) \approx 1.4 \cdot 10^{-6} (2.8 \cdot 10^{-7}) \, \mu b/(sr^2 MeV)$, respectively, whereas the average differential cross section of the quasielastic settings of Fig. 4(a) and 4(b) is about $d^3\sigma/(d\Omega_e dE_e d\Omega_p) \approx 1.1 \cdot 10^{-3} (2.3 \cdot 10^{-3}) \, \mu b/(sr^2 MeV)$. Significant structures are excluded to a level of $10^{-2}$ (5-10$^{-2}$) for the near-threshold settings, and $10^{-4}$ (10$^{-2}$) for the quasielastic settings compared to the height of the neutron peak, respectively.

III. SUMMARY

We have searched for narrow structures in the missing-mass spectra of the electromagnetic H(e,e′$\pi^+$)X and D(e,e′p)X reactions in kinematics corresponding to the
hadronic beam experiments of Tatischeff et al. [2] and Fil’kov et al. [3]. Our measurements exclude narrow nucleon resonances below pion threshold for the H(e,e′π+)X reaction down to the level of 10^{-4} compared to the respective transition to the neutron ground state. For the D(e,e′p)X reaction, narrow structures are excluded to a level of 10^{-4} relative to the neutron peak in the quasielastic and to 10^{-2} in the near-threshold measurements. On the basis of those results the various theoretical attempts [6, 9, 10] for an explanation of the observed structures in Refs. [2, 3] might be questioned. In order to draw a final conclusion on the existence of the narrow resonances of Refs. [2, 3], the hadronic experiments should be repeated with the same accuracy as the present electromagnetic ones.

IV. ACKNOWLEDGEMENT

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