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NUCLEON STRUCTURE FROM PION ELECTRO-PRODUCTION EXPERIMENTS AT MAMI

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Recent pion electro-production experiments of the A1 Collaboration at MAMI are presented. The threshold data in the p(e,e′p)π^0 and d(e,e′d)π^0 channels reveal the chiral dynamics of the pion-nucleon system at low energies. Measurements of the neutral channel in the Δ region address the issue of the pion cloud, while the p(e,e′π^+)n channel gives access to the axial structure of the nucleon.

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1. *Introduction*

Electro-production of neutral or charged pions off nucleons close to the pion threshold is an important tool to explore the structure of protons and neutrons at low energies. The s- and p-wave partial amplitudes in the pπ^0 channel are benchmark tests for predictions of the chiral perturbation theory (ChiPT) which is believed to be a good low-energy approximation to QCD involving nucleon and pion degrees of freedom. Its validity can also be examined in the nπ^+ channel which offers a possibility to extract the axial and induced pseudo-scalar form-factors of the proton. The threshold coherent π^0 production on the deuteron is a sensitive probe of the chiral dynamics of the pion-neutron system. Experiments in the region of the Δ resonance probe the multipole structure of the N $\rightarrow$ Δ transition by isolating interferences of small quadrupole transition amplitudes with the dominant magnetic dipole amplitude, and provide a quantitative measure for the deformation of the nucleon and/or the Δ. This paper presents recent pion electro-production measurements of the A1 Collaboration at MAMI.

2. Neutral channels at threshold

2.1. The proton

Early measurements in the $\mathrm{p(e, e'p)}\pi^0$ channel were designed to access the s-wave amplitudes at threshold [1, 2] and thereby test the low-energy theorems of ChiPT [3]. In the Mainz experiment at $Q^2 = 0.1$ $(\mathrm{GeV}/c)^2$, the s-waves were extracted by using *calculated* p-waves. The predictions for the combinations of p-wave amplitudes $\mathrm{P}_{i=1...5}$ were namely considered to be reliable because the one-pion-loop contributions are much smaller than those of the tree diagrams, contrary to the s-wave amplitudes E_{0+} and L_{0+} which pick up large pion-loop corrections even at threshold and at $Q^2 \to 0$. The low-energy parameters of ChiPT were fitted to the partial cross-sections of Ref. [2], and the photo-production data, the electro-production data and the theory seemed consistent. However, the value of Q^2 was believed to be too high for the convergence of ChiPT.

Therefore, another experiment at $Q^2 = 0.05$ $(\mathrm{GeV}/c)^2$ was recently performed at MAMI [4], in which a model-independent extraction of the multipoles was attempted. The s-wave multipoles and the combinations P_1, P_4, P_5, and $\mathrm{P}_{23} = \frac{1}{2}(\mathrm{P}_2^2 + \mathrm{P}_3^2)$ of the p-waves were extracted. The experiment showed large discrepancies with respect to the calculations. The measured Q^2-dependence of the total cross-section (dominated by systematical uncertainties) strongly deviates from the prediction of ChiPT. Furthermore, there are large discrepancies between ChiPT and the MAID model [5]. While the resolution of the experiment was not good enough to perform a complete separation of the multipoles, it seems that the deviation is hidden in the P_{23} term which is constrained by photo-production and is not free to be readjusted to fit the new data set.

Since the discrepancy is large and seems to persist, this subject urgently needs further investigation. An experiment is planned at MAMI to scan the pertinent Q^2-region, and an independent experiment is planned at JLab [6] with extended kinematical coverage using a large-acceptance spectrometer.

2.2. The deuteron

Coherent π^0 electro-production from the deuteron is an excellent way to obtain information on the electro-production amplitude off a free neutron. In the impulse approximation, the full production amplitude is a coherent isoscalar sum of the free proton and neutron amplitudes. The nuclear binding effects are typically accounted for by means of deuteron form-factors. Interpreted in terms of ChiPT, the $\mathrm{d(e, e'd)}\pi^0$ process establishes a connection to the pion-nucleon chiral dynamics in the proton channel: once the low-energy constants of ChiPT are optimally adjusted to describe the pion photo- and electro-production data sets on the proton, the deuteron data can be used to extract the predictions for the neutron amplitudes without introducing new or readjusting old low-energy parameters.

A cross-section measurement with real photons was performed at SAL [7] using coincidence detection of the π^0-decay photons. Since the missing-mass resolution was insufficient to separate the coherent channel from the deuteron breakup, the breakup contribution was subtracted by using a model, yielding the threshold s-wave amplitude of $E_{\mathrm{d}} = (-1.45 \pm 0.09) \times 10^{-3}/m_\pi$. This value is about 20% below the prediction of ChiPT, $E_{\mathrm{d}} = (-1.8 \pm 0.6) \times 10^{-3}/m_\pi$ [8], but it is within the error bars.

The first experiment at finite Q^2 and close to threshold was recently performed at MAMI [9]. In this experiment, a magnetic spectrometer was used to detect the deuterons, thereby cleanly separating the coherent from the breakup channel. However, the detection of the low-energy deuterons suffering from large energy loss and multiple scattering limited the Q^2 range to 0.1 (GeV/c)^2. The complete centre-of-mass solid angle was covered up to 4 MeV above threshold, and a Rosenbluth separation was performed. We extracted a value of $|L_d| = (0.50 \pm 0.11) \cdot 10^{-3}/m_\pi$ for the longitudinal s-wave amplitude at threshold, and an upper limit of $|E_d| \leq 0.42 \cdot 10^{-3}/m_\pi$. The results are shown in Fig. 1.

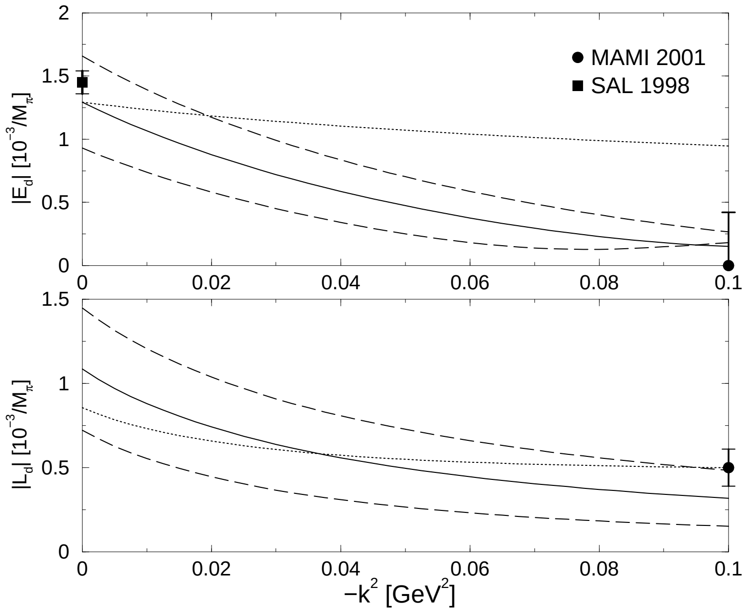

Fig. 1. The Q^2-dependence of the threshold s-wave *multipoles E_{d} and L_{d} for* $\mathrm{d(e,e'd)}\pi^0$. *The solid (dotted) curves represent fits 2 (1) of ChiPT (see [10] for details). The band between the dashed lines centered around fit 2 corresponds to a variation of the single-scattering amplitudes $E_{0+}^{(\mathrm{n})}$ and $L_{0+}^{(\mathrm{n})}$ by $\pm 1 \cdot 10^{-3}/m_\pi$.*

The calculation of the threshold amplitude within ChiPT [10] showed that in order to understand the present data set, it is necessary to calculate the single-scattering (nucleon) amplitudes and three-body interactions in a consistent chiral scheme. A similar conclusion was reached in Ref. [11]. The crucial feature is the inclusion of pion loops with correct anti-symmetrisation, and application of parity and angular momentum conservation in the intermediate state. Rescattering effects cancel out, and the unitary cusp observed in the pπ^0 channel appears to be completely washed out. However, the calculations indicate that the p-wave multipoles are substantial and that the amplitudes possess a more complex momentum dependence than postulated in the original data analysis. Thus, even though consistency between data and theory seems to have been achieved (within the relatively large systematic uncertainties), more precise measurements at lower Q^2 would be beneficial to test these concepts accurately.

3. *The charged channel close to threshold*

Close to the threshold, the transverse and longitudinal cross-sections for p(e, e$'\pi^+$)n in parallel kinematics depend predominantly on the electric (E_{0+}) and the longitudinal (L_{0+}) multipoles, respectively. The E_{0+} amplitude is sensitive to the axial form-factor G_{A}, while the L_{0+} amplitude depends on the pion charge form-factor F_π and the induced pseudo-scalar form-factor G_{P}. Rosenbluth separations of the transverse and longitudinal cross-sections were performed in recent experiments at MAMI at an invariant mass of $W = 1125$ MeV and several values of Q^2 (see Fig. 2 for kinematics coverage).

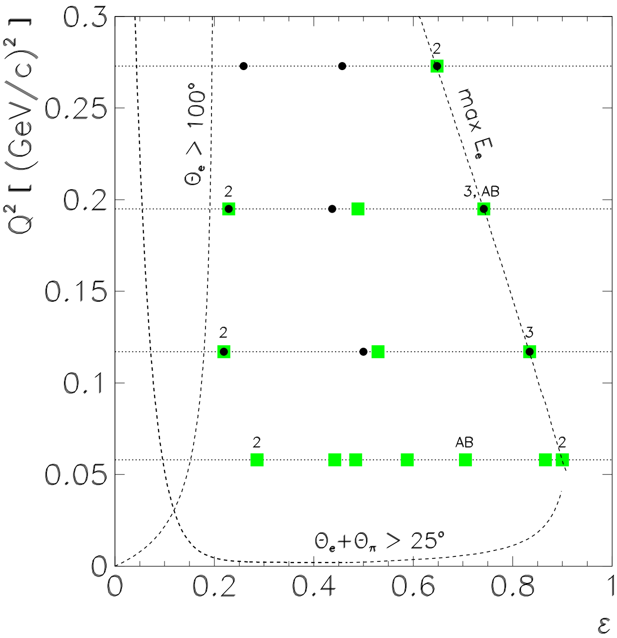

Fig. 2. Kinematics coverage for the Rosenbluth separations in the p(e, e$'\pi^+$)n *channel at* $W = 1125$ MeV/*c. Circles: published data [12]; squares: recently acquired data which are being analysed. The symbols '2' and '3' denote measurements repeated in different time periods, while 'AB' indicates spectrometer swaps which were performed to control systematics.*

For the transverse cross-section, the s-wave dominance is known to persist to relatively high energies above the threshold. Thus the axial mass parameter M_{A} (a cut-off in the dipole parameterisation of G_{A}) has been extracted from the transverse cross-section by using an effective Lagrangian model [12]. It was shown that the extracted value of $M_{\mathrm{A}} = (1.077 \pm 0.039)$ GeV is (0.051 ± 0.044) GeV larger than the axial mass $M_{\mathrm{A}} = (1.026 \pm 0.021)$ GeV known from neutrino scattering experiments. This 'axial mass discrepancy' is consistent with the prediction of ChiPT [13] which originates in pion-loop corrections to the electro-production process.

Unfortunately, the kinematics range of the presently acquired data was too high for a direct application of the ChiPT result. The model-dependent terms, especially in the L_{0+} multipole, are of a size which does not allow to distinguish the pion form-factor from the induced pseudo-scalar form-factor. However, even closer to the threshold, also the longitudinal cross-section will be dominated by the s-wave, and we have

$$
\begin{aligned}
E_{0+}(q^2) &= \frac{c}{\sqrt{2} f_\pi} \left[G_{\mathrm{A}}(q^2) + \frac{q^2}{4M^2} \, G_{\mathrm{A}}(0) G_{\mathrm{M}}^v(q^2) + \cdots \right] , \\
L_{0+}(q^2) &= c \left[D(t) - 2M G_{\mathrm{A}}(0) \right] \frac{\omega F_\pi(k_\pi^2)}{\sqrt{2} m_\pi f_\pi \, (2M + m_\pi)} + \frac{\omega}{m_\pi} \, E_{0+}(m_\pi^2) \, .
\end{aligned}
$$

Here the divergence form-factor

$$
D(t) = \frac{2 f_\pi g_{\pi\mathrm{NN}} m_\pi^2}{m_\pi^2 - t} + 2 \left[M G_{\mathrm{A}}(0) - f_\pi g_{\pi\mathrm{NN}} \right] \frac{\lambda^2}{\lambda^2 - t}
$$

measures the deviation of the induced pseudo-scalar form-factor G_{P} from its pion-pole dominance $(1/(m_\pi^2 - t))$ form. This allows one, by fitting λ to the data, a simultaneous extraction of G_{A} and G_{P}. To access very low Q^2 and pion momenta in the vicinity of the threshold, a dedicated short-orbit spectrometer is being commissioned in Mainz, and is expected to take data soon [14].

4. *The* N $\rightarrow$ Δ *transition*

One of the main goals of the N $\rightarrow$ Δ experiments is to measure the Q^2-dependence of the transition amplitudes. The non-zero electric (E2) and Coulomb (C2) quadrupole amplitudes, which are much smaller than the leading magnetic dipole amplitude (M1), are an indication that the nucleon and/or the Δ deviate from spherical symmetry. Several mechanisms have been proposed to explain the nature of this deviation. In models involving explicit pion degrees of freedom, relatively large contributions to M1 and dominant contributions to E2 and C2 originate in the coupling of the virtual photon to the p-wave pion field. The motivation behind the recent N $\rightarrow$ Δ program at MAMI is to map out the M1, E2, and C2 multipoles in the region of low Q^2 where the pion-cloud effects are expected to play the most important role.

The small quadrupole amplitudes E2 and C2 can be accessed through specific terms in the cross-section which contain interferences of the electro-production multipoles E_{1+} and S_{1+} with the dominant M_{1+}:

$$\begin{aligned}
\sigma_{0\pi}(\theta_\pi^\star) &= \sigma_0(\theta_\pi^\star) + \sigma_{\mathrm{TT}}(\theta_\pi^\star) - \sigma_0(180^\circ) \\
&\sim 2\,(\cos\theta_\pi^\star + 1)\,\Re\,[E_{0+}^* M_{1+}] - 12\,\sin^2\theta_\pi^\star\,\Re\,[E_{1+}^* M_{1+}]\,, \\
\sigma_{\mathrm{LT}}(\theta_\pi^\star) &\sim \sin\theta_\pi^\star\,\Re\,[S_{0+}^* M_{1+}] - 6\,\cos\theta_\pi^\star\,\sin\theta_\pi^\star\,\Re\,[S_{1+}^* M_{1+}]\,, \\
\sigma'_{\mathrm{LT}}(\theta_\pi^\star) &\sim -\sin\theta_\pi^\star\,\Im\,[(-6\cos\theta_\pi^\star\,S_{1+} + S_{0+})^* M_{1+}]\,,
\end{aligned}$$

where $\theta_\pi^\star$ is the emission angle of the pion in the centre-of-mass frame of the πN system and $\sigma_0 = \sigma_{\mathrm{T}} + \varepsilon\sigma_{\mathrm{L}}$. The $\sigma_{0\pi}$ and σ_{LT} terms exhibit large sensitivities to the E2/M1 $\sim \Re\,[E_{1+}^* M_{1+}]$ and the C2/M1 $\sim \Re\,[S_{1+}^* M_{1+}]$ ratios, respectively, while the σ'_{LT} is sensitive to the imaginary part of the $S_{1+}^* M_{1+}$ interference.

In the spring of 2003, new high-precision data in the $\mathrm{p(e,e'p)}\pi^0$ channel were acquired at MAMI in the region of the Δ resonance, at four-momentum transfers of -0.06, -0.127, and -0.2 $(\mathrm{GeV}/c)^2$. The anticipated results for the E2/M1 and C2/M1 ratios as a function of Q^2 are shown in Fig. 3.

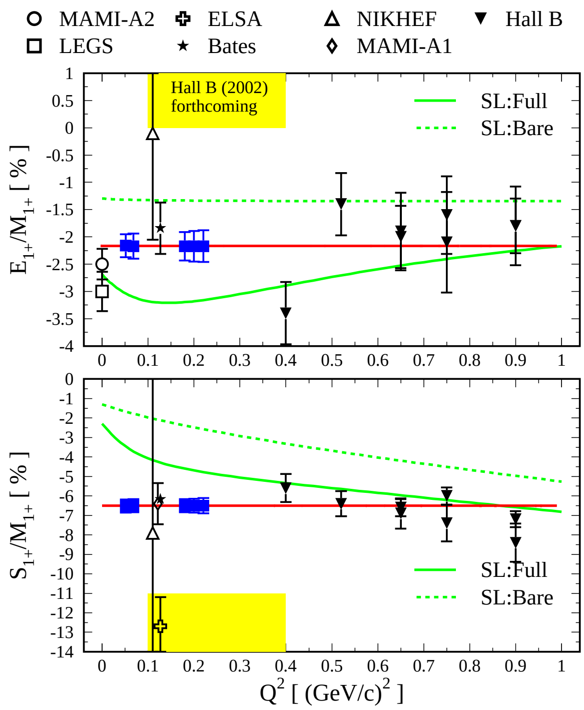

Fig. 3. Recent experimental data on the E2/M1 and C2/M1 ratios compared to the predictions of the model of Sato and Lee [15] (dashed curves: bare nucleon, full curves: including pion cloud) and MAID [5] (constant values of $-2.2\,\%$ and $-6.5\,\%$, respectively). The anticipated MAMI data (taken in the spring of 2003) are shown by full squares.

In addition to our primary goal, the extractions of E2/M1 and C2/M1 ratios at different Q^2, the present data set will try to answer several open questions arising from previous experiments at MIT-Bates and MAMI. For example, the measurement of σ'_{LT} at $Q^2 = 0.2$ (GeV/c)^2 will address the significant disagreement between MAID and the A'_{LT} result from Mainz, which is underestimated by MAID by about 25 % [16]. The measurement of σ'_{LT} at $Q^2 = 0.127$ (GeV/c)^2 which overlaps with Bates will try to yield more insight into the apparent inability of the models to simultaneously describe the polarisation components obtained in the recoil-polarisation measurements [17]. At present, it is unclear where the violation of the consistency relation between P'_x, P'_z, and P^0_y comes from. The multipole structure of σ'_{LT} resembles that of P^0_y, so we expect new data to help resolve this issue. The expected data points in the angular distributions of σ_{LT}, σ'_{LT}, and $\sigma_{0\pi}$ at $Q^2 = 0.127$ and 0.200 (GeV/c)^2 are shown in Fig. 4.

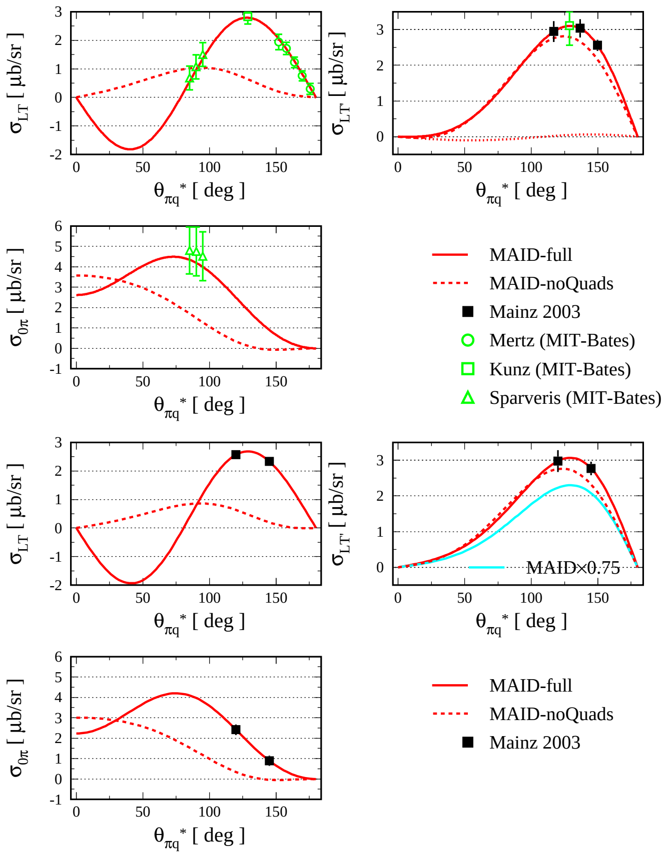

Fig. 4. Angular distributions of σ_{LT}, $\sigma_{\mathrm{LT}'}$, and $\sigma_{\pi 0}$ for $Q^2 = 0.127$ (upper three panels) and 0.200 GeV/c)^2 (lower three panels). The full curves indicate full MAID predictions, the dashed curves correspond to the MAID prediction without the quadrupole amplitudes. For details, see text.

5. *Conclusions*

The pion electro-production experiments recently performed at the MAMI facility have been presented. The threshold data on the neutral channels on proton and deuteron targets will be used to test the predictions of chiral perturbation theory. The charged channel data will give additional insight into the axial structure of the proton, while the electro-production in the region of the Δ resonance will be used as a sensitive tool to probe the pion-cloud effects in the nucleon. The data taken at the three-spectrometer setup of the A1 Collaboration at MAMI are capable of addressing all these issues.

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GRAĐA NUKLEONA IZ MJERENJA ELEKTROTVORBE PIONA U MAMIJU

Predstavljamo nedavna mjerenja elektrotvorbe piona Suradnje A1 u MAMIju. Podaci oko pragova kanala p(e,e′p)π^0 i d(e,e′d)π^0 otkrivaju kiralnu dinamiku sustava pion-nukleon na niskim energijama. Mjerenja neutralnog kanala u području Δ rezonancije daju uvid u strukturu pionskog oblaka, a kanal p(e,e′π^+)n u aksijalnu građu nukleona.