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Experimental tests of Chiral Perturbation Theory

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Abstract. In this paper the current status of the threshold photo- and electroproduction of neutral pions as test of Chiral Perturbation Theory is summarized. The combination of differential cross-section data with polarized photon asymmetries allows to determine a complete set of s- and p-wave amplitudes at threshold for the photoproduction case. These extracted amplitudes are in good agreement with predictions and fits of Heavy Baryon Chiral Perturbation Theory. On the other hand, new data on pion electroproduction shows a significant deviation from the predicted cross-sections at a four-momentum transfer of $Q^2 = 0.05\,\mathrm{GeV}^2/c^2$. For the coherent pion production from the deuteron the photoproduction data agree with Chiral Perturbation Theory. The former reported severe disagreement between the electroproduction s-wave amplitude at a four-momentum transfer of $Q^2 = 0.1\,\mathrm{GeV}^2/c^2$ and first calculations seems to be resolved now.

PACS. 25.30.Rw Electroproduction reactions – 13.60.Le Meson production – 12.39.Fe Chiral Lagrangians

1 Neutral pion photoproduction

Chiral Perturbation Theory is a consistent scheme to utilize the symmetries of QCD to predict observables at the confinement scale. A short introduction on the basic principles of ChPT was given in this conference [1]. A more complete overview of the status of this field can be found, *e.g.*, in ref. [2].

In this paper, the current status of the neutral pion photo- and electroproduction experiments near threshold is discussed. Since the pion is the Goldstone Boson of the chiral symmetry breaking, these experiments are well suited to test calculations in the framework of Heavy Baryon Chiral Perturbation Theory (HBChPT) [3].

First experiments [4] on threshold pion photoproduction were aimed at testing the predictions of Low Energy Theorems [5] for the threshold value of the s-wave multipole amplitude E_{0+}. The severe disagreement between these theorems and the experiments was resolved in the following years by refined calculations in HBChPT [6], which also gave predictions for the p-wave multipole combinations:

$$\begin{aligned} P_1 &= 3E_{1+} + M_{1+} - M_{1-}\,, \\ P_2 &= 3E_{1+} - M_{1+} + M_{1-}\,, \\ P_3 &= 2M_{1+} + M_{1-}\,. \end{aligned}$$

The calculations showed that the s-wave amplitude is only slow converging in the chiral expansion, while the p-wave combinations P_1 and P_2 are strong predictions in this framework. P_3 is given by a low-energy constant of HBChPT and has to be determined by the experiment.

The first experimental access to the multipoles is the measurement of the differential cross-section. With the assumption that only s- and p-waves contribute at threshold, the angular structure of the cross-section is given by

$$\sigma(\theta) = \frac{q}{k}\left(A + B\,\cos\theta + C\,\cos^2\theta\right)$$

with the phase space factor $\frac{q}{k}$ and three angular coefficients,

$$\begin{aligned} A &= E_{0+}^2 + \frac{1}{2}\left({P_2}^2 + {P_3}^2\right)\,, \\ B &= 2\,Re\left(E_{0+}{P_1}^*\right)\,, \\ C &= {P_1}^2 - \frac{1}{2}\left({P_2}^2 + {P_3}^2\right)\,. \end{aligned}$$

Experiments at SAL [7] and MAMI [8,9] are in good agreement and allow for an extraction of the full angular structure of the differential cross-section. But from unpolarized cross-section experiments, only the modulus of the s-wave multipole $|E_{0+}|$ and the p-wave combinations P_1 and $P_{23} := \frac{1}{2}({P_2}^2 + {P_3}^2)$ can be extracted. To further decompose all multipoles, a further observable has to be measured. A convenient choice is the polarized photon asymmetry Σ with the multipole decomposition

$$\Sigma(\theta)\,\sigma(\theta) \sim \sin(\theta)\frac{1}{2}\left(P_3^2 - P_2^2\right).$$

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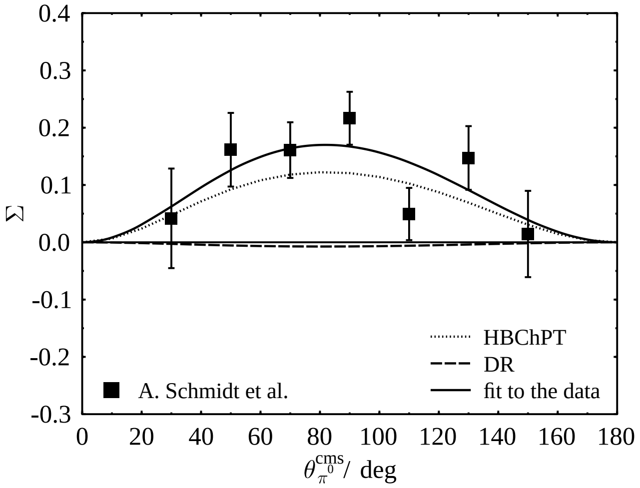

Fig. 1. Polarized photon asymmetry measured at MAMI [9] in comparison with calculations in ChPT [6] and in Dispersion Relations formalism [10].

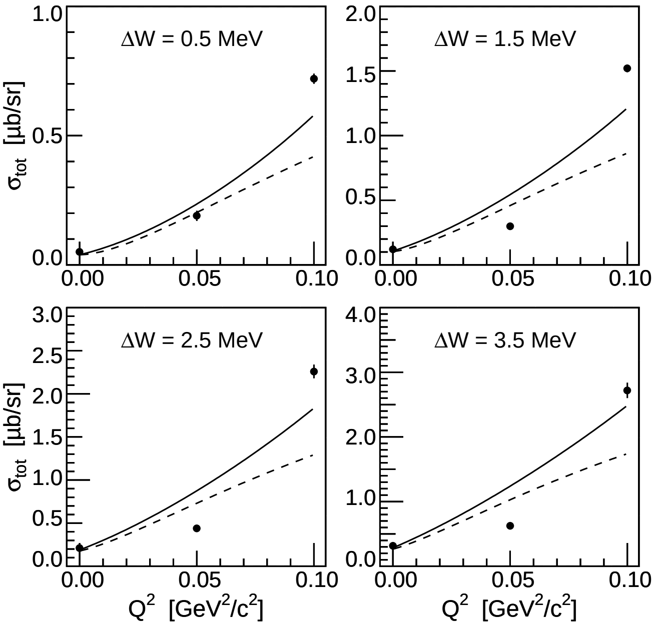

Fig. 2. The total cross-section $\sigma_{\rm tot}$ *versus* Q^2, at a value of $\epsilon = 0.8$. The solid (dashed) line is the prediction of ChPT [13] (MAID [15]), data points at $Q^2 = 0$ and $0.1\,{\rm GeV}^2/{\rm c}^2$ from [9,12].

Such an experiment was performed at MAMI [9] at the tagged-photon beam of the A2 Collaboration with the TAPS detector for the detection of the π^0 decay photons. The polarized photon beam was produced by coherent Bremsstrahlung from a diamond crystal. Figure 1 shows the asymmetry Σ, averaged over the energy range of the experiment.

With this experiment, for the first time a complete separation of the p-waves is possible. The results are given in table 1, in comparison with the predictions of Chiral Perturbation Theory (ChPT) [6] and Dispersion Relations(DR) [10]. Within the error bars, the two existing high-resolution experiments and the quoted calculations agree. The deviation for P_3 of ChPT can be removed by re-fitting the low-energy constants to the new data set.

2 Electroproduction at low Q^2

Additional information on the pion production mechanism can be extracted from electroproduction experiments.

While, *e.g.*, the multipole combination P_3 is basically a fit parameter in the description of the photoproduction data, the extention of this quantity to virtual photons is given in ChPT without further degrees of freedom. In addition, the longitudinal s-wave amplitude L_{0+} and two further longitudinal p-wave combinations can be extracted.

First experiments at a photon virtuality of $Q^2 = 0.1\,({\rm GeV}/c)^2$ aimed at extracting the s-wave amplitudes at threshold [11,12]. These experiments were in reasonable agreement with calculations [13], but the value of $Q^2 = 0.1\,({\rm GeV}/c)^2$ is somewhat to high for the convergence radius of ChPT.

Therefore, a further experiment at the intermediate value of the photon virtuality $Q^2 = 0.05\,({\rm GeV}/c)^2$, halfway between photoproduction and the existing data was performed at MAMI [14].

This experiment showed a surprising discrepancy to the calculations. Figure 2 shows the total cross-section as a function of Q^2. In this observable, the statistical error of all data points is very small and only systematic errors contribute. Thus, the clear discrepancy between data and calculations, but also the increasing discrepancy between ChPT and MAID [15] is visible.

In ref. [14] also an extraction of multipoles in a model-independent manner was attempted. While the resolution of the experiments is not yet good enough to perform a reliable separation of the multipoles, it seems that the deviation is burried in the multipole combination P_{23}, which is already fixed by photoproduction and cannot be adjusted in the calculations to describe the new data set.

Since the discrepancy is large and surprising, this subject urgently needs further investigation. An experiment at MAMI is planned to cover a continuous range in Q^2, while an independent experiment is planned at JLab [16] with extended kinematical coverage using a large acceptance spectrometer.

3 Electroproduction from the deuteron

The low-energy constants of ChPT were adjusted, as shown above, to describe the existing pion photo- and electroproduction data from the proton. By this, one looses some of the predictive power of ChPT, since in threshold experiments the complete amplitude is already given by only few parameters. On the other hand, from the description of the proton amplitudes one can extract predictions for the pion production from the neutron without introducing further degrees of freedom.

Despite this theoretical advantage, the experimental access to the free neutron amplitude is quite difficult. The

Table 1. Experimental multipole amplitudes for photoproduction from MAMI [9] and SAL [7] in comparison with Chiral Perturbation Theory (ChPT)) [6] and Dispersion Relations (DR).

	E_{0+} $(10^{-3}/m_\pi)$	P_1 $(qk \cdot 10^{-3}/m_\pi^3)$	P_2 $(qk \cdot 10^{-3}/m_\pi^3)$	P_3 $(qk \cdot 10^{-3}/m_\pi^3)$
MAMI	-1.31 ± 0.08	10.02 ± 0.2	-10.5 ± 0.2	13.1 ± 0.1
SAL	-1.32 ± 0.05	10.26 ± 0.1		
ChPT	-1.16	10.33 ± 0.6	-11.0 ± 0.6	11.7 ± 0.6
DR	-1.22	10.54	-11.4	10.2

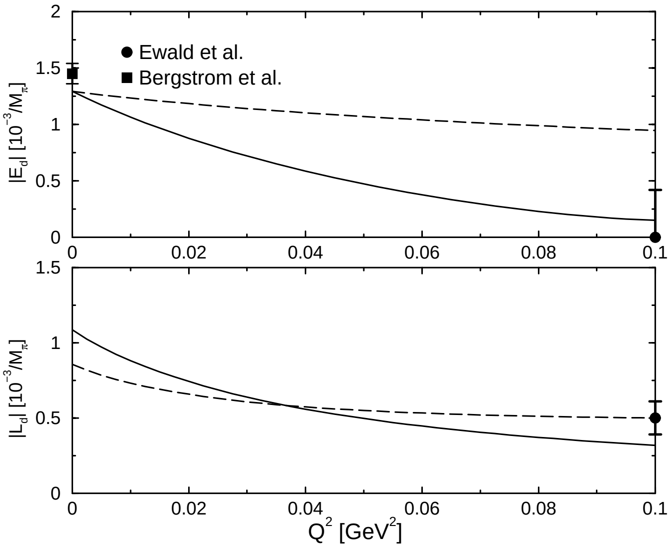

Fig. 3. The extracted s-wave multipoles from MAMI [19] (circles) in comparison with the prediction of ChPT [21]. The solid line shows the fit to the data, while the dashed line was fitted with additional constrains from resonance saturation.

most promising method seems to be the coherent pion production from a deuteron target. In impulse approximation, the production amplitude is basically given by the coherent iso-scalar sum of the free proton and free neutron amplitude, corrected by form factors as parameterization of the deuteron structure.

A first measurement of the photoproduction amplitude was performed at SAL [17]. The IGLOO detector was used to detect the decay photons of the π^0 decay in coincidence. By this technique, the missing mass resolution is not sufficient to separate the coherent channel from the deuteron breakup. By calculating this contribution in a simple model, the authors were able to extract the threshold value of the s-wave amplitude to $E_d = (-1.45 \pm 0.09) \times 10^{-3}/m_\pi$.

This value falls about 20% below the prediction of ChPT [18] of $E_d = (-1.8 \pm 0.6) \times 10^{-3}/m_\pi$ but the agreement seems reasonable within the error bars.

The extension of this experiments to finite Q^2 introduced further experimental difficulties. Due to the background conditions for electroproduction the detection of the pion decay photons had to be replaced by the detection of the recoil deuteron, which suffers at the low energies at threshold from energy loss and multiple scattering. On the other hand, by this technique the coherent channel is clearly separated from the deuteron break-up reaction and can be extracted without model assumptions.

A first threshold measurement of $d(e, e'd)\pi^0$ was performed at MAMI [19]. The detection of the deuteron limited this experiment to a four-momentum transfer of $Q^2 = 0.1\,(\mathrm{GeV}/c)^2$. As for the similar experiments from the proton, the full center-of-mass angle was covered up to 4 MeV above threshold and a Rosenbluth separation was performed.

The first prediction in ChPT for electroproduction [20] could not explain the extracted s-wave amplitudes $|E_d| \approx 0 \cdot 10^{-3}/m_\pi$ and $|L_d| = 0.5 \cdot 10^{-3}/m_\pi$ and missed the experiment by nearly an order of magnitude. The improved calculation [21] showed that it is necessary to calculate elementary nucleon amplitudes and multi-body currents in consistent schemes. Figure 3 shows the result of this calculation in comparison with the data. Within the large systematic error of the data, finally consistency could be achieved. Of course, a measurement at lower Q^2 would be necessary to further test these concepts.

References

1. B. Holstein, this issue, p. 227.
2. A.M. Bernstein, J.L. Goity, Ulf.-G. Meißner (Editors), *Chiral Dynamics* (World Scientific, Singapore, 2001).
3. V. Bernard *et al.*, Nucl. Phys. B **383**, 442 (1992).
4. E. Mazzucato *et al.*, Phys. Rev. Lett. **57**, 3144 (1986); R. Beck *et al.*, Phys. Rev. Lett. **65**, 1841 (1990).
5. P. de Baenst, Nucl. Phys. B **24**, 633 (1970); I.A. Vainshtein, V.I. Zakharov, Nucl. Phys. B **36**, 589 (1972).
6. V. Bernard, N. Kaiser, J. Gasser, Ulf-G. Meißner, Phys. Lett. B **268**, 291 (1991); V. Bernard, N. Kaiser, Ulf-G. Meißner, Z. Phys. C **70**, 483 (1996).
7. J. C. Bergstrom *et al.*, Phys. Rev. C **53**, R1052 (1996).
8. M. Fuchs *et al.*, Phys. Lett. B **368**, 20 (1996); A.M. Bernstein *et al.*, Phys. Rev. C **55**, 1509 (1997).
9. A. Schmidt *et al.*, Phys. Rev. Lett. **87**, 232501 (2001).
10. O. Hanstein *et al.*, Phys. Lett. B **399**, 13 (1997).
11. H.B. van den Brink *et al.*, Phys. Rev. Lett. **74**, 3561 (1995); T.P. Welch *et al.*, Phys. Rev. Lett. **69**, 2761 (1992).
12. M.O. Distler *et al.*, Phys. Rev. Lett. **80**, 2294 (1998).
13. V. Bernard, N. Kaiser, Ulf-G. Meißner, Nucl. Phys. A **607**, 379 (1996); **633**, 695(E) (1998).
14. H. Merkel *et al.*, Phys. Rev. Lett. **88**, 012301 (2002).
15. D. Drechsel *et al.*, Nucl. Phys. A **645**, 145 (1999); S.S. Kamalov *et al.*, Phys. Lett. B **522**, 27 (2001).

16. R. Lindgren *et al.*, Experiment E01-014, JLab, 2001.
17. J.C. Bergstrom *et al.*, Phys. Rev. C **57**, 3203 (1998).
18. S.R. Beane *et al.*, Nucl. Phys. A **618**, 381 (1997).
19. I. Ewald *et al.*, Phys. Lett. B **499**, 238 (2001).
20. V. Bernard, H. Krebs, Ulf-G. Meißner, Phys. Rev. C **61**, 58201 (2000).
21. Ulf-G. Meißner, this issue, p. 487; H. Krebs, V. Bernard, Ulf-G. Meißner, nucl-th/0207072.