Threshold Photo/Electro Pion Production – Working Group Summary

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1 Introduction

Over the last few years, pion production off nucleons by real or virtual photons has become a central issue in the study of the non–perturbative structure of the nucleon, i.e. at low energies. Here, developments in detector and accelerator technology on the experimental side as well as better calculational tools on the theoretical one have allowed to gain more insight into detailed aspects of these processes and the physics behind them. One main trigger were the two papers by the Saclay and the Mainz groups [1,2], which seemed to indicate the violation of a so–called low energy theorem for the reaction \(\gamma p \rightarrow \pi^0p\). This lead to a flurry of further experimental and theoretical investigations. Another cornerstone was the rather precise electroproduction measurement \(\gamma^*p \rightarrow \pi^0p\) at NIKHEF [3]. Here, we wish to summarize the state of the art in calculating and measuring these processes in the threshold region. Furthermore, we outline what we believe have crystalized as the pertinent activities to be done in the near future.

2 Theoretical developments

The chiral perturbation theory (CHPT) machinery to calculate the reactions \(\gamma N \rightarrow \pi^a N\), \(\gamma^* N \rightarrow \pi^a N\) and \(\gamma(\gamma^*) N \rightarrow \pi^a \pi^b N\), where \(N\) denotes the nucleon, \(\pi^a\) a pion of isospin 'a' and \(\gamma (\gamma^*)\) the real (virtual) photon exists as described in some detail in V. Bernard’s lecture [4]. It has become clear that to have precise predictions one has to calculate in the one loop approximation to order \(q^4\) in the effective Lagrangian,

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}^{(1)}_{\pi N} + \mathcal{L}^{(2)}_{\pi N} + \mathcal{L}^{(3)}_{\pi N} + \mathcal{L}^{(4)}_{\pi N}
\]

(2.1)

where the subscript '\(\pi N\)' means that we restrict ourselves to the two flavor case (the pion–nucleon–photon system) and the superscript '(i)' denotes the chiral dimension. While the first term in eq.(2.1) is given entirely in terms of well determined parameters, the string of terms of order \(q^2, q^3\) and \(q^4\) contains the so–called low–energy constants (LECs). At present, their determination induces the biggest uncertainty in

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the chiral predictions since not enough sufficiently accurate low–energy data exist to uniquely pin them down. Therefore, in the case of threshold photo/electro pion production, we follow two approaches. The first one is “clean” CHPT, where the extensive photoproduction data (total and differential cross sections in the threshold region) are used to determine the appearing LECs (see the discussion in Bernard’s lecture [4]). In that case, the predictive power resides in the photoproduction multipoles, polarization observables and the electroproduction processes. For the latter, some novel LECs appear, but they are all connected to single nucleon properties and thus can uniquely be fixed from the electromagnetic and axial radii of the nucleon. With that, the \( k^2 \) dependence (where \( k^2 < 0 \) denotes the photon four–momentum squared) of all electroproduction observables and multipoles is parameter–free fixed. For detailed calculations and predictions to order \( q^3 \) consult the Physics Reports [5]. Furthermore, one gains new insight due to the longitudinal coupling of the virtual photon to the nucleon spin. This rich field has only be glimpsed at and will serve as a good testing ground for the chiral predictions.

Now let us discuss what the limitations of such calculations are, i.e. to what values of \( |k^2| \) and \( \Delta W = W - W_{\text{thr}} \) (with \( W \) the center–of–mass energy of the \( \pi N \) system) these calculations to order \( q^4 \) can be trusted? The answer is, of course, dependent on the observable one looks at. Nevertheless, a good example is given by the one loop calculation of the S–wave cross section \( a_0 \) in \( \gamma^* p \rightarrow \pi^0 p \) [6] in comparison to the data of ref.[3]. Although the trend of the data is well reproduced up to \( k^2 = -0.1 \) GeV\(^2\), it is obvious that for such large four–momentum transfer (\( |k| \approx 2.3M_\pi \)) the one–loop corrections to the tree result are so large that they can not be trusted quantitatively, i.e. one would have to calculate further in the chiral expansion. From the extensive study of elastic pion–pion scattering in the threshold region[7], which is the purest process to test the chiral dynamics, we employ here the same rule of thumb advocated there, namely that as long as the one–loop corrections stay below 50% of the tree result, the predictions can be considered quantitative (accurate). For the S–wave cross section \( a_0 \) and many other observables, we conclude that for a rigorous test of the chiral dynamics, electroproduction experiments should be performed with

\[
|k^2| \leq 0.05 \text{ GeV}^2 \quad \Delta W \leq 15 \text{ MeV}
\] (2.2)

where the number for \( \Delta W \) is derived from photoproduction calculations and deserves more detailed studies. In any case, it is conceivable that one should stay as close to threshold (and the photon point) as experimentally possible.

The second approach to get a handle on the LECs involves the principle of resonance saturation (as discussed in some detail in these proceedings by Ecker [8] and by one of us [9]). Consider e.g. a contact term of order \( q^3 \) with an incoming photon and one outgoing pion. The resonance saturation hypothesis means that the numerical value of the LEC related to this operator is given by baryon excitations like the \( \Delta(1232) \), the \( N^*(1440) \) and others (as discussed here e.g. by Mukhopadhyay [10]) and also t–channel meson exchanges of scalar, vector or axial–vector type. Shrinking such types of diagrams to a point, the pertinent LEC is given in terms of masses and coupling constants related to the particles integrated out from the effective field theory. This, of course, induces some model–dependence but can on the other hand serve as a guideline to understand the numerical values of the LECs from some microscopic picture. However, we would like to stress again that it is preferable to have
enough data to pin down all these low–energy constants, thereby testing the accuracy of the resonance saturation idea (which works very well for strong and semi–leptonic interactions in the meson sector, but not for the non–leptonic weak interactions). This principle could then be used to estimate the contributions of higher order terms as it is frequently done in the meson sector. Also, we wish to point out that all this resonance physics seen in the threshold region is, of course, included in the phenomenological LECs. As long as one is not so ambitious to make statements throughout or above the region of nucleon excitations, resonance contributions do not pose any problem to the consistent chiral expansion.

We would also like to stress the importance of polarization observables. These can be calculated with ease and they serve as a sensitive filter in the multipole analysis which otherwise is difficult to perform and often not unique (in the sense that one has to determine more multipoles than the number of available observables). Another important topic is the neutron. Although no free neutron targets are at our disposal, measurements using the deuteron can serve as neutron probes. For that, it is mandatory to have a precise description of the weakly bound proton–neutron system. This can e.g. be achieved in the relativistic model of Gross and collaborators [11]. Clearly, some model–dependence is induced, but one hopes to be able to minimize this by a) measuring also the proton in the deuteron and comparing to its free space values and b) choosing particular kinematics where the corrections due to meson exchange currents and alike are minimized.

What are the theoretical improvements needed? First, in certain channels (where one has strong final–state interactions) it is mandatory to perform calculations including higher order effects. The most efficient machinery to do this is a combination of dispersion theory with CHPT as discussed in detail for pion form factors or $K\ell^4$–decays in refs.[12]. In essence, consider an observable $Q$ and write a dispersive representation,

$$Q = P(s) \Omega_A(s)$$

where the reduced Omnès function $\Omega_A(s)$ accounts for the phase information (and sums up loops to very high orders), the polynomial $P(s)$ is constrained by chiral symmetry and $s$ is a short–hand notation for the kinematical variables involved. Such a method has e.g. been applied succesfully in the determination of the $\pi N \sigma$–term and the scalar form factor of the nucleon as discussed by Sainio [13]. Also, it is an open question to what extent one should include the $\Delta(1232)$ as a dynamical degree of freedom in the effective field theory. We believe that for the threshold phenomena to be mapped out by the experiments within the constraints of eq.(2.2), it suffices to use the $\Delta$ to estimate LECs and thus treat it as a frozen (integrated out) d.o.f. The most important theoretical issue to be studied in more detail is the role of isospin breaking through virtual photons and the quark mass difference $m_u - m_d$. At present, one puts in the different masses for the neutral and charged pions by hand in a manner consistent with all the symmetries and Ward identities. It is well–known that the pion mass difference is essentially of electromagnetic origin, leading to the believe that this approximation accounts for the most important aspects of isospin breaking. Nevertheless, this has to be clarified in a detailed and thorough study. In any case, threshold pion photo– and electroproduction can not be considered alone but it is intimately connected to other processes like Compton scattering, pion–
Finally, a few words about the extension to three flavors are in order. Here, the theoretical situation is much less satisfactory mostly due to the large kaon loop contributions and huge cancellations with counterterms. Stated differently, the intrinsic small parameter is \((M_K/4\pi F_{\pi})^2 \approx (0.4)^2\) (modulo logarithms) and thus it is mandatory to perform higher order calculations than for the two flavor case. This becomes particularly evident in the scalar sector of the baryon masses and \(\sigma\)-terms as detailed in ref.[14]. As long as a consistent theoretical description of these 2- and 3-point functions is eluding us, we can not make statements about kaon and eta production off the nucleon. However, beautiful new data for \(K\) and \(\eta\) production in the threshold region are becoming available (\(\gamma p \rightarrow \eta p, \gamma p \rightarrow \Sigma K\) or \(\gamma p \rightarrow \Lambda K\)) which should lead to more theoretical effort to understand the chiral SU(3) meson–baryon system.

3 Experimental developments

Driven by the earlier results [1], [2] of the \(\pi^0\)-production at threshold on the proton and the discussion about the validity of low energy theorems experimental activities started in several laboratories in order to study the photo- and electroproduction of charged and neutral pions. The experiment of the electroproduction of neutral pions on the proton at NIKHEF [3] demonstrated the possibility to perform these experiments with the precision to be able to discriminate between different theoretical approaches. H. Blok, Vrije Universiteit Amsterdam, showed preliminary results of the \(^1H(e, e'p)\pi^0\)-reaction at a momentum transfer of \(|k|^2 = 0.1\) (GeV/c)\(^2\), thereby, covering an invariant mass range of 2 to 15 MeV above the production threshold. M. Distler, Universität Mainz, presented the first data of the \(^1H(e, e'p)\pi^0\)-reaction with the new spectrometer set-up at MAMI. Measurements at two polarizations of the virtual photon (\(\varepsilon_1 = 0.89\) and \(\varepsilon_2 = 0.52\)) allow a separation of the transverse and longitudinal contributions.

Due to the large acceptance in the threshold region the out-of-plane cross sections \(\sigma_{TL}\) and \(\sigma_{TT}\) can be determined. The momentum transfer of \(|k|^2 = 0.1\) (GeV/c)\(^2\) like in the NIKHEF-experiment exceeds, however, (see equation 2.2) the region of the validity of present calculations within the framework of CHPT. Nevertheless, for the first time these high quality data will allow the extraction of the \(S\)- and \(P\)-wave multipoles. In addition to these measurements results of the electroproduction of positive pions from an experiment carried out at MAMI have been announced. Besides the possibility to break down the amplitudes into their isospin pieces the extraction of the axial formfactor at low \(|k|^2\) becomes possible. Again, the results of calculations based on CHPT can be checked and compared with results of neutrino induced reactions.

J. Bergstroem, Saskatoon, reported about an ongoing experiment \(^1H(\gamma, \pi^0)\) at SAL (Saskatoon) and R. Beck (Mainz) described a planned experiment of the reaction \(^1H(\vec{\gamma}, \pi^0)\) at threshold. This experiment will allow a clean separation of the \(S\)- and \(P\)-wave contribution to the cross section in the region below and above the threshold of positive pions.
The electric amplitudes of the charged channels are fixed to the first order by the Kroll–Rudermann term. So far, the published experimental data agree within a few percent with this prediction. However, in the $\pi^+$-case there exist no data of the differential cross section close to threshold. Either an extrapolation over more than 5 MeV was performed or the knowledge about the P-wave was used in order to extract the electric multipole from the measurement of the total cross section. J. Bergstroem reported about a recent experiment of the production of negative pions on the deuteron from SAL. F. Klein discussed results for this reaction from Mainz and addressed the problems which arise in order to get information for the elementary amplitude on the neutron.

These problems do not arise by investigating the inverse reaction $\pi^- p \rightarrow \gamma n$. M. Kovash presented new, again preliminary data from TRIUMF which have the accuracy to check the electric amplitude for negative pion production extracted, so far, from a measurement of the Panofski–ratio. As a by-product of this measurement the Panofski–ratio was measured, simultaneously; and, given the impressive quality of the raw data, an improved value for this ratio should be obtained as Pavan demonstrated in reviewing the previous measurements.

These new experimental results demonstrate the renewed interest for the physics questions and show the impressive progress in the experimental techniques.

On this basis even more difficult experiments can be envisaged. The measurement of the neutral pion production on the neutron constitutes such an experiment which would, combined with the older results, check the validity of the isospin decomposition of the production amplitudes. In this connection A. Bernstein proposed a measurement using a polarized beam and a polarized target in order to measure very close to threshold the phase shift of the $\pi^0 - p$ scattering process. Precise measurements on the proton and the neutron would yield a high sensitivity for isospin–breaking effects due to the difference of the current mass of the u– and d–quarks. High precision data from MAMI and ELSA (Bonn) at the $\eta$–threshold are now available for the proton as well as for the neutron. Also data for the kaon–production have been extracted from measurements with the SAPHIR-detector on ELSA. Besides total and differential cross sections the measurement of polarization observables allow in the near future a decomposition in all multipoles. The difficulties to describe these reactions within the framework of CHPT have been addressed in chapter 2.

4 Concluding remarks

Remarkable progress has been achieved in recent years concerning the understanding of the pion production at threshold. Due to the progress in the development of CHPT the foundations of Low Energy Theorems have been revisited and put into a new perspective (for a tutorial, see e.g. ref.[15]). CHPT provides a natural link for all low energy pion reactions. The development of a new generation of electron accelerators in combination with refined detector techniques allow precision experiments, a precondition to explore the implications of the spontaneously broken chiral symmetry of QCD in the baryon sector.
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