I review the interesting tale of the electric dipole amplitude in neutral pion photoproduction and the resulting consequences. I also discuss why there is new life related to P–wave multipoles. Electroproduction is briefly touched upon.

1 THE EARLY YEARS

Some 25 years ago, de Baenst and Vainshtein and Zakharov (VZ) [1,2] independently derived a so–called low–energy theorem (LET) for the electric dipole amplitude $E_{0+}$ measured in threshold $\pi^0$ photoproduction off protons,

$$E_{0+}(s_{\text{thr}}) = -\frac{eg_{\pi N}}{8\pi m} \mu \left\{ 1 - \frac{1}{2} (3 + \kappa_p) \mu + \mathcal{O}(\mu^2) \right\} = -2.3 \times 10^{-3}/M_{\pi^+},$$  

with $s_{\text{thr}} = (m + M_\pi)^2$, $\mu \equiv M_\pi/m \simeq 1/7$ and $M_\pi(m)$ the pion (nucleon) mass as well as $\kappa_p$ the anomalous magnetic moment of the proton and $g_{\pi N}$ the strong pion–nucleon coupling constant. The expansion of $E_{0+}(s_{\text{thr}})$ in powers of the small parameter $\mu$ as given in Eq.(1) will from now on be called the 'low–energy guess' (LEG) [3]. It is of particular interest since in the chiral limit of vanishing pion mass, $E_{0+}(s_{\text{thr}})$ is zero and thus appears to be a good candidate to test our understanding of the explicit chiral symmetry breaking in QCD related to the current quark masses $m_{u,d}$ appearing in the QCD Hamiltonian,

$$M_\pi^2 = -(m_u + m_d) < 0 | \bar{q} q | 0 > / F_\pi^2 + \mathcal{O}(m_{u,d}^2),$$  

with $F_\pi = 93$ MeV the pion decay constant and the scalar quark condensate is believed to be the order parameter of the spontaneous chiral symmetry breaking in QCD. The derivation of the LEG supposedly only assumes very general principles like gauge invariance and PCAC. That, however, is not quite correct. VZ [2] stressed that an extra analyticity assumption has been made. They even checked the validity of this by calculating the rescattering diagram and found it to hold true for what was believed to be the largest correction to the Born terms leading to Eq.(1). The current commutator algebra manipulations used by de Baenst [1] were effectively hiding this subtlety. For a long time, the LEG was dormant since the existing data on threshold neutral pion production off protons were not very accurate but reassuringly close, $E_{0+}^{\text{exp}}(s_{\text{thr}}) = -1.8 \pm 0.6$ (in natural units which I will drop from now on). So one had to wait some time for a serious test of the LEG.

2 SHOCK, RELIEVE AND THE SPOILERS

The papers of the Saclay [4] and Mainz [5] groups both claimed a substantial deviation from the LEG by many standard deviations. As usual, theorists were (too) quick to invent ways to modify the LEG or claiming the discrepancy to be a measure of the light quark
masses. To avoid embarrassment, I will not give references here. It was also pointed out, by some experimenters and theorists, that there were some flaws in the interpretation of the data. In case of the Saclay results, the large rescattering contribution had been incorrectly subtracted. Reinstating that, one finds $-1.5 \pm 0.3$, where the error is a guess. In the Mainz case, the ambiguity in the two solutions could be resolved by imposing the constraint of the total cross section. That results in $E_{0+}(s_{\text{thr}}) = -2.0 \pm 0.2$ (see e.g. [6,7]), in satisfactory agreement with the LEG prediction, Eq.(1). Paradise seemed to be regained.

However, there was a problem. In 1991, Véronique Bernard, Jürg Gasser, Norbert Kaiser and I published a paper in which we showed that based on chiral perturbation theory (CHPT), which is the effective field theory of the Standard Model (SM) at low energies, the expression Eq.(1) is modified at order $\mu^2$. The correct low–energy theorem (LET) reads

$$E_{0+}(s_{\text{thr}}) = -\frac{eg_{\pi N}}{8\pi m} \mu \left(1 - \frac{1}{2} (3 + \kappa_\rho) + \frac{m}{4F_\pi} \right)^2 \mu + O(\mu^2),$$

(3)

The physics underlying this new term at next-to-leading order is well explained in Ref.[8], it simply amounts to a breakdown of the analyticity assumption made by VZ [2], see also the discussion in Refs.[9,10]. Without an explicit loop calculation, this effect at order $\mu^2$ could not have been found. What is distracting, however, is the fact that the coefficient of the second term is now so large that it cancels the leading one and thus even leads to a positive value for $E_{0+}(s_{\text{thr}})$. Consequently, the form of the LET as given in Eq.(3) can not be used to test the chiral dynamics of QCD. Also, what has clouded the discussion for a long time was the accidental closeness of the reexamined Mainz data with the LEG prediction, Eq.(1).

3 CONVERGENCE AT LAST?

CHPT has taught us that reactions involving S–wave interactions between pions or pions and nucleons often require higher order calculations to remove discrepancies between theory and experiment, like in the scalar form factor of the pion, the reaction $\gamma\gamma \to \pi^0\pi^0$, $K \to \pi^0\gamma\gamma$ and alike. It can therefore be expected that the lowest order one loop calculation leading to Eq.(3) is not sufficiently accurate. Thus, Bernard, Kaiser and I performed a higher order calculation for the electric dipole amplitude, i.e. the pertinent S–wave multipole [11]. At that order ($p^4$ in the chiral counting, where $p$ denotes a small momentum), one has to consider one loop graphs with insertions from the dimension two effective pion–nucleon Lagrangian and counter terms of the type

$$\mathcal{L}^\text{ct} = e a_1 \omega M_\pi + e a_2 M_\pi^3,$$

(4)

with $\omega$ the energy of the pion in the $\pi N$ cms. In the threshold region, the pion three–momentum is very small, $q_\pi \approx 0$ and thus $\omega \approx M_\pi$. Naturalness of the low–energy constants $a_{1,2}$ lets us assume that $a_1 \simeq a_2 = \mathcal{O}(1)$ so that effectively only the sum $a_1 + a_2$ counts in the threshold region. Fitting the Mainz data and letting $a_1$ and $a_2$ completely free, one finds $a_1 \simeq -a_2 \approx 50 \text{ GeV}^{-4}$ with $a_1 + a_2 = 6.7 \text{ GeV}^{-4}$ one order of magnitude smaller. On the other hand, if one restricts the values of these low–energy constants by resonance exchange (in this case $\Delta$, $\rho^0$ and $\omega$ excitation), one finds more natural numbers $a_1 \simeq a_2 \simeq 3 \text{ GeV}^{-4}$ with almost the same sum as in the free fit [11]. So there is a clear discrepancy which might be due to (a) some higher order effects or (b) some inconsistency in the data or (c) a combination of both. Resonance exchange saturation of the low–energy constants, which is
well established in the meson sector, leads us to believe that $E_{0^+}(s_{\text{thr}}) \simeq -1.2$ (with some large uncertainty which is hard to quantify in the absence of a two loop calculation). To resolve this puzzle, the experimenters come to our rescue. The new Mainz data of Fuchs et al. [12], shown here by Thomas Walcher in his talk, exhibit a clear reduction of the total cross section below the $\pi^+n$ threshold and show a good agreement with the CHPT calculation based on resonance exchange, see Fig.1. The new experimental value, also corroborated by the SAL measurements [13], knocks the LEG off by many standard deviations,

$$E_{0^+}^{\text{exp}}(s_{\text{thr}}) = -1.33 \pm 0.08 \quad (5)$$

While one might consider the agreement with the CHPT prediction of $-1.2$ accidental, the energy-dependence in the threshold region fits also with the CHPT result based on resonance exchange. In particular, the small value of $E_{0^+}$ at $\pi^+n$ threshold ($\simeq -0.4$) is a clear indication of chiral loops. A simple Born model with form factors can never explain such a trend. It is gratifying to finally have an experimental verification of the expected reduction of the electric dipole amplitude due to loop effects. Good news is that the LEG is out, the bad one is that the original hope of quantitatively testing chiral dynamics in the $S$-wave has been shattered. But that’s not yet the end of the story, fortunately.

![Fig. 1: Re $E_{0^+}$: CHPT prediction [11] versus data [12].](image)

### 4 P–WAVES ARE INTERESTING ? YES, YES & YES !

A quick look in the textbooks shows the P–wave dominance of the total cross section very quickly after threshold. This is, of course, the excitation of the $\Delta(1232)$. Therefore, it is generally believed that chiral dynamics is of no relevance for the three P–waves, $M_{1^+}$, $M_{1^-}$ and $E_{1^+}$ ($E/M$ for electric/magnetic, $l = 1$ for P–wave and $\pm$ for $j = l \pm 1/2$ the total angular momentum of the final $\pi N$ system). However, in the transition matrix element the combinations

$$P_1 = 3E_{1^+} - 2M_{1^+} - M_{1^-}, \quad P_2 = 3E_{1^+} - M_{1^+} + M_{1^-}, \quad P_3 = 2M_{1^+} + M_{1^-}, \quad (6)$$

appear naturally. One quickly realizes that $P_3$ is indeed completely dominated by $\Delta$ and vector meson contributions. Not so for $P_1$ and $P_2$ – a back on the envelope calculation shows
that $\Delta$-exchange drops out to leading order (using the static $\Delta$ well-known from the $\Delta$-hole model). I strongly encourage the sceptical reader to perform this little exercise. It is also worth to stress that already 20+x years ago, Balachandran and collaborators [14] noted this and made predictions for the slopes of $P_1, P_2$ at threshold. However, the method used in [14] only gave the leading term and was only applicable to the isoscalar amplitudes (their method, out-dated by now, could neither give the isovector amplitude nor any next-to-leading order correction). In Ref.[11] novel LETs were derived for the slopes of $P_1, P_2$. Consider first $P_1$,

$$P^{\pi^0p}_{1,\text{thr}} = \frac{eg_{\pi N}}{8\pi m^2} \left\{ 1 + \kappa_p + \mu \left[ -1 - \frac{\kappa_p}{2} + \frac{g_{\pi N}^2(10 - 3\pi)}{48\pi} \right] + \mathcal{O}(\mu^2) \right\},$$  

and similarly for $P_2$

$$P^{\pi^0p}_{2,\text{thr}} = \frac{eg_{\pi N}}{8\pi m^2} \left\{ -1 + \kappa_p + \mu \left[ 3 + \kappa_p - \frac{g_{\pi N}^2}{12\pi} \right] + \mathcal{O}(\mu^2) \right\}.$$  

We note that the $P$-waves scale with the pion momentum, and not with the product of the pion times the photon momentum as commonly assumed, see also Ref.[14]. Eqs.(8,9) are examples of quickly converging $\mu$ expansions,

$$P^{\pi^0p}_{1,\text{thr}} = 0.512 (1 - 0.062) \text{ GeV}^{-2} = 0.480 \text{ GeV}^{-2},$$  

and

$$P^{\pi^0p}_{2,\text{thr}} = -0.512 (1 - 0.0008) \text{ GeV}^{-2} = -0.512 \text{ GeV}^{-2}.$$  

Similar expressions for the neutron can be found in Ref.[11]. Only $P_1$ can be inferred in a model-independent manner from the unpolarized data. The new Mainz analysis [12] leads to

$$P^{\pi^0p}_{1,\text{thr}} = 0.47 \pm 0.01 \text{ GeV}^{-2},$$  

in stunning agreement with the LET prediction. One can also combine the predictions for $P_1$ and $P_2$ to disentangle the magnetic from the electric piece. That has been done by Jack Bergstrom [15] using data from coherent neutral pion photoproduction of $^{12}C$ together with the old Mainz data for $\gamma p \rightarrow \pi^0p$. He finds a good agreement for the magnetic LET $\sim M_{1+} - M_{1-}$ but a sizeable deviation for the electric one ($\sim E_{1+}$). Note that for this latter quantity the large leading term $\sim (1 + \kappa_p)$ cancels out and one is considering the small difference of two small numbers. A direct measurement of the photon asymmetry $\Sigma(\theta)$ underway at MAMI will help to settle this issue.

5 SOME REMARKS ON THE NEUTRON

In Ref.[11] the electric dipole amplitude for the reaction $\gamma n \rightarrow \pi^0n$ was also calculated, using the low-energy constants determined from resonance exchange. The updated version for this quantity based on the new data from Mainz [12] to fix the counter term coefficients is shown in Fig.2. The stunning result is that it is quite a bit larger in magnitude than the corresponding proton one. This result seems counterintuitive if one uses the classical dipole argument to estimate the relative strength of the electric dipole amplitude in charged and
neutral pion production. Quantum physics, however, is not always adhering to such notions as exemplified here. It would therefore be very important to measure this quantity. In the absence of pure neutron targets, this is a difficult job. For example, in the deuteron the large charge–exchange amplitude has to be accounted for very precisely before one could get at the elementary \( n\pi^0 \) amplitude [16], compare also the CHPT calculation for \( \pi^0 \) production off the deuteron by Beane et al. [17]. This is certainly a third generation experiment. However, it would be very important to have independent information on all photoproduction channels, \( \gamma p \rightarrow \pi^+ n, \gamma n \rightarrow \pi^- p, \gamma p \rightarrow \pi^0 p \) and \( \gamma n \rightarrow \pi^0 n \), since that would ultimately lead to a test of isospin symmetry. Needless to say, a more systematic treatment of the pion–nucleon–photon system including virtual photon loops and the quark mass difference \( m_u - m_d \) has to be done before such data could be interpreted correctly. This is a challenge to both the experimenters and the theorists.

6 NEUTRAL PION ELECTROPRODUCTION

A rapidly developing field is the extension to electroproduction. This is motivated by the facts that (a) virtual photons can also couple longitudinally to the nucleon spin and (b) that all multipoles depend on the energy and the momentum transfer. Therefore, much richer information can be obtained in comparison to the case of real photons. First measurements at \( k^2 = -0.1 \) GeV\(^2\) (where \( k^2 \) is the photon virtuality) performed at NIKHEF were reported in Refs.[18,19]. The S–wave cross section extracted in [18] can be understood within the framework of relativistic CHPT [20]. However, in that case one has no consistent power counting and is thus limited in accuracy. In particular, the S–wave multipoles \( E_{0+} \) and \( L_{0+} \) have to be calculated to higher orders. Then, two new counter terms appear (at order \( p^4 \)) which can e.g. be fixed from a best fit to the differential cross section data of Ref.[19]. The preliminary result of such a fit is shown in Fig.3. For the resonance fit, i.e. estimating these two constants from \( \Delta \) and vector meson excitation, there is one new \( N\Delta \gamma \) coupling parametrized by a coupling constant \( g_3 \) and an off–shell parameter \( X' \) [21]. One notices that the free (denoted by the dash–dotted line in Fig.3) and the resonance fit (solid line) are roughly consistent (but not exactly). We remark that in Ref.[19] the electroproduction P–wave \( L \)–\( T \)–\( E \)–\( P \) presented in Ref.[22] (these are the generalizations of Eqs.(7,8) for virtual
photons) were used to extract the S–wave multipoles. Our preliminary analysis seems to lead to somewhat smaller values for $E_{0+}(\Delta W)$ (with $\Delta W$ the energy above the pion–nucleon threshold), somewhere between $+2$ and $+2.5$ for $\Delta W = 2 \ldots 15$ MeV. It is worth to stress that the electric dipole amplitude has changed sign as compared to the photoproduction case. The longitudinal multipole $L_{0+}$ stays negative from the photon point up to $k^2 = -0.1$ GeV$^2$. More precise data have been taken at MAMI and were shown by Thomas Walcher here [23]. The preliminary analysis of these data (also at $k^2 = -0.1$ GeV$^2$) seems to indicate an L/T ratio quite consistent with Born terms but not with the relativistic CHPT result. However, what one really should compare to are the improved $p^4$ calculations which will soon be available (with the new low–energy constants fixed from the NIKHEF data, cf. Fig.3). Clearly, the real test of the CHPT prediction will be the comparison to the MAMI data taken at lower $k^2$. These data have not yet been analyzed. Of particular interest is the value of $k^2$ where the electric dipole amplitude changes sign. There is much more to come in terms of quantitative comparisons between theory and experiment.

7 SUMMARY AND OUTLOOK

For the case of neutral pion photo/electroproduction, let me summarize the recent developments as follows:

- In the S–wave, the effect of chiral loops clearly shows up on a qualitative level. For a precise test of chiral dynmaics, one would need to perform much more accurate calculations presumably by a synopsis with dispersion theory. This remains to be
done.

- The real quantitative tests of chiral dynamics are related to the $P$-waves. This is an important new result which comes quite unexpectedly. For the large $P$-wave multipoles, rather accurate calculations exist and improvement is needed for the small multipoles like $E_{1+}$. On the experimental side, polarization experiments will help to disentangle the small from the large multipoles due to much increased sensitivities. Such experiments are either planned or underway.

- In $\pi^0$ electroproduction, accurate data are just becoming available and the same holds true for a more refined theoretical description. In the very near future, there will be a huge body of data to be compared with theoretical expectations. In particular, measurements at smaller photon virtuality, say at $k^2 = -0.05$ GeV$^2$, are urgently called for.

Other topics of interest I could not address in detail are the photo- and electroproduction of charged pions, to find out the deviations from the leading Kroll–Ruderman LET and to pin down the axial form factor $G_A(k^2)$ at low momentum transfer. Furthermore, precise kaon and eta production data have been taken and partly been published. The extension to the three–flavor sector is not trivial due to the (a) closeness of some resonances in certain channels and (b) the more sizeable symmetry breaking effects due to the larger $K$ and $\eta$ masses. With respect to the second problem, some progress has been made recently in a complete $p^4$ calculation of the baryon octet masses and the pion–nucleon $\sigma$–term, see Ref.[24]. Furthermore, there now seems to be a consistent method of implementing the $\Delta$ in the effective field theory as discussed by Joachim Kambor [25]. This method can then be used to further extend the range of applicability of CHPT and to calculate e.g. the much discussed $E2/M1$ ratio measured at the resonance position.

Finally, to appreciate the rapid progress made in this field I recommend to read the summary which Berthold Schoch and I wrote in the summer of last year [26] – it is quite amazing to see how much theory and experiment have improved and the resulting shift of emphasis is also noteworthy.

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