Selected Topics in Near Threshold Pion Photoproduction and Compton Scattering off Nucleons*

Thomas R. Hemmert
Theoretische Physik T39, Physik Department, TU München

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Abstract

Some open topics in the field of low energy photon-nucleon interactions are discussed—which in my opinion are of interest both for obtaining new information on nucleon structure and for precision tests of our theoretical understanding of chiral dynamics. In particular, I discuss p-wave multipoles in charged pion photoproduction off protons as well as the role of spin-dependent effects in (unpolarized) Compton scattering off nucleons. There the concept of dynamical spin polarizabilities is found to be essential for the understanding of differential Compton cross sections above 120 MeV cms photon energy.

1 Introduction/Motivation

Near threshold pion photoproduction as well as low energy Compton scattering off single nucleons are certainly well established electro-nuclear processes known already for several decades. The continuing interest in these reactions at the beginning of the 21st century—from my personal opinion—is twofold. On the one hand one wants to be sure to understand these fundamental, “simple” interactions involving single nucleons very precisely before one can draw any conclusions regarding the role of few-body forces and/or (nuclear) many body effects when studying scattering processes in more complicated systems like nuclei or nuclear ensembles like stars. The other aspect has to do with our understanding of the nature of the strong interaction. At this point in time QCD is the established theory for strong interactions. However, its real world applications to issues typically addressed in nuclear physics are rather limited, owing

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to its confinement properties at low energies. In order to develop a systematic theoretical description of the strong interaction in this crucial low energy domain, already in the late 1970s pioneering studies were begun to map QCD onto a field theory written in terms of its Goldstone Boson degrees of freedom. Such an effective field theoretic framework—usually in the literature called chiral perturbation theory (ChPT)—was extended from the pure Goldstone Boson sector to more complex scenarios involving one and more nucleons/baryons in the late 1980s, respectively early 1990s. Nowadays, at the beginning of the 21st century, an impressive variety of theoretical tools ranging from non-relativistic perturbation theory to non-perturbative resummation methods are at the chiral practitioners’ disposal, covering physics topics from ultra low energy hadronic atoms to nuclear matter systems above saturation density. At the core of all these applications is the general chiral effective Lagrangian of QCD, which connects all these seemingly disparate physical scenarios via its chiral field tensors and coupling constants/counterterms. Coming back to the issues discussed at this workshop in Lund, I went through this introductory detour to emphasize that a high quality description in terms of chiral effective field theory for such elementary reactions like pion photoproduction or nucleon Compton scattering indeed has far-ranging consequences for a much wider spectrum of physical processes.\textsuperscript{2} Admittedly, at this stage, chiral effective field theory—despite its many stunning successes—is certainly far from constituting a closed chapter in our understanding of the strong interaction in its really interesting domain.\textsuperscript{3} However, the prospect of unifying large sections in the wide field of strong interaction studies/nuclear physics into one systematic theoretical framework/lingua franca constitutes a big attraction, that undoubtedly will lead to further progress in theoretical understanding and technique. For this program to proceed it is \textit{essential} that high precision low energy experiments like pion photoproduction or nucleon Compton scattering continue to be performed at accelerator laboratories like MAX-LAB. Only when the energy, momentum, flavor and multipole dependence of the elementary reactions are known to high precision chiral effective field theory can be further developed and will thus improve its predictive

\textsuperscript{1}I prefer the term “chiral effective field theory” (ChEFT) instead of ChPT to take into account the fact that during the past decade many non-perturbative techniques have been applied to studies in ChEFT. The unifying principles behind all these studies should be a general effective Lagrangian framework consistent with the spontaneous + explicitly broken chiral symmetry of QCD, written in terms of Goldstone Boson degrees of freedom coupled to arbitrary external sources as well as matter fields. In addition, a power-counting scheme needs to be specified, which enables the theorist to select a finite number of contributing vertices from the infinitely large most general effective chiral Lagrangian as well as allows a systematic calculation of higher order corrections. Contrary to popular opinion, a “unique” chiral power counting does not exist—at least not for systems with more than 2 active flavors or more than one type of external matter field. The label “ChPT” attached on a particular calculation therefore always needs to be accompanied by the specification of the power-counting employed.

\textsuperscript{2}I consider this feature to be the main difference between chiral effective field theory and (chiral) modeling for these very processes.

\textsuperscript{3}For example, issues of different flavor and power-counting schemes, higher order corrections, relativistic unitarization as well as new regularization schemes certainly need to be further developed
power/theoretical soundness in physically interesting scenarios where high precision data are much harder or even impossible to come by. In the following I will focus on two low energy electromagnetic interactions which are both interesting in their own right and at the same time will also help to further constrain chiral effective field theory—(charged) pion photoproduction as well as the role of spin-dependent structures in nucleon Compton scattering.

2 Near Threshold Pion Photoproduction

2.1 Multipole Truncation

The general matrix element pertaining to pion photoproduction off a nucleon contains 4 structure functions $F_i(E_\pi, z)$. For a photon with four-momentum $k^\mu = (\omega, \hat{q})$ and polarization vector $e^\mu = (\epsilon_0 = 0, \hat{e})$ producing a pion with four-momentum $q^\mu = (E_\pi, \hat{q})$ in the cms frame it reads

$$M_{\gamma N \rightarrow N\pi} = \frac{M_N}{4\pi \sqrt{s}} T \cdot \epsilon$$

$$= \chi^\dagger \{ F_1(E_\pi, z) i \hat{\sigma} \cdot \hat{e} + F_2(E_\pi, z) \hat{\sigma} \cdot \hat{q} \cdot (\hat{k} \times \hat{e}) + F_3(E_\pi, z) i \hat{\sigma} \cdot \hat{k} \cdot \hat{e} \cdot \hat{q} + F_4(E_\pi, z) i \hat{\sigma} \cdot \hat{q} \} \chi,$$

with $z = \cos \theta_{\text{cms}} = \hat{q} \cdot \hat{k}$. $\sigma^i$ denotes the Pauli matrix in spin space between the two-component spinors $\chi/\chi^\dagger$ of the incoming/outgoing nucleon.

Near threshold the expression given above can be simplified by performing a multipole expansion and truncating the resulting amplitude at the p-wave level. Performing the appropriate projections one finds

$$M^{l=1}_{\gamma N \rightarrow N\pi} = \chi^\dagger \{ E_0+(E_\pi) i \hat{\sigma} \cdot \hat{e} + P_1(E_\pi) i \hat{\sigma} \cdot \hat{k} \cdot \hat{e} \cdot \hat{q} + P_2(E_\pi) i \hat{\sigma} \cdot \hat{q} + P_3(E_\pi) \hat{\epsilon} \cdot (\hat{q} \times \hat{k}) \} \chi$$

(2)

Usually the predictions of chiral effective field theory calculations for single pion photoproduction are then discussed at the level of the contributing s-wave multipole $E_{0+}(E_\pi)$, as well the 3 p-wave multipoles $P_i(E_\pi)$, $i = 1, 2, 3$. One of the nice features of the p-wave truncation of Eq.(2) is the resulting simple form for the unpolarized differential cross section. To $l=1$ one obtains

$$\frac{d\sigma}{d\Omega} \bigg|_{l=1} = \frac{|\hat{q}|}{|k|} \left[ A(E_\pi) + B(E_\pi) z + C(E_\pi) z^2 \right],$$

(3)

Historically the p-wave multipoles have been denoted by $E_{1+}, M_{1+}, M_{1-}$. They are connected to the structures $P_i$ introduced in Eq.(2) via

$$P_1(E_\pi) = 3 E_{1+}(E_\pi) + M_{1+}(E_\pi) - M_{1-}(E_\pi)$$
$$P_2(E_\pi) = 3 E_{1+}(E_\pi) - M_{1+}(E_\pi) + M_{1-}(E_\pi)$$
$$P_3(E_\pi) = 2 M_{1+}(E_\pi) + M_{1-}(E_\pi)$$
with

\begin{align*}
A(E_\pi) &= |E_{0+}|^2 + \frac{1}{2} |P_2|^2 + \frac{1}{2} |P_3|^2 \\
B(E_\pi) &= 2 \text{Re} (E_{0+} P_1^*) \\
C(E_\pi) &= |P_1|^2 - \frac{1}{2} |P_2|^2 - \frac{1}{2} |P_3|^2.
\end{align*}

By fitting the three energy-dependent parameters \( A, B, C \) to the differential cross section one can therefore determine three bi-linear combinations of the four (complex) low energy multipoles \( E_{0+}, P_1, P_2, P_3 \). I will discuss the predictions of chiral effective field theory for these quantities in the next two sections.

Finally, it is noted that important additional information pertaining to the dynamics in the p-wave multipoles can be obtained by utilizing linearly polarized photons measuring the photon asymmetry \( \alpha_\gamma \). However, I will not discuss this interesting possibility here as the plans for polarized photons at MAX-LAB unfortunately will not cover the required energy range in the near future \( \beta \).

2.2 Neutral Pion Photoproduction

Within chiral effective field theory neutral pion photoproduction near threshold is probably the best studied low energy electromagnetic production process on a single nucleon. After all, it was in this reaction where it was first shown that ChPT can also be utilized in the baryon sector to calculate quark-mass dependent corrections beyond the venerable results of current algebra in a systematic approach. On the theoretical side, both the s- and the p-wave multipoles discussed in the previous section are now known to next-to-leading one-loop order (i.e. \( O(p^4) \)) within the SU(2) heavy baryon approach \( \theta \). Further studies utilizing relativistic frameworks and/or the inclusion of explicit Delta degrees of freedom are underway, pointing again to the importance of this process both as a benchmark for further development of theoretical tools as well as to its importance as a basic building block in theoretical studies of electromagnetic reactions in light nuclei. On the experimental side good data in the threshold region now exist both for differential cross sections as well as for the photon asymmetry, leading to an experimental determination of all 4 s- and p-wave multipoles rather close (or extrapolated) to threshold \( \delta \). The agreement between theory and experiment is impressive \( \varepsilon \).

What remains to be done in the neutral pion sector? Aside from interesting ideas to study the cusp behavior in detail \( \zeta \), I think it would be interesting to have direct experimental information on the energy dependence of the \( E_{0+}, P_i \) multipoles or of the structure functions \( F_i \). We note that (in isospin notation) in neutral pion photoproduction off protons one is sensitive to the linear structure function combination

\[ F_{1,2,3,4}^{\gamma p\rightarrow p\pi^0} = \left[ F_{1,2,3,4}^{(+)i} + F_{1,2,3,4}^{(0i)} \right], \quad i = 1, 2, 3, 4, \]

whereas for the (hypothetical) production process off a (free) neutron target one
finds
\[ F_i^{\gamma n \rightarrow n\pi^0} = \left[ F_i^{(+)} - F_i^{(0)} \right], \quad i = 1, 2, 3, 4. \] (6)

From my point of view, the really interesting part with respect to nucleon structure is therefore encoded in the structure function \( F_i^{(0)} \) (or its \( E_0^{(0)} \), \( P_i^{(0)} \) components), as it is this piece that dominates the difference between proton and neutron structure at low energies (see also the discussion in section 3). While theoretical analyses of neutral pion photoproduction off the deuteron with the goal to gain insight into the production off the neutron are still struggling with the proper separation of deuteron structure effects, another way to improve our understanding of the makeup of the neutron could be provided by precision studies of the energy dependence of the structure functions in neutral pion photoproduction off protons (Eq.(5)). This suggestion is based on the fact that the \((+)-\) and the \((0)-\) components actually have quite a different energy dependence as well as different resonance components associated with them \( \bar{3} \). Given sufficiently accurate data from the proton over a range of energies, one might be able to constrain the small \( F_i^{(0)} \) contributions in this way and via Eq.(6) thus also learn more about neutron structure.

### 2.3 Charged Pion Photoproduction

In the case of charged pion photoproduction off hydrogen the four physical structure functions \( F_i(E_\pi, z) \) for the process \( \gamma p \rightarrow n\pi^+ \) can be obtained from the isospin amplitudes via
\[ F_i^{\gamma p \rightarrow n\pi^+} = \sqrt{2} \left[ F_i^{(0)} + F_i^{(-)} \right], \quad i = 1, 2, 3, 4 \]

Given that here the \((-)-\) components contribute to the process instead of the \((+)-\) components of the previous section, one should not be surprised that—in addition to a different Born term structure—also the one-loop contributions as well as the role of counter terms/short distant physics are quite different in charged pion photoproduction compared to the neutral case. As far as sound predictions based on chiral effective field theory are concerned, charged pion photoproduction (as far as its non-trivial, non-Born contributions are concerned) is harder to deal with than the neutral pion analogue. Already at the leading-one-loop (i.e. \( O(p^3) \)) level in heavy baryon ChPT one has to deal with 5 different counterterm contributions \( \bar{3} \). However, mainly based on data of the inverse reaction \( \pi^- p \rightarrow \gamma n \) measured at TRIUMF, predictions for the 4 s- and p-wave multipoles at threshold now exist, which overall agree reasonably well with existing dispersion relation analyses for these multipoles \( \bar{3} \), but also show interesting discrepancies by as much as 30\%. Interestingly, these p-wave multipoles—to my knowledge—have not yet been directly tested by experiment. Certainly the s-wave multipole \( E_{0+} \) at threshold has received repeated attention (it is dominated by the Kroll-Ruderman term) and also is the topic of a letter-of-intent at this workshop \( \bar{3} \). However, in my opinion a study of the p-wave multipoles—be it only very close threshold or maybe better even with
their energy-dependence—is much more interesting. A recent analysis shows that the relative importance of $O(p^3)$ contributions—i.e. the interplay between counterterms and chiral loops—in the case of charged pion photoproduction is larger in the p-wave multipoles than in $E_{0+}$. I may also add—on a very speculative note—that if an experiment really found discrepancies relative to the currently accepted numbers (e.g. see [7]) for the s- and p-wave multipoles of charged pion photoproduction (respectively their (0)- or (−)-components) in the near threshold region, such a find could also have important consequences for nucleon (neutron?) structure quantities like the GDH-integral or the forward spin-polarizability, which are typically evaluated via sum rules with the low energy components carrying a large weight. Of course new experiments on charged pion photoproduction near threshold would also provide important constraints for chiral effective field theory, precisely because of the delicate interplay between short and long-distance physics in this reaction. I would therefore like to ask my colleagues from the experimental side to give this reaction some thought as to whether a good (even unpolarized) experiment can be done there.

3 Low Energy Compton Scattering off Nucleons

Beautiful data on Compton scattering off protons exist nowadays over a wide range of energies and angles [9]. Unfortunately—for reasons that I have never understood—most of the theoretical discussion in Compton scattering focuses on just 2 numbers: The (static) electric and magnetic dipole polarizabilities $\alpha_E, \beta_M$. These static polarizabilities are defined as the first structure dependent terms in a low energy expansion in photon energy $\omega$ of the Compton cross section. However, this low energy expansion itself (typically truncated at $\omega^2$) is only valid up to ca. 70 MeV photon energy, whereas most Compton data available hardly start at such low energies—constituting a rather compromising mismatch between a theoretical concept and experimental reality. In practice one has dealt with this problem by utilizing the machinery of dispersion relations. Using as input Compton data above pion threshold as well as available information on single and double pion photoproduction, the dispersion machinery has been the tool of choice to extrapolate Compton data from the Delta region and beyond down to $\omega = 0$, where the static polarizabilities are properly defined. Recently, it was pointed out [10] that this energy dependence in its various multipole channels used for such an extrapolation (but usually “hidden” in the dispersion machinery) is interesting both in its own right and from the point of view of chiral dynamics. It will not come as a surprise to professional physicists that the task “to get 2 numbers correct” can be achieved within a large variety of nucleon structure models, as such providing no definitive insight into the physical mechanisms at work in nucleon polarizabilities. In Ref. [11] we therefore proposed the concept of “dynamical polarizabilities”, based upon the well-known multipole expansion for Compton scattering. These dynamical polarizabilities are functions of the photon energy $\omega$ and, in the limit $\omega \to 0$, reproduce the usual (static) polarizabilities. The energy dependence of these
polarizabilities is a measure of the dispersion effects in that particular multipole channel, i.e. one expects to see pertinent resonance features, relaxation phenomena or cusps associated with the onset of inelasticities. For more details on the nature of dispersion effects I refer to standard textbooks on classical electrodynamics, the concepts taught there can all be carried over to a discussion of the electromagnetic structure of the nucleon. Obviously, one can also utilize dispersion theory to analyze the energy dependence of dynamical polarizabilities—after all it had this very information built in from the start. In Fig. 1 I show a comparison between a dispersion analysis (solid curves), leading-one loop heavy baryon ChPT (short dashed curves), as well as leading-one-loop SSE (long-dashed curves) for the dynamical isoscalar electric/magnetic dipole and quadrupole polarizabilities of the nucleon. In the electric dipole polarizability all 3 approaches agree remarkably well, displaying an enormous cusp at the pion production threshold. In the magnetic polarizability the SSE approach and the dispersion analysis both predict a rapidly increasing paramagnetic response of the nucleon when the photon energy goes up. This feature is due to the strong $\gamma N \Delta$ M1 excitation, which in heavy baryon ChPT only gradually gets built up via higher order terms. The dynamical electric quadrupole polarizability $\alpha_E$ also shows good agreement between the dispersion analysis and SSE, while for the dynamical magnetic quadrupole polarizability $\beta_M$ all 3 frameworks differ. From the structures displayed in Fig. 1 it should be clear, that the very energy dependence of these dynamical polarizabilities is largely due to chiral dynamics! With the concept of dynamical polarizabilities any theoretical calculation of nucleon structure can now be put to a much more stringent test. It’s not enough anymore to reproduce roughly the right size for the static values of the polarizabilities, one can now also ask the question whether the mechanisms supposedly responsible for the electromagnetic stiffness of the nucleon also reproduce correctly the associated energy dependence/dispersion effects.

How do we know what the correct energy dependence of the dynamical polarizabilities looks like? Amazingly, as shown in [11], up to cms photon energies of 170 MeV a truncation of the multipole expansion for Compton scattering at $l=1$ is entirely consistent with all existing (unpolarized) Compton data on the proton! Remember, the dynamical polarizabilities are defined as functions of energy. This finding therefore offers the possibility to choose one particular cms photon energy (e.g. $\omega_0 = 150$ MeV), replace the theoretical predictions at this particular energy by 6 free parameters and try to determine these 6 parameters.
from the angular dependence measured at that energy. In such a fashion one could attempt to experimentally map out the dynamical dipole polarizabilities at different points $\omega_0$ and in this way test what we as theorists are dreaming up. Note that we have 6 structures to deal with because at $l=1$, in addition to the dynamical electric and magnetic dipole polarizabilities $\alpha_{E1}(\omega_0)$, $\beta_{M1}(\omega_0)$, one also has to take into account the 4 dynamical dipole spin-polarizabilities $\gamma_{M11}(\omega_0)$, $\gamma_{E1E1}(\omega_0)$, $\gamma_{M1E2}(\omega_0)$, $\gamma_{E1M2}(\omega_0)$. A comparison between predictions from dispersion analysis, leading-one-loop heavy baryon ChPT and leading-one-loop SSE for these 4 elusive nucleon spin structure components is shown in Fig.2 [11]. We note that for the purely electric and the purely magnetic dipole spin-polarizabilities SSE and the dispersion analysis are again in good agreement, while chiral effective field theory and the dispersion analysis systematically differ for the mixed dipole spin-polarizabilities. At the moment it is not clear whether this deviation is entirely due to missing higher order terms in the chiral effective field theories—experimental input regarding these essentially unknown nucleon structure quantities would therefore be extremely interesting.

Finally, I want to close this presentation with a brief discussion of Fig.3 [15]. The dash-dotted curve shows the theoretical prediction for the Compton differential cross-sections at $l=0$, i.e. all polarizabilities are set to zero, only the Born terms are kept. The interesting feature in this plot can be seen from the difference between the dotted and the dashed curves. The dashed curve constitutes the full $l=1$ leading-one-loop SSE prediction (which, as already mentioned, though being truncated at $l=1$ provides an excellent description of the data), whereas the dotted curve also comes from $l=1$ leading-one-loop SSE, but with the four dynamical dipole spin-polarizabilities discussed above by hand forced to be zero. We therefore conclude that even in an unpolarized Compton experiment, assuming that one knows the dynamical spin-independent dipole polarizabilities $\alpha_{E1}(\omega)$, $\beta_{M1}(\omega)$ reasonably well, there seems to be interesting sensitivity to the dynamical dipole spin polarizabilities in the photon energy region above 120 MeV (cms). Clearly, a detailed analysis together with experts from the experimental side has to be performed to properly evaluate this exciting possibility.

In summary, I want to emphasize that in past few decades of Compton scattering off the proton we have heard a lot about electric and magnetic polarization of hadrons; complete separation of all 6 dipole structures presumably can only be obtained if one also resorts to polarized Compton scattering. Studies in this direction are under way [13].

8One can show [11] that in the limit $\omega \rightarrow 0$ one is able reproduce the static dipole spin polarizabilities obtained in the leading-one-loop SSE calculation of Ref.[14].

9Certainly in $\gamma_{M1E2}$ an excitation/deexcitation of the Delta resonance via a combination of $M1$ and $E2$ transitions is not yet taken into account at leading-one-loop order in either of the 2 chiral effective field theories considered here, as the $\gamma_{N\Delta} E2$ transition only comes in at higher orders in the chiral expansion.

10Note that the difference between the 2 curves in Fig.4 is not due to large effects associated with the pion pole, as this structure is subsumed in our Born terms. (This is also the reason why the $l=0$ truncation—i.e. all polarizabilities set to zero—provides such a decent description of the data in the backward direction.)
larizabilities of the nucleon. However, the spin polarizabilities are still largely uncharted territory and present a real frontier for the field of nucleon structure studied with electromagnetic probes. I hope that the field takes up the challenge and attempts to measure these structures, even if this requires polarized Compton experiments. I am also optimistic that some of the puzzling results in Compton scattering off the deuteron will appear in a new light, once the here present leading-one-loop SSE framework is combined with a chiral potential ansatz. Work along these lines is beginning this fall.

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Figure 1: Comparison between leading-one-loop SSE (long dashed curve), leading-one-loop heavy baryon ChPT (short dashed curve) and dispersion theory (full curve) for the isoscalar dynamical dipole and quadrupole polarizabilities of the nucleon. [1]
Figure 2: Comparison between leading-one-loop SSE (long dashed curve), leading-one-loop heavy baryon ChPT (short dashed curve) and dispersion theory (full curve) for the isoscalar dynamical dipole spin-polarizabilities of the nucleon. [1]
Figure 3: Dash-dotted curve: \( l=0 \) (Born term) result for the Compton cross section. The complete \( l=1 \) leading-one-loop SSE prediction is shown as the dashed curve, whereas in the dotted curve all spin-polarizabilities have been set to zero (by hand). Surprisingly, there seems to exist good sensitivity to the (dynamical) spin-polarizabilities for photon energies above 120 MeV (c.m.).