PION PHOTOPRODUCTION IN A GAUGE-IN Variant CHIRAL UNITARY FRAMEWORK

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We investigate pion photoproduction off the proton in a manifestly gauge-invariant chiral unitary extension of chiral perturbation theory. In a first step, we consider meson-baryon scattering taking into account all next-to-leading order contact interactions. The resulting low-energy constants are determined by a fit to s-wave pion-nucleon scattering and the low-energy data for the reaction \( \pi^- p \to \eta n \). Having determined the low-energy constants, we then analyse the data on the s-wave multipole amplitudes \( E_{0+} \) of pion and eta photoproduction. These are parameter-free predictions, as the two new low-energy constants are determined by the neutron and proton magnetic moments.

Keywords: Meson photoproduction; chiral unitary approach; meson-baryon scattering.

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\footnote{Speaker at the conference.
1. Introduction and Summary

Pseudoscalar meson photoproduction off protons is one of the premier tools to unravel the spectrum and properties of baryons made of the light up, down and strange quarks, as witnessed e.g. by the dedicated baryon resonance programs at ELSA (Bonn) and CEBAF (Jefferson Laboratory). Some of the low-lying resonances like the Roper $N^*(1440)$, the $S_{11}(1535)$ or the $\Lambda(1405)$ exhibit features that can not easily be reconciled with a simple constituent quark model picture. Therefore, it was speculated since long that some of these peculiar states and their properties can be explained if one assumes that they are generated through strong coupled-channel dynamics. Arguably the best tool to address such a dynamical generation of resonances is unitarized chiral perturbation theory.\(^1,2\)

Our investigation is divided into two steps. First, for the meson-baryon scattering we consider the Bethe-Salpeter equation (BSE) with a kernel, consisting of all local terms of the leading (LO) and next-to-leading (NLO) chiral order. Moreover, we consider all six coupled-channels, i.e. \{\(\pi^0p, \pi^+n, \eta p, K^+\Lambda, K^+\Sigma^0, K^0\Sigma^+\)\} that are relevant for pion photoproduction. The solution of this problem was formulated without using the on-shell approximation\(^3\) that is common in most works on related subjects. To pin down the parameters of the approach we fit the elastic \(\pi N\) scattering in both s-waves as well as the recent data\(^4\) on \(\pi^-p \to \eta n\).

In the second step we utilize a gauge-invariant chiral unitary coupled-channel approach as it was already applied to kaon\(^5\) and eta\(^6\) photoproduction based on the leading order chiral effective Lagrangian. We extend this approach including all local terms of the next-to-leading chiral order applying it to s-wave photoproduction of pions, where a large data basis already exists. Starting from the already fitted hadronic amplitude, only two new parameters appear in the photoproduction amplitude, which can be determined from the nucleon magnetic moments and thus parameter-free predictions emerge. We find a good description of the s-wave multipole \(E_{0+}\) for pion photoproduction in the \(S_{11}\)-wave and also for \(\eta\) photoproduction.

2. Framework and Results

**Hadronic sector** We denote the overall four-momentum as well as the in- and outgoing meson momenta by \(p\), \(q_1\) and \(q_2\), respectively. For the meson-baryon scattering amplitude \(T(q_2, q_1; p)\) and potential \(V(q_2, q_1; p)\) the integral equation to solve reads in \(d\) dimensions

\[
T(q_2, q_1; p) = V(q_2, q_1; p) + \int \frac{d^d l}{(2\pi)^d} V(q_2, l; p) S(p - l) \Delta(l) T(l, q_1; p),
\]

where \(S\) and \(\Delta\) represent the baryon (of mass \(m\)) and the meson (of mass \(M\)) propagator, respectively, and are given by \(iS(p) = i/(p - m + i\epsilon)\) and \(i\Delta(k) = i/(k^2 - M^2 + i\epsilon)\). As described in an earlier publication\(^3\) we utilize dimensional regularization to treat the divergent loop integrals, where the purely baryonic integrals are set to zero from the beginning, while only an energy-independent constant
is subtracted from the fundamental meson-baryon loop integral. The kernel of the above equation is derived from the chiral Lagrangian of the first and second chiral order.\textsuperscript{7,8} The solution of this problem is taken from the publication,\textsuperscript{9} to which we refer the reader for further details.

All 17 free parameters of this approach (low-energy and subtraction constants) are determined from a fit to the $S_{11}$ and $S_{31}$ $\pi N$ partial waves for energies in the range $(m_p + M_{\pi}) < W_{\text{c.m.s.}} < 1.56$ GeV from the analysis (W108) by the SAID collaboration.\textsuperscript{10} Additionally we consider the quite recent but already very established results on $\pi^- p \rightarrow \eta n$ differential cross sections measured by Prakhov et al.\textsuperscript{4}

The results of the fit to the data on hadronic scattering are presented in Fig. 1. The parameters of the model are all of the natural size, see our original publication\textsuperscript{9} for the precise numerical values. For $\pi N$ scattering, we obtain a very nice agreement with the partial wave analysis by the SAID collaboration including the structure stemming from the $N^*(1535)$. Additionally, beyond the fitting region we observe a second structure, which can successfully be identified with the second $S_1$ pion-nucleon resonance. At the same time the pion induced eta production is reproduced rather well, see the right panel of Fig. 1, where, for compactness, the result for four of seven fitted pion lab momenta is presented. For more details, precise numerical values and discussion we refer the reader to our original publication.\textsuperscript{9}

**Photoproduction** Our main goal is to see how the resonances reproduced in the hadronic sector manifest themselves in the photoproduction amplitude which, additionally, is imposed to be gauge invariant. While there are different ways to construct such an amplitude, we follow the most natural one.\textsuperscript{11–14} There in the first step the dressed baryon to meson-baryon vertex is constructed from the unitarized meson-baryon scattering amplitude. Then, a photon is coupled to every possible place of this amplitude. Such a diagrammatic approach is gauge-invariant and also obeys the

![Fig. 1. Best fit of our approach to the $\pi N$ s-waves (left) as well as to $\pi^- p \rightarrow \eta n$ differential cross sections (right). On the left, the bold vertical line represents the energy region, up to which the fit has been done. On the right, a fit at only four energies is presented. The error bands in both figures reflect the uncertainty of the fitting parameters stemming from the experimental uncertainty. For more details see the main part of this manuscript.](image-url)
unitarity in the subspace of meson-baryon states automatically. For consistency, the strength of photon coupling is calculated form the leading and next-to-leading order chiral Lagrangian.

Such a photoproduction amplitude contains, besides the already fitted parameters, only two new unknowns, namely the low-energy constants $b_{12}$ and $b_{13}$ from the NLO chiral Lagrangian.\cite{7,8} Fortunately, we can fix their values to those determined from the analysis of the magnetic moment of the nucleon.\cite{15} The prediction of our model for $E_{0+}$ of pion photoproduction is presented in Fig. 2. In the energy region where the hadronic fit was performed ($W_{\text{cms}} < 1.56$ GeV) we observe a very nice agreement with the outcome of more phenomenological approaches by SAID\cite{16} and MAID\cite{17} groups. For higher energies the prediction is less reliable. However, as discussed in our original publication\cite{9} the agreement can be improved if the axial as well as the ‘magnetic’, i.e. $b_{12/13}$, LECs are used as free parameters.

The prediction of our approach for $E_{0+}$ of eta photoproduction is presented in Fig. 3, where it is compared with fits by the ETAMAID\cite{18} and Bonn-Gatchina\cite{19} groups. Seemingly there is a large qualitative agreement between our prediction and the phenomenological analysis by the ETAMAID and Bonn-Gatchina group. On a quantitative level we observe that the real part of the $E_{0+}$ is suppressed compared to the outcome of the phenomenological analysis. We wish to emphasize once again that the axial and ‘magnetic’ LECs are taken from a tree level calculation only. Using these as free parameters, a nice agreement with the results of ETAMAID and Bonn-Gatchina group can be achieved. This, however, is not the original purpose of this work, namely a parameter-free prediction of the photoproduction after fixing the hadronic scattering.

![Fig. 2. Prediction of the present approach for pion photoproduction. The bands are due to the uncertainty of the hadronic amplitude as well as the error bars on $b_{12}$ and $b_{13}$. For comparison best fits of the MAID\cite{17} (circles) and SAID\cite{16} (squares) models are represented by blue and black points with errorbars, respectively.](image-url)
Fig. 3. $E_{\eta N}$ for eta photoproduction as predicted based on hadronic solution I. For comparison, we also present the results of the ETAMAID\textsuperscript{18} (circles) and Bonn-Gatchina\textsuperscript{19} (squares) analyses.

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