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Some recent results in baryon chiral perturbation theory

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Abstract. I present and discuss recent results on elastic pion-nucleon scattering and near-threshold neutral-pion electroproduction off deuterium obtained in the framework of chiral perturbation theory.

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1 Introduction

Chiral perturbation theory (CHPT) is a well established and systematic tool to analyze in a model-independent manner the reactions between pions, nucleons and photons (or other external sources), based on a systematic power counting in terms of small external momenta and quark (pion) masses. In this paper I want to present new results on isospin violation in elastic pion-nucleon scattering and neutral pion electroproduction off deuterium. The latter study was partly motivated by the dramatic difference between the prediction for the S-wave cross-section in [1] and the recent MAMI experiment [2]. As it turns out, this puzzle has been resolved as explained below.

2 Isospin violation in pion-nucleon scattering

We first want to apply CHPT to one of the most studied processes, elastic pion-nucleon scattering. More precisely, we will consider systematically effects of isospin violation (IV) due to the light quark mass difference, $m_u \neq m_d$, and electromagnetism, $q_u \neq q_d$. Before discussing in some detail isospin violation in πN scattering, a few general remarks are in order. In QCD plus QED, we have *two* sources of isospin violation. In QCD, the light-quark mass difference leads to isovector terms, as reflected in the quark mass term (for two flavors)

$$\mathcal{H}_{\rm QCD}^{\rm mass} = m_u \bar{u}u + m_d \bar{d}d = \frac{1}{2}(m_u + m_d)(\bar{u}u + \bar{d}d) + \frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)\,,$$

where the last term is clearly of isovector nature leading to strong IV. Naively, one could expect huge IV effects since $|(m_u - m_d)/(m_u + m_d)| \simeq 1/3$. However, the scale one should compare to is the hadronic one, so that one indeed anticipates very small effects, $(m_u - m_d)/\Lambda_\chi < 1\%$. Only in processes involving neutral pions one can expect much bigger effects [3]. The other source of IV is electromagnetism (em). Hadron mass shifts due to virtual photon exchange between quarks can be estimated as $\delta m \simeq \alpha_{\rm em} \cdot \Lambda_{\rm QCD} \cdot \mathcal{O}(1) \sim$ few MeV. In fact, typical em mass splittings in meson and baryon multiplets are of this order. Therefore, these two types of IV have to be considered *consistently*. This can be done by including virtual photons in the chiral effective Lagrangian of pions and nucleons, treating the electric charge e as another small parameter. This was done for the case of pion-nucleon scattering in the framework of heavy-baryon chiral perturbation theory to third order in ref. [4], leading to a new phase shift analysis (valid for pion lab momenta below 100 MeV as deduced from the isospin symmetric fourth-order calculation [5]). The resulting S- and P-wave phases for the three measured physical channels $\pi^\pm p \to \pi^\pm p$ and $\pi^- p \to \pi^0 n$ (charge exchange) are shown in fig. 1. CHPT does not leave any doubt about the correct definition of the *hadronic* masses of pions and nucleons and allows to extract the strong part of the scattering amplitude in a unique way. At this order, there is only one strong IV-violating operator whose strength can be fixed from the np mass difference. The em corrections are a bit more subtle. First, there are one- and two-photon exchanges, the latter amount to a few percent correction for the kinematics pertinent to the existing data. More precisely, for pion lab momenta $\boldsymbol{q}_\pi$, two-photon exchange is suppressed compared to one-photon exchange by a factor $e^2 M_\pi/(32|\boldsymbol{q}_\pi|) \leq 0.04$ for $|\boldsymbol{q}_\pi| \geq 10\,$MeV. Then there are soft photon contributions in terms of loops and external leg radiation. Only the sum of these is IR finite and their contribution depends of course on the detector resolution. We have used $\Delta E_\gamma = 10\,$MeV. In addition, there are hard photon contributions encoded in contact

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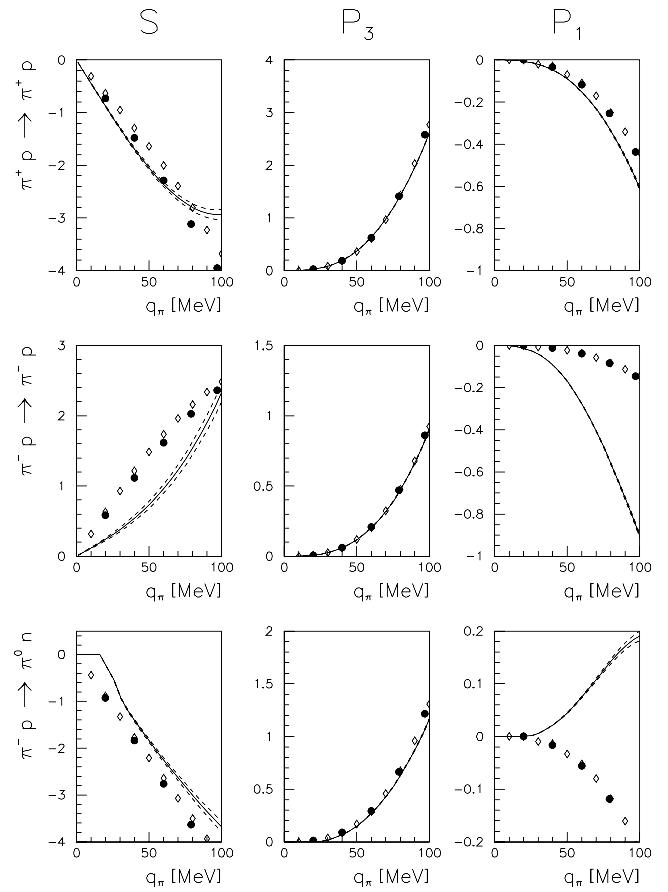

Fig. 1. Strong pion-nucleon phase shifts as a function of the pion laboratory momentum q_π for the three measured channels. Shown are the S-wave and the $j = 1/2$, $3/2$ P-waves. The solid line corresponds to the CHPT solution [4], the dashed one to the one-sigma uncertainty range. Also shown are the KA85 [6] (full dots) and the SP98 [8] (open diamonds) phases.

terms with undetermined low-energy constants (LECs). After determining the unknown LECs by a fit to experimental data, one can switch off all electromagnetic interactions and describe QCD with unequal up- and down-quark masses and $e^2 = 0$. The so-determined strong phase shifts (mostly) agree with those of previous works [6–9] in the P-waves, but one finds a sizeably different behavior in the S-waves (in particular for $\pi^- p$ elastic scattering), compare fig. 1. This difference can be traced back to the inclusion (in CHPT) or omission (in other approaches) of *non-linear* photon-pion-nucleon couplings, *i.e.* vertices of the type $\bar{N}N\pi\pi\gamma$. Such vertices are a consequence of chiral symmetry and thus must be included. One should investigate how such non-linear couplings can be included in the often used dispersion theoretical approaches to em corrections [10]. Given the hadronic amplitudes constructed in [4], one can address the question of isospin violation by studying the usual triangle relation involving elastic $\pi^\pm p$ scattering and the charge exchange reaction (for a general discussion of such triangle ratios, see [11] and references therein). An important advantage of the CHPT calculation lies in the fact that one can easily separate

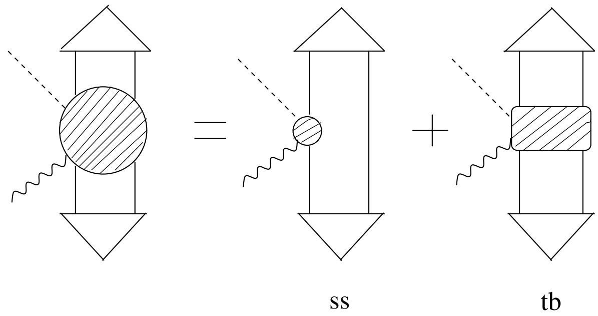

Fig. 2. Decomposition of the interaction kernel into the single-scattering (ss) and three-body (tb) contribution.

dynamical from static isospin breaking, the latter are due to hadron mass differences. Dynamical isospin breaking only occurs in the S-wave and is very small, $\sim 0.75\%$, in agreement with the estimate given above. Static effects do not increase the size of isospin violation in the S-wave significantly; by no means can one account for the reported 7 % isospin breaking [12,13]. These are presumably due to a mismatch between the models for the strong and the em interactions used in these works. Note also that one finds large error bars on the parameter values in the CHPT analysis. In order to improve this situation, one would like to fit to more experimental data. However, a third-order CHPT calculation allows to describe scattering data for pion laboratory momenta not much higher than 100 MeV, a region where the data situation is not yet as good as one would hope. A fourth-order calculation would certainly allow to fit to data higher in energy, but, on the other hand, would also introduce many more unknown coupling constants. Since isospin breaking effects are expected to be most prominent in the low-energy region, one might question the usefulness of extending the analysis to full one-loop (fourth) order. Additional data for pion-nucleon scattering at very low energies would be very helpful in this respect. Also a combined fit to several reactions involving nucleons, pions, and photons, *e.g.* pion electro- and photoproduction, as well as $\pi N \to \pi\pi N$, would help in pinning down the fundamental low-energy constants more precisely.

3 π^0 electroproduction off deuterium

In [14], we have studied neutral-pion electroproduction off deuterium in the framework of CHPT at and above threshold. For doing that, we have developed a general multipole decomposition for neutral-pion production off spin-1 particles that is particularly suited for the threshold region and formulated in close analogy to the standard CGLN amplitudes for pion production off nucleons (spin-1/2 particles). A similar work was previously published in [15]. The interaction kernel and the wave functions are based consistently on chiral effective field theory. The kernel decomposes into a single scattering and a three-body contribution, cf. fig. 2. We have chirally expanded the various contributions working to first non-trivial loop

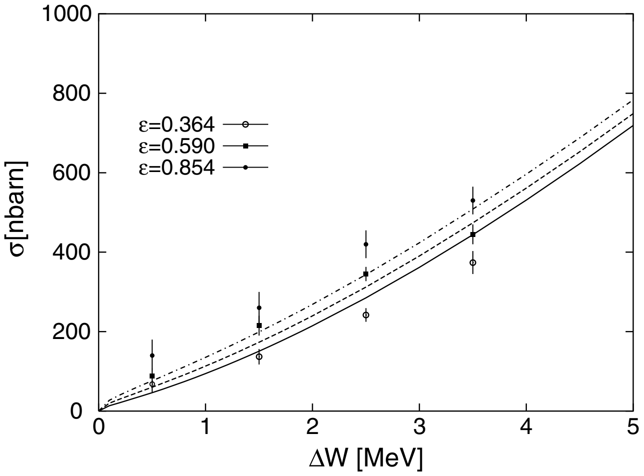

Fig. 3. Two-parameter fit of the near-threshold total cross-section in neutral-pion electroproduction off deuterium. The data are from MAMI [2].

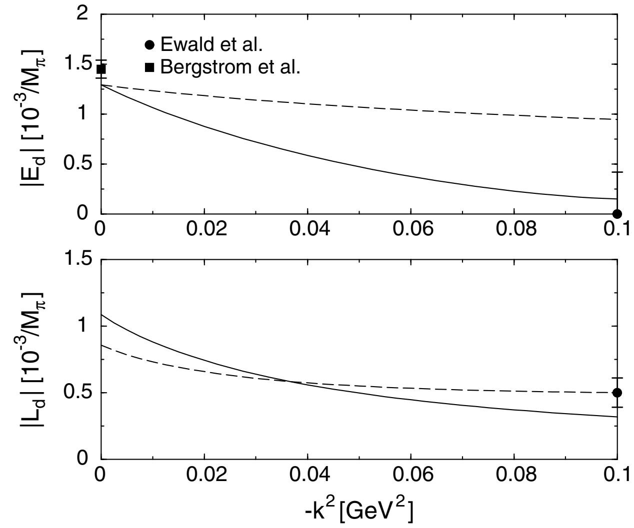

Fig. 4. Threshold multipoles E_d and L_d as a function of the photon virtuality in comparison to the photoproduction data from SAL [17] and the electroproduction data from MAMI [2].

order $\mathcal{O}(q^3)$, with the exception of the S-waves for the single-scattering contribution. These have to be included to fourth order with one additional fifth-order term [16]. All parameters for pion production off the proton and the ones appearing in the three-body terms are fixed. The longitudinal neutron S-wave amplitude contains effectively two parameters, which we have determined by two different procedures. In the fits of type 1 we have fitted the fifth-order parameter to the threshold multipole L_d from ref. [2] (and assuming resonance saturation to pin down the other LEC). The second procedure is based on a two-parameter fit to the total cross-section data from ref. [2], see fig. 3. All results are completely insensitive to the wave functions used, showing that this reaction is sensitive to the long-range pion exchange firmly rooted in the chiral symmetry of QCD. The predicted differential cross-sections are satisfactorily described for both fit procedures, although some systematic discrepancies for the higher values of the excess energy ΔW remain. In particular, for fit 1 the total cross-section rises too steeply with pion excess energy. The calculated S- and P-wave multipoles exhibit a more complex pion energy and photon virtuality dependence as assumed in the fits of ref. [2]. Within one standard deviation, the chiral predictions for the threshold multipoles $|E_d|$ and $|L_d|$ are consistent with the data at $k^2 = 0$ [17] and $k^2 = -0.1\,\mathrm{GeV}^2$ [2], cf. fig. 4. In [1], we had calculated these threshold multipoles to third order and performed a shift to the fourth-order predictions for the single-scattering contributions. This led to a too large longitudinal multipole L_d and thus a much too large S-wave cross-section. The properly calculated S-wave cross-section is consistent with the MAMI data, see table 3 in [14]. Clearly, the calculation presented here needs to be improved, in particular, the fourth order corrections to the P-waves and the three-body terms have to be included (note that similar work for the P-waves in neutral-pion photoproduction off protons has only appeared recently [18]). However, we have demonstrated that chiral perturbation theory can be used successfully to analyze pion electroproduction data off the deuteron which gives access to the elementary neutron amplitude. It would be very interesting to also have data at lower photon virtuality, which might also help to resolve the mystery surrounding the proton data at $k^2 = -0.05\,\mathrm{GeV}^2$.

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References

1. V. Bernard, H. Krebs, Ulf-G. Meißner, Phys. Rev. C **61**, 058201 (2000).
2. I. Ewald *et al.*, Phys. Lett. B **499**, 238 (2001).
3. S. Weinberg, Trans. N.Y. Acad. Sci. **38**, 185 (1977); Ulf-G. Meißner, S. Steininger, Phys. Lett. B **419**, 403 (1998); N. Fettes, Ulf-G. Meißner, S. Steininger, Phys. Lett. B **451**, 233 (1999).
4. N. Fettes, Ulf-G. Meißner, Nucl. Phys. A **693**, 693 (2001).
5. N. Fettes, Ulf-G. Meißner, Nucl. Phys. A **676**, 311 (2000).
6. R. Koch, Nucl. Phys. A **448**, 707 (1986).
7. E. Matsinos, arXiv:hep-ph/9807395.
8. SAID on-line program, R.A. Arndt *et al.*, see website `http://gwdac.phys.gwu.edu/`.
9. A. Gashi *et al.*, hep-ph/0009081.
10. J. Hamilton, B. Tromberg, I. Øverbrø, Nucl. Phys. B **60**, 443 (1973); B. Tromberg, J. Hamilton, Nucl. Phys. B **76**, 483 (1974); B. Tromberg, S. Waldenstrøm, I. Øverbrø, Phys. Rev. D **15**, 725 (1977).
11. N. Fettes, Ulf-G. Meißner, Phys. Rev. C **63**, 045201 (2001).
12. W.R. Gibbs, Li Ai, W.B. Kaufmann, Phys. Rev. Lett. **74**, 3740 (1995).

13. E. Matsinos, Phys. Rev. C **56**, 3014 (1997).
14. V. Bernard, H. Krebs, Ulf-G. Meißner, arXiv:nucl-th/0702072.
15. H. Arenhövel, Few-Body Syst. **25**, 127 (1998); **27**, 141 (1999).
16. V. Bernard, N. Kaiser, Ulf-G. Meißner, Nucl. Phys. A **607**, 379 (1996).
17. J.C. Bergstrom *et al.*, Phys. Rev. C **57**, 3203 (1998).
18. V. Bernard, N. Kaiser, Ulf-G. Meißner, Eur. Phys. J. A **11**, 209 (2001).