The Missing Three-Nucleon Forces: Where Are They?

R. Machleidt*

Department of Physics, University of Idaho, Moscow, Idaho 83844, USA

Abstract. In recent years, there has been substantial progress in the derivation of nuclear forces from chiral effective field theory. Accurate two-nucleon forces (2NF) have been constructed up to next-to-next-to-next-to-leading order (N\textsuperscript{3}LO) of chiral perturbation theory and applied in microscopic nuclear structure calculations with a good degree of success. However, chiral three-nucleon forces (3NF) have been used only at N\textsuperscript{2}LO, improving some microscopic predictions, but leaving also several issues, like the “A\textsubscript{y} puzzle” of nucleon-deuteron scattering, unresolved. Thus, the 3NF at N\textsuperscript{3}LO is needed for essentially two reasons: For consistency with the 2NF, and to (hopefully) improve some critical predictions of nuclear structure and reactions. However, there are indications that the 3NF at N\textsuperscript{3}LO (in the so-called \Delta-less version of the theory) is rather weak and may not solve any of the outstanding problems. If this suspicion is confirmed, we have to go beyond, which may be similar to opening Pandora’s Box. In this talk, I will discuss the various possible scenarios and how to deal with them.

1 Introduction

The problem of a proper derivation of nuclear forces is as old as nuclear physics itself, namely, almost 80 years [1, 2]. The modern view is that, since the nuclear force is a manifestation of strong interactions, any serious derivation has to start from quantum chromodynamics (QCD). However, the well-known problem with QCD is that it is non-perturbative in the low-energy regime characteristic for nuclear physics. For many years this fact was perceived as the great obstacle for a derivation of nuclear forces from QCD—impossible to overcome except by lattice QCD. The effective field theory (EFT) concept has shown the way out of this dilemma. One has to realize that the scenario of low-energy QCD is characterized by pions and nucleons interacting via a force governed by spontaneously broken approximate chiral symmetry. This chiral EFT allows for a systematic low-momentum expansion known as chiral perturbation theory (ChPT) [3]. Contributions are analyzed in terms of powers of small momenta over the large scale: \((Q/\Lambda\chi)\nu\), where \(Q\) is generic for a momentum (nucleon three-momentum or pion four-momentum) or pion mass and \(\Lambda\chi \approx 1\) GeV is the chiral symmetry breaking scale. The early applications of ChPT focused on systems like \(\pi\pi\) [4] and \(\pi N\) [5], where the Goldstone-boson character of the pion guarantees that the expansion converges.

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The past 15 years have also seen great progress in applying ChPT to nuclear forces [6–20]. As a result, nucleon-nucleon (NN) potentials of high precision have been constructed which are based upon ChPT carried to next-to-next-to-next-to-leading order (N^3LO) [17, 19, 20]. Thus, the groundwork for the derivation of nuclear forces from chiral EFT is laid and the attention now turns to more detailed conceptual questions as well as the construction of higher order corrections. To be more specific, the most crucial open issues in the field of chiral nuclear forces are

– the renormalization of chiral nuclear potentials and
– subleading chiral few-nucleon forces.

This talk is devoted to the latter issue. The renormalization problem is discussed in length elsewhere in the literature [21].

I will first provide a general overview of how nuclear forces emerge from chiral EFT (Section 2) and then discuss in more detail the specific issue of sub-leading few-nucleon forces (Section 3). Section 4 contains a summary and a prospect for the future.

2 Nuclear forces from chiral EFT: Overview

2.1 Chiral perturbation theory and power counting

Effective Langrangians have infinitely many terms, and an unlimited number of Feynman graphs can be calculated from them. Therefore, we need a scheme that makes the theory manageable and calculable. This scheme which tells us how to distinguish between large (important) and small (unimportant) contributions is chiral perturbation theory (ChPT), and determining the power $\nu$ of the expansion has become known as power counting.

Nuclear potentials are defined as sets of irreducible graphs up to a given order. The power $\nu$ of a few-nucleon diagram involving $A$ nucleons is given by:

$$\nu = -2 + 2A - 2C + 2L + \sum_i \Delta_i ,$$

(1)

with

$$\Delta_i \equiv d_i + \frac{n_i}{2} - 2 ,$$

(2)

where $C$ denotes the number of separately connected pieces and $L$ the number of loops in the diagram; $d_i$ is the number of derivatives or pion-mass insertions and $n_i$ the number of nucleon fields (nucleon legs) involved in vertex $i$; the sum runs over all vertices contained in the diagram under consideration. Note that $\Delta_i \geq 0$ for all interactions allowed by chiral symmetry. For an irreducible $NN$ diagram (“two-nucleon force”, $A = 2$, $C = 1$), Eq. (1) collapses to

$$\nu = 2L + \sum_i \Delta_i ,$$

(3)
The power formula Eq. (1) allows to predict the leading orders of multi-nucleon forces. Consider a \( m \)-nucleon irreducibly connected diagram \((m\text{-nucleon force})\) in an \( A \)-nucleon system \((m \leq A)\). The number of separately connected pieces is \( C = A - m + 1 \). Inserting this into Eq. (1) together with \( L = 0 \) and \( \sum_i \Delta_i = 0 \) yields \( \nu = 2m - 4 \). Thus, two-nucleon forces \((m = 2)\) start at \( \nu = 0 \), three-nucleon forces \((m = 3)\) at \( \nu = 2 \) (but they happen to cancel at that order), and four-nucleon forces at \( \nu = 4 \) (they don’t cancel). Thus, ChPT provides a straightforward explanation for the empirically known fact that \( 2\text{NF} \gg 3\text{NF} \gg 4\text{NF} \) . . . .

In summary, the chief point of the ChPT expansion is that, at a given order \( \nu \), there exists only a finite number of graphs. This is what makes the theory calculable. The expression \( \left( Q/\Lambda \right)^{\nu+1} \) provides a rough estimate of the relative size of the contributions left out and, thus, of the accuracy at order \( \nu \). In this sense, the theory can be calculated to any desired accuracy and has predictive power.

2.2 The hierarchy of nuclear forces

Chiral perturbation theory and power counting imply that nuclear forces emerge as a hierarchy controlled by the power \( \nu \), Fig. 1.

In lowest order, better known as leading order (LO, \( \nu = 0 \)), the \( NN \) amplitude is made up by two momentum-independent contact terms \((\sim Q^0)\), represented by the four-nucleon-leg graph with a small-dot vertex shown in the first row of Fig. 1 and static one-pion exchange (1PE), second diagram in the first row of the figure. This is, of course, a rather crude approximation to the two-nucleon force, but accounts already for some important features. The 1PE provides the tensor force, necessary to describe the deuteron, and it explains \( NN \) scattering in peripheral partial waves of very high orbital angular momentum. At this order, the two contacts which contribute only in \( S \)-waves provide the “intermediate-range” attraction which, indeed, is a rather rudimentary description of reality.

In the next order, \( \nu = 1 \), all contributions vanish due to parity and time-reversal invariance.

Therefore, the next-to-leading order (NLO) is \( \nu = 2 \). Two-pion exchange (2PE) occurs for the first time (“leading order 2PE”) and, thus, the creation of a more realistic description of the intermediate-range attraction is starting here. Since the loop involved in each pion-diagram implies already \( \nu = 2 \) [cf. Eq. (3)], the vertices must have \( \Delta_i = 0 \). Therefore, at this order, only the lowest order \( \pi NN \) and \( \pi \pi NN \) vertices are allowed which is why the leading order 2PE is rather weak. Furthermore, there are seven contact terms of \( \mathcal{O}(Q^2) \), shown by the four-nucleon-leg graph with a solid square, which contribute in \( S \) and \( P \) waves. The operator structure of these contacts include a spin-orbit term besides central, spin-spin, and tensor terms. Thus, essentially all spin-isospin structures necessary to describe the two-nucleon force phenomenologically have been generated at this order. The main deficiency at this stage of development is an insufficient intermediate-range attraction.

This problem is finally fixed at order three \((\nu = 3)\), next-to-next-to-leading order (NNLO). The 2PE involves now the \( \Delta_i = 1 \) \( \pi \pi NN \) seagull vertices (proportional
to the $c_i$ LECs) denoted by a large solid dot in Fig. 1. These vertices represent correlated 2PE as well as intermediate $\Delta(1232)$-isobar contributions. It is well-known from the meson phenomenology of nuclear forces [1, 22] that these two contributions are crucial for a realistic and quantitative 2PE model. Consequently, the 2PE now assumes a realistic size and describes the intermediate-range attraction of the nuclear force about right. Moreover, first relativistic corrections come into play at this order. There are no new contacts.

The reason why we talk of a hierarchy of nuclear forces is that two- and many-nucleon forces are created on an equal footing and emerge in increasing number as we go higher and higher orders. At NNLO, the first set of nonvanishing three-nucleon forces (3NF) occur [9, 23], cf. column ‘3N Force’ of Fig. 1. In fact, at the previous order, NLO, irreducible 3N graphs appear already, however, it has been shown by Weinberg [7] and others [9, 24, 25] that these diagrams all cancel. Since nonvanishing 3NF contributions happen first at order $(Q/\Lambda)$, they are very weak as compared to the 2NF which starts at $(Q/\Lambda)^0$.

More 2PE is produced at $\nu = 4$, next-to-next-to-next-to-leading order ($N^3$LO), of which we show only a few symbolic diagrams in Fig. 1. Two-loop 2PE graphs

Figure 1. Hierarchy of nuclear forces in ChPT. Solid lines represent nucleons and dashed lines pions. Small dots, large solid dots, solid squares, and solid diamonds denote vertices of index $\Delta = 0, 1, 2,$ and 4, respectively. Further explanations are given in the text.
show up for the first time and so does three-pion exchange (3PE) which necessarily involves two loops. 3PE was found to be negligible at this order [26]. Most importantly, 15 new contact terms $\sim Q^4$ arise and are represented by the four-nucleon-leg graph with a solid diamond. They include a quadratic spin-orbit term and contribute up to $D$-waves. Mainly due to the increased number of contact terms, a quantitative description of the two-nucleon interaction up to about 300 MeV lab. energy is possible at N$^3$LO [17]. Besides further 3NF, four-nucleon forces (4NF) start at this order. Because the leading order 4NF comes into existence one order higher than the leading 3NF, 4NFs are weaker than 3NFs.

Since 2003, a very quantitative chiral $NN$ potential (at N$^3$LO) [17] exists which has been applied successfully in many nuclear structure calculations [27–31]. Therefore, the chiral two-nucleon force appears to be in good shape (except for the renormalization issue discussed elsewhere [21]). However, there are still open questions in the few-nucleon-force sector as we will explain now in more detail.

### 3 Few-nucleon forces

Nuclear three-body forces in ChPT were initially discussed by Weinberg [7]. The 3NF at NNLO, was derived by van Kolck [9] and applied, for the first time, in nucleon-deuteron scattering by Epelbaum et al. [23]. The leading 4NF (at N$^3$LO) was recently constructed by Epelbaum [32] and found to contribute in the order of 0.1 MeV to the $^4$He binding energy (total $^4$He binding energy: 28.3 MeV) in a preliminary calculation [33], confirming the traditional assumption that 4NF are essentially negligible. **Therefore, the focus is on 3NF.**

For a 3NF, we have $A = 3$ and $C = 1$ and, thus, Eq. (1) implies for 3NF

$$\nu = 2 + 2L + \sum_i \Delta_i .$$

We will use this equation to analyze 3NF contributions order by order. The lowest possible power is obviously $\nu = 2$ (NLO), which is obtained for no loops ($L = 0$) and only leading vertices ($\sum_i \Delta_i = 0$). This 3NF happens to vanish [7]. The first non-vanishing 3NF occurs at NNLO.
3.1 The 3NF at NNLO

The power $\nu = 3$ (NNLO) is obtained when there are no loops ($L = 0$) and $\sum_i \Delta_i = 1$, i.e., $\Delta_i = 1$ for one vertex while $\Delta_i = 0$ for all other vertices. There are three topologies which fulfill this condition, known as the two-pion exchange (2PE), 1PE, and contact graphs (Fig. 2). In this figure, vertices represented by a small dot carry $\Delta_i = 0$ while large solid dots have $\Delta_i = 1$.

The 3NF at NNLO (Fig. 2) has been evaluated (without the $1/M_N$ corrections) [9,23] and applied in calculations of few-nucleon reactions [23,34,35], structure of light- and medium-mass nuclei [27–30], and nuclear matter [31] with a fair deal of success. However, the famous ‘$\alpha$ puzzle’ of nucleon-deuteron scattering is not solved [23, 34], and the even bigger problem with the analyzing power in $p-^3\text{He}$ scattering [36, 37] will certainly not be fixed at this order. Furthermore, the spectra of light nuclei leave room for improvement [29].

We note that there are further 3NF contributions at NNLO, namely, the $1/M_N$ corrections of the NLO 3NF diagrams. Part of these corrections have been calculated by Coon and Friar in 1986 [25]. These contributions are believed to be very small.

In summary, because of various unresolved problems in microscopic nuclear structure, the 3NF beyond NNLO is very much in need. In fact, it is no exaggeration to state that the 3NF at sub-leading orders is presently one of the most important outstanding issues in the chiral EFT approach to nuclear forces.

3.2 The 3NF at $N^3\text{LO}$

According to Eq. (4), the value $\nu = 4$, which corresponds to $N^3\text{LO}$, is obtained for the following classes of diagrams.

**3NF loop diagrams at $N^3\text{LO}$**. For this group of graphs, we have $L = 1$ and, therefore, all $\Delta_i$ have to be zero to ensure $\nu = 4$. Thus, these one-loop 3NF diagrams can include only leading order vertices, the parameters of which are fixed from $\pi N$ and $N N$ analysis. We show two samples of this very large class of diagrams in Fig. 3. One sub-group of these diagrams (“$2\pi$ exchange graphs”) has been calculated by Ishikawa and Robilotta [38], and two other topologies ($2\pi-1\pi$ and ring diagrams) have been evaluated by the Bonn-Jülich group [39]. The remaining topologies, which involve a leading order four-nucleon contact term (e.g., second
The Missing Three-Nucleon Forces: Where Are They?

The order $\nu = 4$ is also obtained for the combination $L = 0$ (no loops) and $\sum_i \Delta_i = 2$. Thus, either two vertices have to carry $\Delta_i = 1$ or one vertex has to be of the $\Delta_i = 2$ kind, while all other vertices are $\Delta_i = 0$. This is achieved if in the NNLO 3NF graphs of Fig. 2 the power of one vertex is raised by one. The latter happens if a relativistic $1/M_N$ correction is applied. A closer inspection reveals that all $1/M_N$ corrections of the NNLO 3NF vanish and the first non-vanishing corrections are proportional to $1/M_N^2$ and appear at N$^4$LO. However, there are non-vanishing $1/M_N^2$ corrections of the NLO 3NF and there are so-called drift corrections [40] which contribute at N$^3$LO (some drift corrections are claimed to contribute even at NLO [40]). We do not expect these contributions to be sizable. Moreover, there are contributions from the $\Delta_i = 2$ Lagrangian [41] proportional to the low-energy constants $d_i$. As it turns out, these terms have at least one time-derivative, which causes them to be $Q/M_N$ suppressed and demoted to N$^4$LO.

Thus, besides some minor $1/M_N^2$ corrections, there are no tree contributions to the 3NF at N$^3$LO.

**Summarizing the entire N$^3$LO 3NF contribution:** For the reasons discussed, we anticipate that this 3NF is weak and will not solve any of the outstanding problems. In view of this expectation, we have to look for more sizable 3NF contributions elsewhere.

### 3.3 The 3NF at N$^4$LO of the $\Delta$-less theory

The obvious step to take is to proceed to the next order, N$^4$LO or $\nu = 5$, of the $\Delta$-less theory which is the one we have silently assumed so far. (The $\Delta$-full theory will be introduced and discussed below.) Some of the tree diagrams that appear at this order were mentioned already: the $1/M_N^2$ corrections of the NNLO 3NF and the trees with one $d_i$ vertex which are $1/M_N$ suppressed. Because of the suppression factors, we do not expect sizable effects from these graphs. Moreover, there are also tree diagrams with one vertex from the $\Delta_i = 3$ $\pi N$ Lagrangian [42, 43] proportional to the LECs $c_i$. Because of the high dimension of these vertices and assuming reasonable convergence, we do not anticipate much from these trees either.

However, we believe that the loop contributions that occur at this order are truly important. They are obtained by replacing in the N$^3$LO loops (Fig. 3) one vertex...
by a $\Delta_i = 1$ vertex [with LEC $c_i$]. We show one symbolic example of this large group of diagrams in Fig. 4(a). This 3NF is presumably large and, thus, what we are looking for.

The reasons, why these graphs are large, can be argued as follows. Corresponding 2NF diagrams are the three-pion exchange (3PE) contributions to the $N\bar{N}$ interaction. In analogy to Figs. 3 and 4(a), there are 3PE 2NF diagrams with only leading vertices and the ones with one (sub-leading) $c_i$ vertex (and the rest leading). These diagrams have been evaluated by Kaiser in Refs. [26] and [44], respectively. Kaiser finds that the 3PE contributions with one sub-leading vertex are about an order magnitude larger then the leading ones.

3.4 $N^3$LO 3NF contributions in the $\Delta$-full theory

The above considerations indicate that the $\Delta$-less theory exhibits, in some cases, a bad convergence pattern. The reason for the unnaturally strong subleading contributions are the large values of the $\Delta_i = 1$ LECs, $c_i$. The large values can be explained in terms of resonance saturation [45]. The $\Delta(1232)$-resonance contributes considerably to $c_3$ and $c_4$. The explicit inclusion of the $\Delta$ takes strength out of these LECs and moves this strength to a lower order, thus improving the convergence [8, 12, 46–48]. Figure 4 illustrates this fact for the 3NF under consideration: the diagram of the $\Delta$-less theory shown in (a) is (largely) equivalent to diagram (b) which includes one $\Delta$ excitation. Note, however, that diagram (a) is $N^4$LO, while diagram (b) is $N^3$LO. Moreover, there are further $N^3$LO one-loop diagrams with two and three $\Delta$ excitations, which correspond to diagrams of order $N^5$LO and $N^6$LO, respectively, in the $\Delta$-less theory.

This consideration clearly shows that the inclusion of $\Delta$ degrees of freedom in chiral EFT makes the calculation of sizable higher-order 3NF contributions much more efficient.
4 Summary, Conclusions and Outlook

The past 15 years have seen great progress in our understanding of nuclear forces in terms of low-energy QCD. Key to this development was the realization that low-energy QCD is equivalent to an effective field theory (EFT) which allows for a perturbative expansion that has become known as chiral perturbation theory (ChPT). In this framework, two- and many-body forces emerge on an equal footing and the empirical fact that nuclear many-body forces are substantially weaker than the two-nucleon force is explained automatically.

In spite of the great progress and success of the past 15 years, there are still some unresolved issues that will need our attention in the near future. One problem is the proper renormalization of the chiral two- and many-nucleon potentials. This has not been the subject of my talk, but a thorough discussion together with a comprehensive list of the vast literature on the subject can be found in Ref. [21].

The other unfinished business are the few-nucleon forces beyond NNLO (“sub-leading few-nucleon forces”). In this talk, we chose to elaborate on this topic, and the bottom line can be summarized as follows:

– The chiral 3NF at NNLO is insufficient. Additional sizable 3NF contributions are needed.
– The chiral 3NF at N^3LO (in the \(\Delta\)-less theory) most likely does not produce sizable contributions.
– Sizable contributions are expected from one-loop 3NF diagrams at N^4LO of the \(\Delta\)-less or N^3LO of the \(\Delta\)-full theory (Fig. 4). These 3NF contributions may turn out to be the missing pieces in the 3NF puzzle and have the potential to solve the outstanding problems in microscopic nuclear structure.

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1 Note that the Illinois 3NF [49] includes two one-loop diagrams with one and two \(\Delta(1232)\)-isobars. The deeper reason for this may be in arguments we are presenting.
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