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Historical Perspective and Future Prospects for Nuclear Forces

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Abstract. The nuclear force is the heart of nuclear physics and, thus, the significance of this force for all of nuclear physics can hardly be overstated. Research on this crucial force has by now spanned eight decades and we are still not done. I will first review the rich history of hope and desperation, which had spin-off far beyond just nuclear physics. Next, I will present the current status in the field which is charcterized by the application of an effective field theory (EFT) that is believed to represent QCD in the low energy regime typical for nuclear physics. During the past two decades, this EFT has become the favorite vehicle to derive nuclear two- and many-body forces. Finally, I will take a look into the future: What developments can we expect from the next decades? Will the 30-year cycles of new and "better" ideas for efficiently describing nuclear forces go on for ever, or is there hope for closure?

1 Introduction

The development of a proper theory of nuclear forces has occupied the minds of some of the brightest physicists for eight decades and has been one of the main topics of physics research in the 20th century. The original idea was that the force is created by the exchange of lighter particles (than nucleons) known as mesons, and this idea gave rise to the birth of a new sub-field of modern physics, namely, (elementary) particle physics. The modern perception of the nuclear force is that it is a residual interaction (similar to the van der Waals force between neutral atoms) of the even stronger force between quarks, which is mediated by the exchange of gluons and holds the quarks together inside a nucleon. We will subdivide the full story into four phases, for which we also state the approximate time frame:

- Phase I ($\approx 1930 - 1960$): Pion Theories,
- Phase II ($\approx 1960 - 1990$): Meson Models,
- Phase III ($\approx 1990 - 2020$): Chiral Effective Field Theory,
- Phase IV ($\approx 2020-????$) Future: EFT Based Models(?),

and will now tell the tale for each phase.

2 Phase I (≈1930 – 1960): Pion Theories

After the discovery of the neutron in 1932, it was clear that the atomic nucleus is made up from protons and neutrons. In such a system, electromagnetic forces cannot be the reason why the constituents of the nucleus are sticking together. Therefore, the concept of a new strong nuclear interaction was introduced. In 1935, the first theory for this new force was developed by the Japanese physicist Yukawa [1], who suggested that the nucleons would exchange particles between each other and this mechanism would create the force. Yukawa constructed his theory in analogy to the theory of the electromagnetic interaction where the exchange of a (massless) photon is the cause of the force. However, in the case of the nuclear force, Yukawa assumed that the "force-makers" (which were eventually called "mesons") carry a mass of a fraction of the nucleon mass, which limits the effect of the force to a finite range. The meson predicted by Yukawa was finally found in 1947 in cosmic ray and in 1948 in the laboratory and called the pion. Yukawa was awarded the Nobel Prize in 1949.

Based upon Yukawa's idea, first field-theoretic attempts to derive the nucleon-nucleon (NN) interaction focused on pion exchange. While the one-pion exchange turned out to be very useful in explaining NN scattering data and, in particular, the properties of the deuteron [2], multi-pion exchange was beset with serious ambiguities [3, 4] that could not be resolved in a satisfactory way. Thus, the "pion theories" of the 1950s are generally judged as failures—for reasons we understand today: pion dynamics is constrained by chiral symmetry, a crucial point that was unknown in the 1950s.

3 Phase II (≈1960 – 1990): Meson Models

In the early 1960's, heavier (non-strange) mesons were found in experiment, notably the vector (spin-1) mesons $\rho(770)$ and $\omega(782)$ [5]. Because of the problems with the pion theories, theoreticians were now happy to extend meson theory by including more and different species of mesons. This led to the one-boson-exchange (OBE) models, which were started in the 1960's and turned out to be very successful.

3.1 The one-boson-exchange model

One-boson-exchange models typically include about half a dozen of bosons with masses up to about 1 GeV, Figure 1. Not all mesons are equally important. The leading actors are the following four particles:

- The pseudoscalar pion with a mass of about 138 MeV and isospin $I = 1$ (isovector). It is the lightest meson and provides the long-range part of the potential and most of the tensor force.

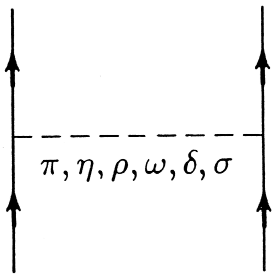

Figure 1. The one-boson-exchange model. Solid lines denote nucleons and the dashed line represents mesons.

- The isovector ρ meson, a 2π P-wave resonance of about 770 MeV. Its major effect is to cut down the tensor force provided by the pion at short range.
- The isoscalar ω meson, a 3π resonance of 783 MeV and spin 1. It creates a strong repulsive central force of short range ('repulsive core') and the nuclear spin-orbit force.
- The scalar-isoscalar $f_0(500)$ or σ boson with a mass around 500 MeV. It provides the crucial intermediate range attraction necessary for nuclear binding. The interpretation as a particle is controversial [6]. It may also be viewed as a simulation of effects of correlated S-wave 2π-exchange.

Obviously, just these four mesons can produce the major properties of the nuclear force.*

Classic examples for OBE potentials (OBEPs) are the Bryan-Scott potentials started in the early 1960's [8], but soon many other researchers got involved, too [9–11]. Since it is suggestive to think of a potential as a function of r (where r denotes the distance between the centers of the two interacting nucleons), the OBEPs of the 1960's where represented as local r-space potentials.

An important advance during the 1970's has been the development of the *relativistic OBEP* [12, 13]. In this model, the full, relativistic Feynman amplitudes for the various one-boson-exchanges are used to define the potential. These nonlocal expressions do not pose any numerical problems when used in momentum space. The very quantitative and successful CD-Bonn potential [14] is of this nature.

3.2 Beyond the OBE approximation

Historically, one must understand that, after the failure of the pion theories in the 1950's, the OBE model was considered a great success in the 1960's.

*The interested reader can find a more detailed and pedagogical introduction into the OBE model in sections 3 and 4 of Ref. [7].

On the other hand, one has to concede that the OBE model is a great simplification of the complicated scenario of a full meson theory for the NN interaction. Therefore, in spite of the quantitative success of the OBEPs, one should be concerned about the approximations involved in the model. Major critical points include:

- The scalar isoscalar σ 'meson' of about 500 MeV.
- The neglect of all non-iterative diagrams.
- The role of meson-nucleon resonances.

Two pions, when 'in the air', can interact strongly. When in a relative P-wave ($L = 1$), they form a proper resonance, the ρ meson. They can also interact in a relative S-wave ($L = 0$), which gives rise to the σ boson. Whether the σ is a proper resonance is controversial, even though the Particle Data Group lists an $f_0(500)$ or $\sigma(500)$ meson, but with a width 400-700 MeV [6]. What is for sure is that two pions have correlations, and if one doesn't believe in the σ as a two pion resonance, then one has to take these correlations into account. There are essentially two ways to take care of these two-pion exchange contributions to the NN interaction (which generates the intermediate range attraction): dispersion theory and field theory.

In the dispersion-theoretic approach the (empirical) πN amplitude is related to the NN amplitude by causality (analyticity), unitarity, and crossing symmetry. The Stony Brook [15] and Paris [16] groups have pursued this line of research. They could show that the intermediate-range part of the nuclear force is, indeed, decribed correctly by the 2π-exchange as obtained from dispersion integrals.

A field-theoretic model for the 2π-exchange contribution was developed by the Bonn group [17]. The model includes contributions from isobars as well as from $\pi\pi$ correlations. This can be understood in analogy to the dispersion relations picture.

This could have been the happy end of the theory of nuclear forces. However, with the rise of QCD to the ranks of the authoritative theory of strong interactions, meson theory is demoted to the lower level of a model (even though a beautiful one), and we have to start all over again—in the next section.

4 Phase III (≈1990 – 2020): Chiral Effective Field Theory

The problem with a derivation of nuclear forces from QCD is two-fold. First, each nucleon consists of three valence quarks, quark-antiquark pairs, and gluons such that the system of two nucleons is a complicated many-body problem. Second, the force between quarks, which is created by the exchange of gluons, has the feature of being very strong at the low energy-scale that is characteristic of nuclear physics. This extraordinary strength makes it difficult to find converging expansions. Therefore, during the first round of new attempts, QCD-inspired quark models became popular. The positive aspect of these models is that they try to explain nucleon structure (made up from three constituent quarks) and nucleon-nucleon interactions (six quarks) on an equal footing. Some of the gross features of the two-nucleon force, like the "hard core" are explained successfully in such models. However, from a critical point of view, it must be noted that these quark-based approaches are yet another set of models and not a theory. Alternatively, one may try to solve the six-quark problem with brute computing power, by putting the six-quark system on a four dimensional lattice of discrete points which represents the three dimensions of space and one dimension of time. This method has become known as lattice QCD and is making progress. However, such calculations are computationally very expensive and cannot be used as a standard nuclear physics tool.

Around 1990, a major breakthrough occurred when the nobel laureate Steven Weinberg applied the concept of an effective field theory (EFT) to low-energy QCD [18, 19]. He simply wrote down the most general Lagrangian that is consistent with all the properties of low-energy QCD, since that would make this theory equivalent to low-energy QCD. A particularly important property is the so-called chiral symmetry, which is said to be "spontaneously" broken. Massless spin-$\frac{1}{2}$ fermions posses chirality, which means that their spin and momentum are either parallel ("right-handed") or anti-parallel ("left-handed") and remain so forever. Since the quarks, which nucleons are made of ("up" and "down" quarks), are almost mass-less, approximate chiral symmetry is a given. Naively, this symmetry should have the consequence that one finds in nature hadrons of the same mass and spin, but with opposite parities ("parity doublets"). However, this is not the case in the lower part of the hadron spectrum and such failure is termed a "spontaneous" breaking of the symmetry, which creates a Goldstone boson, the pion. Thus, the pion becomes again the main player in the production of the nuclear force, *but now constrained by chiral symmetry.* This effective field theory can be expanded in powers of momentum Q over "scale" Λ_χ, where Λ_χ denotes the "chiral symmetry breaking scale" which is about 1 GeV. This scheme is also known as chiral perturbation theory (ChPT) and allows to calculate the various terms that make up the nuclear potential systematically power by power, or order by order. Another advantage of the chiral EFT approach is its ability to generate not only the force between two nucleons, but also many-nucleon forces, on the same footing [20].

4.1 The ranking of nuclear forces

The power of an irreducible diagram involving A nucleons is given by

$$\nu = -2 + 2A - 2C + 2L + \sum_i \Delta_i \,, \tag{1}$$

with

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

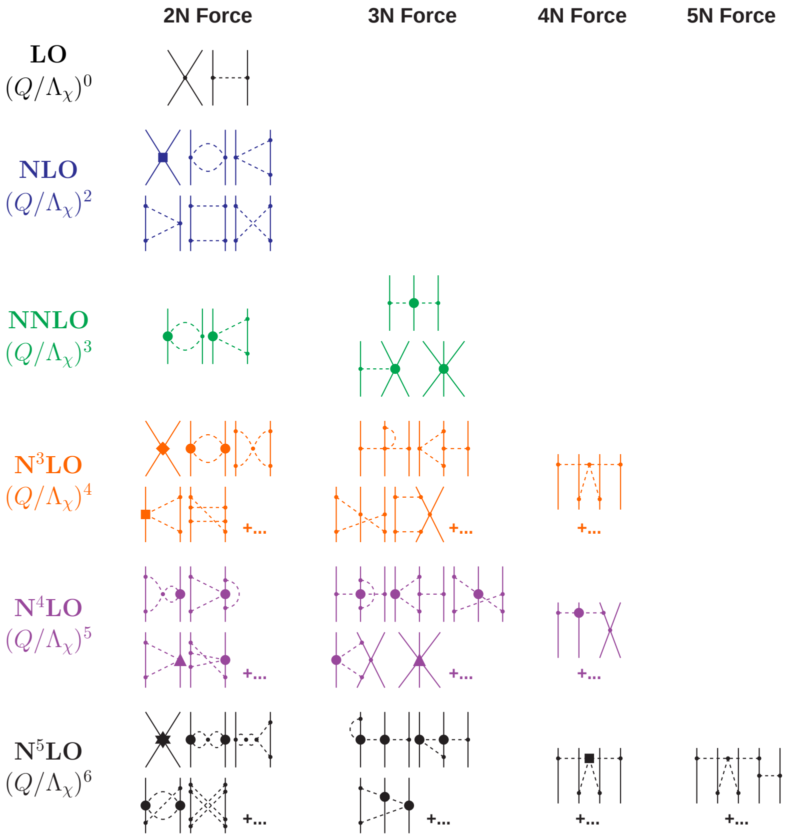

Figure 2. Hierarchy of nuclear forces in ChPT. Solid lines represent nucleons and dashed lines pions. Small dots, large solid dots, solid squares, triangles, diamonds, and stars denote vertices of index $\Delta_i = 0, 1, 2, 3, 4$, and 6, respectively. Further explanations are given in the text.

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 i contained in the diagram under consideration.

Ranking nuclear force contributions by their power leads to the hierarchy displayed in Figure 2.

This hierarchy starts to become interesting at order $\nu = 3$ or next-to-next-to-leading order (NNLO), where the two-pion exchange (2PE) contains the so-called $\pi\pi NN$ seagull vertices with two derivatives (represented by a large solid dot in Figure 2). These vertices parametrize correlated 2PE and intermediate $\Delta(1232)$-isobar excitations. Consistent with what the meson theory of the nuclear force [16, 17] has shown (cf. Section 3), the 2PE now produces medium-

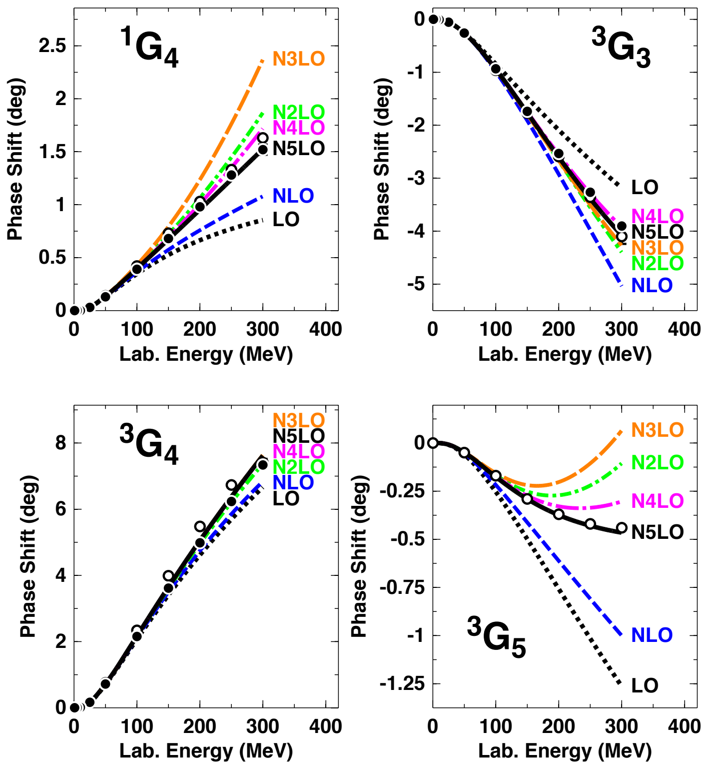

Figure 3. Phase-shifts of neutron-proton scattering in G waves at all orders of ChPT from LO to N^{5}LO. The filled and open circles represent results from phase-shift analyses

range attraction of considerable strength, bringing the description of the NN force to an almost quantitative level. The effect of pion-exchange contributions are seen best in peripheral partial waves of NN scattering, since the contact terms do not contribute at large angular momenta L. Therefore, we show in Figure 3 the phase-shifts in G-waves ($L = 4$), demonstrating the size of the N2LO (=NNLO) contribution in comparison to the other orders. Finally, the first non-vanishing 3NF contribution makes its apearance at NNLO.

For $\nu = 4$, or next-to-next-to-next-to-leading order (N^{3}LO), we can display only a few representative diagrams in Figure 2. There is a large attractive one-loop 2PE contribution (the bubble diagram with two large solid dots), which over-estimates the 2NF attraction at medium range (cf. Figure 3). Two-pion-exchange graphs with two loops contribute for the first time and so does three-pion exchange (3PE), which is negligibly small at this order. The most important feature at this order is the presence of 15 additional contacts $\sim Q^4$. These contacts impact states with orbital angular momentum up to $L = 2$, and lead

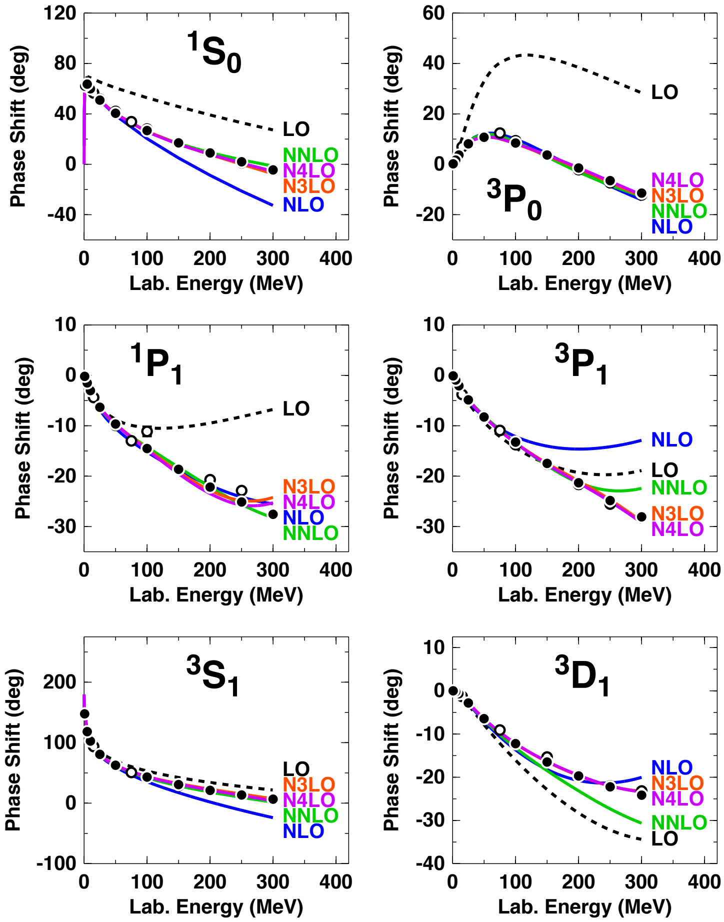

Figure 4. Phase-shifts of neutron-proton scattering for states with $J = 0$ and 1, at all orders of chiral EFT from LO to N^{5}LO. Filled and open circles as in Figure 3. From Ref. [22].

to a quantitative description of the lower partial waves up to approximately 300 MeV in the laboratory system, Figure 4 [20–22]. More 3NF diagrams show up at N^{3}LO, as well as the first contributions to four-nucleon forces (4NF). We then see that forces involving more and more nucleons appear for the first time at higher and higher orders, which gives theoretical support to the fact that 2NF $\gg$ 3NF $\gg$ 4NF ....

Further 2PE and 3PE occur at N^{4}LO (fifth order). The contribution, which was first calculated by Entem *et al.* [23], turns out to be moderately repulsive (cf. Figure 3), thus compensating for the attractive surplus generated at N^{3}LO. The long- and intermediate-range 3NF contributions at this order have been evaluated [24, 25], but not yet applied in nuclear structure calculations. They are expected to be sizeable.

Finally turning to N^5LO (sixth order): The dominant 2PE and 3PE contributions to the 2NF have been derived by Entem *et al.* [26]. The effects are small indicating the desired trend towards convergence of the chiral expansion for the 2NF (Figure 3).

5 Phase IV (≈2020 – ????) Future: EFT Based Models(?)

One of the most fundamental aims in theoretical nuclear physics is to understand nuclear structure and reactions in terms of the basic forces between nucleons. As demonstrated in the previous section, the advantage of chiral EFT is that it generates these forces (two- and many-body forces) on an equal footing and in a sytematically improvable way (order by order).

In the pursuit of the fundamental aim, during the past decade, a large number of applications of these chiral NN potentials (up to N^3LO) together with chiral 3NFs (at NNLO) have been conducted. These investigations include few-nucleon reactions, structure of light- and medium-mass nuclei, and infinite matter. Although satisfactory predictions have been obtained in many cases, serious problems persist, like, the "radius problem" [27] and the overbinding of intermediate-mass nuclei [28].

Naturally, one would suspect 3NFs as the most likely mechnism to solve the open questions, particularly, since most current calculations incluce 3NFs only at NNLO. However, the 3NFs at N^3LO and N^4LO are so nightmarishly complicated that it is far beyond the means of an average many-body theoretician to ever include them all. Thus, it appears that chiral EFT, when pursued consistently, becomes ultimately unmanageable.

In view of this frustrating situation, a separate culture has emerged in recent years that takes the liberty to give up the dogmatic perception of chiral effective field *theory*. In this culture, the 2NF and 3NF are treated on the manageable NNLO level. To obtain better results for finite nuclei, the forces are fit (besides to the usual two- and three-nucleon data) also to the properties of light nuclei up to oxygen [29–31]. Aproaches of this kind are, of course, *models*.

Thus, chiral EFT may ultimately suffer the same fate as meson theory: As explained in Sections 2 and 3, meson theory was originally (Phase I) designed to be a quantum field *theory*, but later (Phase II) had to be demoted to the level of a *model* (a very successful model, though). In analogy, during the next phase (Phase IV), we may have to resign ourselves to *chiral EFT based models* (that may hopefully have great success).

The history of nuclear forces clearly shows a pattern of 30-year phases. If these cycles will go on forever or if Phase IV will be the last one, nobody knows at this time.

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