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Nuclear Forces and Chiral Theories

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Abstract. Recent successes in *ab initio* calculations of light nuclei (A=2-6) will be reviewed and correlated with the dynamical consequences of chiral symmetry. The tractability of nuclear physics evinced by these results is evidence for that symmetry. The relative importance of three-nucleon forces, four-nucleon forces, multi-pion exchanges, and relativistic corrections will be discussed in the context of effective field theories and dimensional power counting. Isospin violation in the nuclear force will also be discussed in this context.

1 Introduction

The purview of my talk is chiral (symmetry) aspects of nuclear forces. In order to treat this expanding topic, I will ask and answer three questions. The first question is: What is chiral symmetry (CS) and where does it come from? The second question is: What influence does chiral symmetry have on nuclear physics? Finally, my last question is: What are effective field theories, and why should we be interested in them? The answer to the first question will illustrate how QCD plays a significant role even in the low-energy regime appropriate to nuclear ground and low-lying exited states, where quarks and gluons are not the most appropriate degrees of freedom to perform dynamical calculations. The second answer will discuss how the symmetries of QCD persist when one uses pions and nucleons as the relevant degrees of freedom in a nucleus, and what those symmetries imply in nuclei (power counting). The last question will outline an approach to nuclear physics (chiral perturbation theory or χPT) that is very recent and does not yet approach the quantitative sophistication of traditional nuclear physics. I will outline a recent calculation of isospin violation in the nuclear force and try to illustrate why this approach is superior in many ways to the traditional approach. Finally, I will conclude and summarize.

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2   What is Chiral Symmetry and Why Is It Important?

We are all aware of QCD. Seldom has a theory made such a profound impact on a field such as nuclear physics and yet produced so few hard results. Everyone talks QCD, but in the low-energy regime for more than one nucleon (traditional nuclear physics) there are few successes at relating QCD to nuclear structure. The reasons for this are clear. The success of QCD is founded in large part on its theoretical structure. It is a structurally simple theory when written in terms of quark and gluon fields. Indeed, the theory manifests its symmetries in terms of these variables, particularly in the limit of vanishing quark masses.

One such symmetry[1] is chiral $SU(2)_R \times SU(2)_L$ symmetry, where "R" and "L" refer to right-handed and left-handed (helicity) quarks [1] that separately transform in a particular way in the QCD Lagrangian. In other words, those types of quarks don't talk to each other. The vacuum of our world doesn't share this symmetry and spontaneous symmetry breaking is the result, which leads to massless pions (for massless quarks). If the quarks are given a small mass, these Goldstone bosons derive a small mass, as well. The resulting $SU(2)_V \times SU(2)_A$ symmetry has a conserved vector current and partially conserved axial current (PCAC), which would be conserved if pions were massless.

The "simple" symmetries of QCD pose a problem for nuclear physics, however. We don't ordinarily describe nuclei in terms of quarks. Although there is nothing improper with viewing a nucleus as a large "container" filled with quarks and gluons, our basic description is in terms of "physical" degrees of freedom. If one bombards any nucleus with low-energy photons (for example), nucleons are ejected. At somewhat higher energies pions are emitted. These ejecta are clearly the appropriate degrees of freedom for low-energy ($\lesssim$ a few hundred MeV) nuclear physics, as our gedanken experiment shows.

Chiral symmetry can be expressed in terms of the physical degrees of freedom, but the description is more complicated and not particularly obvious. Unfortunately this also means that determining the constraints of CS for a nucleus is nontrivial and is buried in details of the nuclear force. Chiral models (or theories) exist for the various building blocks required for constructing a nuclear force. We will discuss these details later. We can summarize this section by stating:

- Chiral symmetry arises naturally in QCD at the quark level and persists in nuclear physics dynamics expressed in terms of nucleons and pions.

3   What Influence does Chiral Symmetry Have on Nuclear Physics?

The influence of CS (or more generally, QCD) on nuclear physics can be stated on several levels. Most are obvious, but they should be stated nonetheless.

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[1] A similar chiral symmetry arises in QED if the electron mass is set to zero. This symmetry accounts for differences between Mott and Rutherford back-scattering of electrons from nuclei. This difference provides a mechanism for the separation of charge and transverse multipoles.

- The pion has a very small mass.

- The pion is a pseudoscalar particle.

- The pion is an isovector particle.

- Chiral symmetry forbids extremely large πN interactions.

- The large-mass scale, Λ, associated with QCD is ~ 1 GeV.

The first four items involve the pion. They and their consequences have been well known for decades (even before QCD). The last item is newer and its consequences for nuclear physics are much more subtle.

The first and most obvious of these properties leads to OPEP being the longest-range part of the nuclear force and plausibly the most important component. The second follows from the Goldstone theorem and the properties of the axial current; it leads to a spin-dependent pion-nucleon interaction. Since the strong-interaction Hamiltonian must be an overall scalar, the pion's negative parity must be balanced by another negative parity, which can only come from a vector (e.g., the pion momentum). This vector must then be contracted with a pseudovector, of which only the nucleon spin suffices. Thus we arise at the usual $\sigma \cdot q_\pi$ form of the πN interaction. When we form OPEP, the resulting spin dependence becomes a tensor force, an important distinction from the much-more-tractable central forces.

These two features account for the OPEP dominance seen in light nuclei. Most of the potential energy derives from the tensor force, while OPEP dominates[2] the potential energy: $\langle V_\pi \rangle / \langle V \rangle \sim 75\%$. This complete dominance is due in part to cancellations, but the overall importance of OPEP is a consequence of chiral symmetry.

The isovector nature of the pion is of the utmost importance in meson-exchange currents. This area of nuclear physics provided the first unambiguous evidence for pion degrees of freedom in nuclei. The motion of **charged** particles in any system produces a current. This fact and the long range of OPEP guarantee the pion a dominant role. Recent work in this area[3] is based on χPT and power counting, but we have no space to pursue this very interesting topic.

Another unambiguous demonstration of pion degrees of freedom in nuclei has an added cachet: it comes with error bars. Beginning approximately fifteen years ago, the Nijmegen group have implemented a sophisticated and successful program of Phase Shift Analysis (PSA) of the NN interactions. Their methodology includes treating all known long-range components of the electromagnetic interaction, such as Coulomb, magnetic moment, vacuum polarization, etc., as well as the tail of the NN interaction beyond 1.4 fm, which includes OPEP. The inner interaction region is treated in a phenomenological fashion. This allows an accurate determination of the πN coupling constants[4]. In order to check for systematic errors in the analysis, they also fitted the masses of the exchanged pions (both charged and neutral) and found:

$$m_{\pi^\pm} = 139.4(10)\,\text{MeV}, \tag{1a}$$

$$m_{\pi^0} = 135.6(13)\,\mathrm{MeV}. \tag{1b}$$

The small error bars ($\lesssim 1\%$) further demonstrate the importance of OPEP in the nuclear force. They are currently investigating the tail of the rest of the NN interaction.

A valuable byproduct of this work is the ability to construct potentials by directly fitting to the data, rather than to phase shifts, and to utilize the entire NN data base. Several potential models, such as the Argonne V_{18} model, have been constructed in this way and fit the NN data base far better than any previous attempts. One useful corollary of this work[5] is that a baseline has been set for the triton binding energy (~ 7.62 MeV) using local NN potentials. Nonlocal potential components are mandated by relativity and these are currently under intensive investigation.

3.1 An Opinionated Symmetry

The constraints of chiral symmetry are most easily stated in the form of "opinions", which are detailed below. Because this symmetry is not realized in the usual way (viz., comparing matrix elements of operators that should be (nearly) equal), our tests of CS in nuclei are somewhat indirect. We choose to express the results of such tests as: chiral symmetry and dimensional power counting have an **opinion** about

- the relative size of various components of the two-nucleon force (2Nf);

- the relative sizes of three-nucleon forces (3Nf) and 2Nf;

- the relative sizes of four-nucleon forces (4Nf) and 2Nf, $\cdots$;

- the relative sizes of various components of the nuclear electromagnetic currents, such as the impulse approximation, pion-exchange currents, heavy-meson-exchange currents, etc.;

- the size of relativistic corrections to various parts of the dynamics.

These "opinions" are the result of dimensional power counting – expressing the results of dynamical calculations in terms of powers of the ratio of an average momentum (or energy) component, $\bar{p}$, to Λ, the large-mass QCD scale. Thus, $(\bar{p}/\Lambda)^N$ represents the progression in the sizes of various operators in the nuclear medium. There are rules[6] for determining N for a given case, allowing comparisons to be made. Moreover, in light nuclei we expect $\bar{p} \sim m_\pi c^2$. This estimate is useful but should not be taken too literally.

Power counting is not merely based on our wishes (however strong they may be), but rather on an analysis[6] of the structure of the (generic) effective Lagrangian (based on QCD) underlying nuclear physics. That analysis suggests that the various (dimensional) couplings are given by powers of f_π, the pion decay constant ($\sim$93 MeV), Λ (discussed above), and dimensionless constants (~ 1). The latter assumption is what makes the whole scheme quantitative. Thus, the sizes of individual nuclear operators are expected to be

expressible as $\sim (\bar{p}/\Lambda)^N$. One last ingredient is needed in order to make the scheme useful. If N were negative, higher-order terms in perturbation theory (such as loops) could become quite large. Chiral symmetry prevents that and mandates[6] $N \geq 0$. This non-obvious and nontrivial requirement allows a convergent perturbation theory for low-energy strong-interaction dynamics. Also not obvious is the fact that this condition is equivalent to "pair suppression", an ad hoc (but phenomenologically necessary) procedure that historically was used to eliminate large and unphysical two-pion-exchange forces.
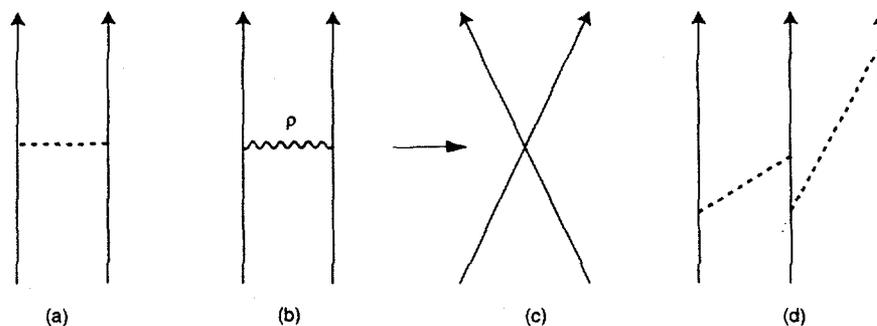

Figure 1. Time-ordered perturbation theory diagrams for nuclear potentials in χPT, with OPEP shown in (a), ρ-exchange in (b) becomes a contact interaction in (c), while overlapping pion exchanges contribute to the 3Nf in (d). Pions are depicted by dashed lines, while nucleons are shown as solid lines.

We can now discuss the various "opinions" in turn. The smallest values of N for the nuclear force correspond to OPEP (shown in Fig. (1a)) and a generic short-range interaction, illustrated in Fig. (1c). Typically the latter might arise from ρ-exchange, as indicated in Fig. (1b), whose range is shrunk to a point. Massive, unstable particles, resonances, etc., cannot propagate very far in the low-energy regime appropriate to effective field theories, and their interaction range is therefore shrunk to a point. Finite-range effects are introduced as derivatives of zero-range interactions. Higher values of N correspond to n-body forces with $N \sim 2n$, and 2-body forces arising from loops. A typical (time-ordered) contribution to a three-nucleon force is shown in Fig. (1d). Thus we expect 4Nf to be smaller than 3Nf, and the latter to be smaller than 2Nf. Indeed, the rule of thumb is that adding nucleons irreducibly to a process increases N by two (each) and adding a loop adds two also. Examples of the latter are two-pion-exchange two-nucleon forces and vertex corrections to one-pion exchange. These forces are therefore considerably weaker than OPEP.

We can also ask the obvious question: do models exist that violate the constraints of CS and generate large 2Nf, 3Nf, $\cdots$? The answer is yes and the problem is indicated in Fig. (2). Pure PS coupling (i.e., γ_5) of a pion to a nucleon leads to large "pair" terms as shown in this figure. These terms are each

$\sim (M/m_\pi)$ larger than chiral models generate, where M is the nucleon mass. Two such factors are thus ~ 50 times larger than what is physically allowed. Very large many-body forces, such as the 4Nf in Fig. (2b), would severely limit the tractability of nuclear physics calculations. They are forbidden by the chiral condition, $N \geq 0$. Thus, CS makes many-nucleon forces small and nuclear physics tractable.
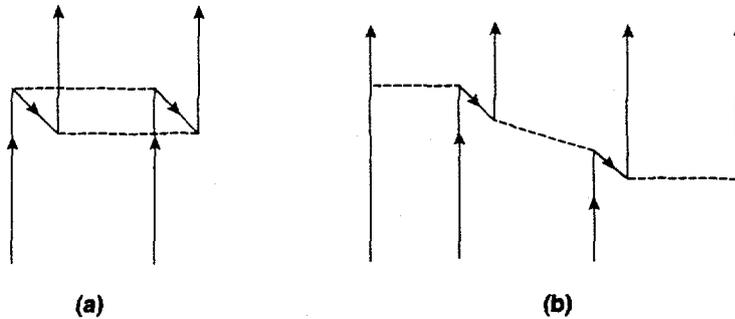
Figure 2. Time-ordered perturbation theory diagrams that emphasize "pair" contributions to the NN force in (a) and to the 4Nf in (b). Pions are depicted by dashed lines, while nucleons are shown as solid lines.

Finally, we note that relativistic corrections fit into this scheme, but have nothing explicitly to do with chiral symmetry. The question of what determines Λ, or even what quantities Λ might subsume, has been deliberately avoided. We simply note that the nucleon mass, M, has a size $\sim \Lambda$, and that an expansion in powers of $1/M$ should behave like an expansion in $1/\Lambda$ (i.e., it should behave like $(\bar{p}/\Lambda)^N$).

3.2 Nuclear Few-body Calculations

Testing these ideas in few-nucleon systems is relatively easy. Few areas of nuclear physics have made such substantive progress in the previous 10 years as few-nucleon physics[7]. We are now solving the Schrödinger equation accurately[8] for the A = 2-6 systems. Such accurate solutions are usually called "exact" or "complete" if their error is $\lesssim 1\%$. The emergence of Green's Function Monte Carlo techniques as the method of choice for nuclear ground states has made accurate calculations possible for systems that were thought to be far out of our reach 10 years ago.

A subset of results from a recent calculation[8] is shown in Table 3.1, including the approximate date when "exact" solutions were first obtained for each nuclear state. The calculations were solutions of the Schrödinger equation for a Hamiltonian containing a recent (accurately fit) NN force and a weak 3Nf, which was adjusted to fit the ^{3}H binding energy. There was no 4Nf. The

agreement between theory and experiment is excellent.

Table 3.1. Calculated and experimental ground-state energies (in MeV) of few-nucleon systems, together with (approximate) dates when they were first accurately solved for "realistic" potentials.

^{A}X(J^π)	^{2}H(1^+)	^{3}H($\frac{1}{2}^+$)	^{4}He(0^+)	^{5}He($\frac{3}{2}^-$)	^{5}He($\frac{1}{2}^-$)	^{6}Li(1^+)
Solved	~1950	1984	1987	1990	1990	1994
Expt.	-2.22	-8.48	-28.3	-27.2	-25.8	-32.0
Theory	-2.22	-8.47(2)	-28.3(1)	-26.5(2)	-25.7(2)	-32.4(9)

We can also extract from these results the (average) amounts of potential energy accruing from 2Nf and 3Nf, and an upper limit estimate of 4Nf from the error bar on the α-particle energy:

$$\langle V_{NN} \rangle \sim 20\,\text{MeV/pair}, \qquad (2a)$$

$$\langle V_{3Nf} \rangle \sim 1\,\text{MeV/triplet}, \qquad (2b)$$

$$\langle V_{4Nf} \rangle \lesssim 0.1\,\text{MeV/quartet}. \qquad (2c)$$

This geometric progression is in accordance with power-counting predictions. We emphasize again that weak many-nucleon forces are essential for tractability. Although we can use the vast amount of NN scattering data to fit the 2Nf, we have no such options for the 3Nf.

As we stated earlier, the long-range two-pion-exchange 2Nf is weak because of CS. There have been a number of recent papers[9] treating aspects of the problem. Ordóñez et al. was the first to develop a chiral force. Ballot et al. shows how CS arranges cancellations to keep the force weak. Because this potential is relatively weak, no experimental demonstration of its existence yet exists.

4 Effective Field Theories and Isospin Violation in the NN Force

We have already mentioned effective field theories several times. These theories[10] can be viewed as approximations to a known theory (such as QCD) or to an unknown (as yet) theory that is valid to a larger energy scale. Such theories are typically non-renormalizable and can even be nonrelativistic (or semirelativistic). A price is paid for the lack of renormalizability. As the order of the calculation increases, more and more parameters appear that must be fit to data, making higher-order calculations both more difficult and less predictive. What saves the scheme is that for sufficiently low energies the expansion is a series in $\bar{p}/\Lambda$, and should converge fairly rapidly in most circumstances.

Why is this better than simply using a model? Models typically have fewer parameters, for example. The strengths of this scheme are at least threefold:

- The individual terms in the Lagrangian are based on symmetry (e.g., CS).

- It is **not** a model – at low energies it should have all of the content of the original or covering theory (but less predictive power).

- Power counting allows one to estimate with reasonable accuracy the size of various contributions without detailed calculations.

The latter is an extremely useful and powerful technique, as we have seen.

As an illustration we will review the work of van Kolck[11] on isospin violation in the nuclear force, and estimate the size of isospin violation in one-pion-range nuclear forces by comparing to results from the Nijmegen PSA. In the latter work, after accounting for well-established forms of isospin violation such as the NN Coulomb force, magnetic moment interactions between the nucleons, the $n - p$ mass difference in the nucleon's kinetic energy, etc., three πN coupling constants were determined[4]. These correspond to π^0-exchange between two protons, $f^2_{\pi^0 pp}$, or the exchange between a neutron and proton of a π^0, $f_{\pi^0 pp} f_{\pi^0 nn}$, or a charged pion, $f^2_{\pi^c np}$. OPEP depends linearly on f^2, which we define as

$$f^2 = \frac{1}{4\pi} \left(\frac{g_A \, m_{\pi^+} + d}{2 f_\pi} \right)^2 , \tag{3}$$

where g_A is the axial-vector coupling constant and $d - 1$ is the Goldberger-Treiman(GT) discrepancy (> 0) and a measure of chiral-symmetry breaking. In terms of d and $G \sim 13$ (the "pseudoscalar" form of the πN coupling constant) we write the GT relation[12] in the form

$$\frac{G}{M} = \frac{g_A \, d}{f_\pi} . \tag{4}$$

For reference purposes we note that setting d to 1 and using current values of g_A and f_π produces $f_0^2 = 0.0718(5)$ in eq. (3).

Table 4.1. Pion-nucleon coupling constants determined by the Nijmegen[4] PSA.

$f^2_{\pi^0 pp}$	$f_{\pi^0 pp} f_{\pi^0 nn}$	$f^2_{\pi^c np}$	Type
0.0751(6)	0.0752(8)	0.0741(5)	np and pp
	0.0745(9)	0.0748(3)	np only

Two sets of coupling constants are available and are shown in Table 4.1. The combined np and pp data sets yield the three values in the first line, while a preliminary solution for np scattering alone gives the two values in the second line. These values are all roughly 4% greater than the value of f_0^2 above, implying that $d - 1$ is $\sim 2\%$, much lower than most previous values. We note that systematic effects would enter these results in different ways. The pp data must be carefully corrected for the Coulomb interaction, which plays only a very minor role in np scattering. We also note that charge-symmetry breaking (CSB) in the pion-range force involves a $pp - nn$ comparison and does not contribute in the second (np only) case, but charge dependence (CD) will.

In qualitative terms our three experimental numbers from Nijmegen determine the isospin-symmetric d and the CSB and CD πN coupling constants.

The formalism for analyzing these results has been developed by van Kolck[11]. Isospin violation (IV) can be divided into 3 convenient types based on its origin. The u-d quark-mass difference generates one type of IV that has the (tensorial) character of the third component of total isospin, and should be proportional to ϵm_π^2, where $\epsilon = \frac{m_d - m_u}{m_d + m_u} \sim 0.3$ characterizes the quark masses. These contributions are also chiral-symmetry breaking. Hard electromagnetic (EM) processes at the quark level will have a different (tensorial) isospin character and generate the second type, which should be proportional to $\bar{\delta} m_\pi^2$, the (squared) difference of the pion masses. Soft EM processes form the third category and are of order α, the fine structure constant. There are a daunting number of individual diagrams that must be calculated[13] and we will present here only a much simplified overview of where individual mechanisms (most of which are well known) fit into this scheme.

The first difficulty is that we must try to place these categories into an approximate (size) relationship with each other. van Kolck has argued that since the pion mass difference is primarily of type II (i.e., EM) and the nucleon mass difference mostly type I (i.e., quark mass difference), these terms should be considered on the same level. Although this prescription probably underestimates most EM contributions slightly, it results in the entries in Table 4.2. The order refers to power counting, with OPEP roughly of order 0, while tree and loop refer to the structure of the corresponding diagrams, such as those in Fig. (3). The upper entry in each box describes the fundamental interaction, while the lower (bold-faced) entry describes its effect on the nuclear dynamics.

Some examples can be correlated with entries in Fig. (3). Isospin violations are indicated by a cross, so that Fig. (3a) indicates the CD effect of the pion-mass difference on OPEP. This is listed in the first box (1-tree) together with the pp Coulomb force shown in Fig. (3b). Smaller EM effects (magnetic moment interactions, etc.) are listed in the third box under Breit interaction. The shift of nucleon masses ($\delta M_N \sim M_n - M_p$) has three consequences: (1) an overall energy shift that does not affect physics; (2) a change in the kinetic energies, $p^2/2M$, of the individual nucleons according to whether they are neutrons or protons (indicated in the third box); (3) the effect of the mass difference inside loops. The nucleon mass splitting is proportional to t_z, the third component of total (nucleon) isospin, which equals $(Z-N)/2$ and is fixed. On the other hand in loops where pions are circulating it is possible for an np pair to virtually dissociate into $pp\pi^-$. This changes the nucleons' isospin and demonstrates that loops with different nucleon masses can therefore play a role in IV.

All of the effects listed above (except loop contributions) are included in the Nijmegen analysis, and we don't need to correct for them. Two additional categories do play a role: the effect of isospin violation in the $\pi^0 N$ coupling constants (indicated by the cross in Fig. (3c)), and $\pi - \gamma$ range NN forces[14] of the type shown in Fig. (3d) and the fourth box in Table 4.2. The latter are not included in analyzing NN scattering data and their effect is unknown, although their order is the same as CD modifications of f^2.

Table 4.2. Contributions to isospin violation in the NN force in orders 1,2, and 3 beyond the usual OPEP, including tree and loop processes, are shown in individual boxes. The first entry of each type corresponds to the elementary vertex, while directly below the single line (in boldface) is the corresponding nuclear contribution. Charge-dependent and charge-symmetry-breaking processes are denoted CD and CSB, respectively.

| ORDER	QUARK MASSES	ELECTROMAGNETIC
1-tree	Nucleon masses	Coulomb interaction Pion masses
	Overall energy shift	**pp Coulomb force** **OPEP(masses) [CD]**
2-tree	πN interaction Pion masses	Nucleon masses
	OPEP(π_0) [CSB] **OPEP(masses) [CD]**	**Overall energy shift**
3-tree	Nucleon kinetic energies	Other nucleon EM πN interaction
	Nucleus kinetic energy	**Breit interaction** **OPEP(π_0) [CD + CSB]**
3-loop	Nucleon masses and KE Pion masses - OPEP OPEP(π_0) [CSB]	Nucleon masses and KE Pion masses - OPEP **OPEP(π_0) [CD and CSB]** **$\pi - \gamma$ NN forces [CD]**

(a) (b) (c) (d)
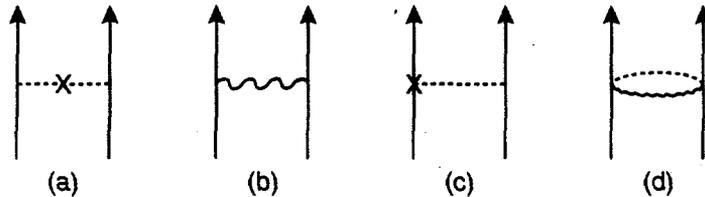
Figure 3. Nuclear isospin-violating interactions, with the pion-mass-difference effect on OPEP shown in (a), the static Coulomb interaction in (b), the isospin-violating pi-nucleon coupling illustrated in (c), and the double-seagull (transverse-)photon-pion exchange is sketched in (d). Solid lines are nucleons, dashed lines are pions, small wavy lines are (virtual) transverse photons, while large wavy lines are Coulomb interactions.

Ignoring loops and terms that contribute to them, we can write van Kolck's *chiral-symmetry-breaking and isospin-violating terms that contribute at tree*

level in the form:

$$L \sim -\frac{1}{f_\pi} \overline{N}\boldsymbol{\sigma} \cdot \boldsymbol{\nabla}[g_A \, d\, \boldsymbol{t} \cdot \boldsymbol{\pi} - \frac{\beta_1}{2}\pi_0 - \frac{\bar{\beta}_{10}}{2}t_z\pi_0]N \, . \tag{5}$$

The three terms in order are the usual πN coupling (including the GT discrepancy) and the CSB and CD πN vertices. This form can be analyzed with the Nijmegen coupling constants to produce the results in Table 4.3. We had previously estimated $d-1$; the values of β_1 and $\bar{\beta}_{10}$ are consistent with zero and there is no evidence of any systematic disagreement between the two sets of results. We note that the dimensional power counting estimate of β_1 is $\sim 6 \cdot 10^{-3}$, while that of $\bar{\beta}_{10}$ is $\sim 3 \cdot 10^{-3}$. Thus, our results (consistent with zero) are also consistent with expectations of a very small isospin violation.

Table 4.3. GT discrepancy and isospin-violating pion-nucleon coupling constants determined by the Nijmegen PSA.

$d-1$	β_1	$\bar{\beta}_{10}$	Type
1.6(5)%	1(9) $\cdot 10^{-3}$	-19(16)$\cdot 10^{-3}$	np and pp
2.1(5)%		5(16)$\cdot 10^{-3}$	np only

5 Summary

Chiral symmetry arises at the quark level in QCD and persists in descriptions based on pions and nucleons as effective degrees of freedom. One-pion exchange dominates in the binding of light nuclei and in meson-exchange currents. Chiral symmetry provides order in nuclear forces: without this symmetry nuclear physics would be intractable. Turning the argument around, the tractability of nuclear physics provides strong evidence for chiral symmetry, which weakens N-body forces as N increases and n-pion exchanges compared to OPEP. Isospin violation upper limits obtained from the Nijmegen PSA are compatible with dimensional power counting estimates. Finally, few-nucleon systems continue to be the testing ground for new ideas in nuclear physics because of our ability to calculate accurately in those systems.

6 Acknowledgments

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