Is chiral symmetry manifested in nuclear structure?

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Abstract. Spontaneously broken chiral symmetry is an established property of low-energy quantum chromodynamics, but finding direct evidence for it from nuclear structure data is a difficult challenge. Indeed, phenomenologically successful energy-density functional approaches do not even have explicit pions. Are there smoking guns for chiral symmetry in nuclei?

1. Challenge

Spontaneously broken chiral symmetry is a key property of quantum chromodynamics (QCD) at low energies. It gives rise to pseudo-scalar Goldstone bosons, the pions, which because of non-zero light quark masses are not massless, but are much lighter than other hadrons. For nuclear forces, the immediate consequence is the one-pion-exchange (OPE) potential with its long range and characteristic tensor structure. In more detail there are constraints on the form of interactions in effective low-energy Lagrangians\textsuperscript{[1 2 3]}. Since nuclear structure is ultimately determined by low-energy QCD and the nuclear Fermi momentum is comparable to $2m_\pi$, one might expect stark evidence from data for the fingerprint of chiral symmetry. Thus we pose the question: Can we find smoking guns for chiral symmetry in nuclei?

Because calculations based on chiral symmetry consequences (understood broadly to range from including OPE to full consistency with chiral symmetry constraints in low-energy Lagrangians) are becoming increasingly able to describe nuclear structure, one might think the question is moot. But we are not asking here whether theories or models consistent with chiral symmetry are sufficient to describe data, but whether the experimental data says this physics is necessary. This is a more difficult question and one with some counterexamples to the need for explicit chiral symmetry. At one extreme, pionless effective field theory (EFT) describes few-body scattering at very low energies and nuclear binding up to at least the alpha particle\textsuperscript{[1 4]}. At the other extreme, energy-density functional approaches to medium and heavy nuclei (such as Skyrme) have wide phenomenological success without explicit pions\textsuperscript{5}. 
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In trying to identify manifestations of chiral symmetry, it is important to make the distinction between long-range chiral physics and short-range physics, which may be free of chiral symmetry constraints. Nuclear structure will in general have contributions from both. To find a smoking gun, one will likely need to identify observables (or combinations of observables) that are sensitive to the long-range parts.

Because it is spontaneously broken, chiral symmetry most directly relates processes with different numbers of pions. Clear signatures of chiral symmetry, even of the most basic pion properties (such as OPE), can become a more subtle question for processes with no pions in the initial or final state, which include nuclear structure properties such as binding energies and spectra. The signatures can be particularly obscured for bulk properties, where the pion effects at the mean-field level may be washed out by spin and isospin averaging.

2. Smoking guns for chiral symmetry in other contexts

For our challenge to find smoking guns in nuclear structure we adopt a broad definition of evidence for chiral symmetry, which encompasses the quantitative implications of a light pion and its quantum numbers (such as OPE) as well as the more subtle effects that constrain low-energy chiral Lagrangians. Such smoking guns for spontaneously broken chiral symmetry are readily found in data from other strong interaction contexts. The spectrum of mesons is the most obvious, where \( m_\pi^2 \ll m_\rho^2 \) manifests the approximate Goldstone boson nature of the pion and would-be parity doublets (e.g., the \( \rho \) and \( a_1 \)) are split in mass. The physics of low-energy \( \pi-\pi \) and \( \pi-N \) scattering, which is governed by chiral physics, provide many other examples. Here the successes of chiral perturbation theory closely tie experiment and theory through chiral symmetry [6, 7].

For nucleon-nucleon (NN) interactions, the situation is more subtle. For example, the unnaturally large NN scattering lengths are not related to chiral symmetry, but dominate the physics at very low energies. However, a compelling prototype for the sort of direct evidence for chiral symmetry we seek from nuclear structure data can be found in the partial-wave analyses of NN scattering by the Nijmegen group and collaborators. This example also lets us define more concretely what we are looking for. Simply an improved \( \chi^2 \) for a fit to NN data using interactions with an input one-pion exchange potential (or two-pion exchange) is not the strong and direct evidence we prefer. (After all, it is possible to fit this data accurately with inverse scattering potentials with no pion exchange component.) Rather it is the unbiased extraction through the fitting process of pion parameters that we call a smoking gun.

As part of the analysis described in Ref. [8], the masses of the charged and neutral pions were used as fit parameters. The extracted values agreed with experiment within estimated one percent errors. At the same time the pion-nucleon coupling was obtained from the fit and found consistent with extracted values from \( \pi-N \) scattering [8, 9]. The data provides very clear signals for this coupling; indeed, the \( pp\pi^0 \) coupling is said to be determined from each individual partial wave except for \( ^1S_0 \) [8].
Subsequent studies looked at the partial wave analysis with a finer microscope and found direct evidence of two-pion exchange (TPE) physics \[10,11\]. Fitting the pion mass again but now as a parameter in the TPE potential gave agreement with experiment at the ten percent level. Other evidence includes consistency of the $c_i$ couplings of the sub-leading TPE with determinations from $\pi-N$ scattering. It is worth noting that the sub-leading TPE provides the long-range part of three-nucleon (3N) forces. Finding smoking guns for chiral symmetry in nuclear structure may therefore be tied to including 3N interactions.

In the example of NN phase shifts, the sensitivity to pion physics can be enhanced by concentrating on the peripheral partial waves (e.g., G-waves and higher are fully explained by pion exchanges). This isolates the long-distance physics, which is chiral physics. Even so, a careful analysis of statistical and systematic errors together with a large database was required to cleanly extract the direct evidence for sub-leading chiral effects. This highlights the difficulty in meeting the challenge for nuclear structure, where the chiral origin of mid-range physics from TPE may be difficult to resolve.

3. Opportunities

There are many opportunities to build on existing efforts in the search for chiral smoking guns. The growing applications of chiral EFT to nuclear structure through no-core shell model, coupled cluster, and lattice EFT calculations are building foundations for the desired evidence from data and for investigations similar to the NN partial-wave analyses. We emphasize again that while phenomenological success starting from microscopic theories incorporating chiral symmetry is gratifying, this type of indirect evidence is not what we are looking for. As the accuracy improves, however, we can ask whether distinctions that point to pions and then more subtle chiral symmetry constraints will become apparent (as with TPE in the prototype partial-wave analysis). For nuclear structure evidence, many-body force contributions from long-range TPE may be key.

Other possibilities for smoking guns are in shell-model calculations that start from interactions including pion physics, with monopole (or more) adjustments fit to reproduce spectra and binding energies in a major shell. Do the fits of shell-model interactions favor pion exchanges for the long-range parts? If so, is it possible to isolate data that are most sensitive to the long-range parts (e.g., to constrain their sub-leading contributions)?

A third category may provide the greatest challenge to finding explicit chiral symmetry: energy-density functionals (EDF). Accurate calculations of binding energies and other properties are made across the mass table by EDF’s such as Skyrme or Gogny, which do not have explicit pions. Relativistic EDF’s in principle start with pions but they do not contribute at the mean-field level used in relativistic phenomenology. Naive dimensional analysis for fit parameters in EDF’s (Skyrme or covariant) is suggestive of chiral signatures \[12,13\] but is not quantitative enough to be conclusive. We expect
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generalized EDF’s will be needed to find smoking guns.

There have been many studies that hint at a special role for chiral symmetry in nuclear structure. These include a wide array of models that implement a partial restoration of chiral symmetry at finite density, in-medium QCD sum rules, and Brown-Rho scaling (see for example Refs. [14, 15]). None of these rise as yet to the level of a smoking gun for nuclear structure; the challenge is to make them sufficiently quantitative and predictive based on data (rather than model input).

Other direct possibilities for finding smoking guns of chiral symmetry may lie with in-medium chiral EFT, which has been under recent development (see Refs. [3, 16] and references therein). There are open questions, such as the convergence of the perturbative approach, but it has the explicit chiral ingredients needed. We can ask: are there unique predictions from long-range pion physics? These may be difficult to find, as illustrated by the subtleties in pinning down the origin of the spin-orbit splittings in nuclei. One might hope for the same type fitting as in NN phase shifts. A possibility already being considered is the fitting of energy-density functionals that have been supplemented with long-range chiral EFT physics. This would mean letting the pion parameters float in the fits in the same way as in the Nijmegen phase shift analyses. The answer is as yet unknown to even the most basic question: Do medium and heavy nuclei know the pion mass and coupling?

What can we say in general about where one should look for chiral symmetry signatures? Searching in bulk properties will be difficult because of the averaging of pion contributions and the important role of short-range physics. The task is to identify observables (analogous to peripheral partial waves) that isolate contributions from long-range pion physics. Past suggestions have included single-particle energies, where the pion tensor force may be isolated; isotope chains, where small differences from the isospin dependence due to pion exchanges including long-range 3N forces may be amplified; collective excitations with pionic quantum numbers; electroweak axial-charge transitions and properties of pionic atoms (see for example Refs. [16, 17, 18]).

4. Final comments

Our challenge to nuclear structure theorists is to search for direct manifestations of chiral symmetry in nuclei. Success in this quest will help to unify descriptions of strong-interaction phenomena, identify sensitivities that can suggest profitable new experiments, guide microscopic calculations of nuclear properties toward greater precision, and foreshadow what to expect under extreme conditions. It can also lead to ties to lattice QCD, whose growing successes give rise to dreams of direct calculations of the lightest nuclei, enabling new insights to chiral symmetry in nuclear structure. However, the challenge to find smoking guns can also be constructively answered in a negative way, by showing that explicit chiral symmetry is not necessary for particular nuclear structure observables. So an alternative question to pose is: where are effective field theories of nuclei without pionic degrees of freedom applicable?
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