Large Lorentz Scalar and Vector Potentials in Nuclei

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Abstract

In nonrelativistic models of nuclei, the underlying mass scales of low-energy quantum chromodynamics (QCD) are largely hidden. In contrast, the covariant formulations used in relativistic phenomenology manifest the QCD scales in nuclei through large Lorentz scalar and four-vector nucleon self-energies. The abundant and varied evidence in support of this connection and the consequences are reviewed.

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I. PROLOG

Large Lorentz scalar and four-vector nucleon self-energies or optical potentials, each several hundred MeV in the interior of heavy nuclei, are key but controversial ingredients of successful relativistic phenomenology\(^1\)\(^2\). The controversy has persisted because there can be no direct experimental verification (or refutation) of such large nuclear potentials. Here we revisit this issue from the modern perspectives of effective field theory (EFT) and density functional theory (DFT)\(^3\). We argue that the large potentials in the covariant representation used in relativistic phenomenology are manifestations of the underlying mass scales of low-energy quantum chromodynamics (QCD), which are largely hidden in nonrelativistic treatments.

The connection between low-energy QCD scales and nuclear phenomenology can be made by applying Georgi and Manohar’s Naive Dimensional Analysis (NDA) and naturalness\(^4\). These principles prescribe how to count powers of the pion decay constant \(f_\pi \approx 94\) MeV and a larger mass scale \(\Lambda\) in effective lagrangians or energy functionals. The mass scale \(\Lambda\) is associated with the new physics beyond the pions: the non-Goldstone boson masses or the nucleon mass. The signature of these low-energy QCD scales in the coefficients of a relativistic point-coupling model\(^6\) was first pointed out by Friar, Lynn, and Madland\(^7\). Subsequent analyses have extended and supplemented this idea, testing it in nonrelativistic mean-field models as well as in different types of relativistic models\(^8\)\(^9\). Estimates of contributions to the energy functional from individual terms, based on NDA power counting, are quantitatively consistent with direct, high-quality fits to bulk nuclear observables\(^10\). Naturalness based on NDA scales has proved to be a very robust concept: nuclei know about these scales!

The EFT perspective, with the freedom to redefine and transform fields, implies that there are infinitely many representations of low-energy QCD physics. However, not all are equally efficient or physically transparent. One of the possible choices is between relativistic and nonrelativistic formulations. (In the context of EFT, these can be related by the heavy-baryon expansion.) We suggest that the relativistic formulation offers greater insight.

Relativistic phenomenology for nuclei has often been motivated by the need for relativistic kinematics when extrapolating to extreme conditions of density, temperature, or momentum transfer. However, this obscures the issue of relativistic vs. nonrelativistic approaches for nuclei under ordinary conditions. The important aspect of relativity in ordinary nuclear systems is not that a nucleon’s momentum is comparable to its rest mass, but that maintaining covariance allows scalars to be distinguished from the time components of four vectors.

Despite a long history of criticisms of relativistic approaches\(^11\)\(^12\),\(^13\), the use of a relativistic formulation should not itself be a point of contention. The EFT/DFT perspective has largely abrogated the objections, as we discuss more fully in Ref.\(^14\). Furthermore, recent developments in baryon chiral perturbation theory support the consistency (and usefulness) of a covariant EFT, with Dirac nucleon fields in a Lorentz invariant effective lagrangian

\(^1\)In this paper we use “relativistic phenomenology” to refer only to field-theory based models, and not to the relativistic hamiltonian models discussed in Ref.\(^1\).
A similar framework underlies relativistic approaches to nuclei. In the nuclear medium, a covariant treatment implies distinct scalar and four-vector nucleon self-energies. The relevant question is: what are their mean values? Relativistic phenomenology suggests several hundred MeV in the center of a heavy nucleus.

Historically, the successes of nonrelativistic nuclear phenomenology have been cited to cast doubt on the relevance of large scalar and vector potentials. But in a nonrelativistic treatment of nuclei, the distinction between a potential that transforms like a scalar and one that transforms like the time component of a four-vector is lost. Because the leading-order contributions of these two types are opposite in sign, an underlying large scale characterizing individual covariant potentials would be hidden in the nonrelativistic central potential. Furthermore, the EFT expansion implies that even potentials as large as 300 to 400 MeV are sufficiently smaller than the nucleon mass that a nonrelativistic expansion should converge, if not necessarily optimally. Thus the success of nonrelativistic nuclear phenomenology provides little direct evidence about covariant potentials.

If there were an approximate symmetry that enforced the cancellation between scalar and vector contributions, then it would be desirable to build the cancellation into any EFT lagrangian or energy functional. (Chiral symmetry alone does not lead to scalar-vector fine tuning.) However, if the cancellation is accidental or of unknown origin, then hiding the underlying scales may be counterproductive. We argue that nuclei fall into the second category, with the relevant scales set not by the nonrelativistic binding energy and central potential (tens of MeV), but by the large covariant potentials (hundreds of MeV). The signals of large underlying scales would be patterns in the data that are simply and efficiently explained by large potentials, but which require more complicated explanations in a nonrelativistic treatment.

Scattered through the literature over many years is evidence to support our contention that a representation with large fields, which is achieved only with a covariant formulation, is natural. We believe that in light of the EFT and DFT reinterpretation of relativistic phenomenology, it is appropriate at this time to compile and update the arguments to highlight their strengths and weaknesses. In the following section, we give a concise list of empirical and theoretical evidence that large scales are natural for nuclei, with short descriptions and pointers to more detailed discussions. We also include with each item a brief discussion (which we will call a “loophole”) of how large fields could be avoided, even in a covariant formulation.

II. QCD SCALES IN NUCLEI

1. Covariant density functionals fit to nuclei. Conventional density functional theory (DFT) is based on energy functionals of the ground-state density of a many-body system, whose extremization yields a variety of ground-state properties. In a covariant generalization of DFT applied to nuclei, these become functionals of the ground-state scalar density $\rho_s$ as well as the baryon current $B_{\mu}$. Relativistic mean-field models are analogs of the Kohn–Sham formalism of DFT, with local scalar and vector fields $\Phi(x)$ and $W(x)$ appearing in the role of relativistic Kohn–Sham potentials. The mean-field models approximate the exact functional, which includes...
FIG. 1. Contributions to the energy per particle in $^{208}$Pb for two relativistic point-coupling models from Ref. [11] are shown as large unfilled symbols (one model on each side of the error bars). Absolute values are shown. The filled symbols denote the sum of the values for each power of the density. The small symbols indicate estimates based on NDA, with the error bars corresponding to natural coefficients from 1/2 to 2. The binding energy per nucleon in nuclear matter is denoted with $\epsilon_0$. See Ref. [14] for more details.

all higher-order correlations, using powers of auxiliary meson fields or nucleon densities.

The scalar and vector potentials are determined by extremizing the energy functional, which gives rise to a Dirac single-particle hamiltonian. The isoscalar part (for spherical nuclei) is

$$h_0 = -i\nabla \cdot \alpha + \beta\left(M - \Phi(r)\right) + W(r),$$

where $M$ is the nucleon mass and we define $M^* \equiv M - \Phi$. It is not necessary to assume that $\Phi$ is simply proportional to a scalar meson field $\phi$. In fact, $\Phi$ could be proportional to $\phi$ (as in conventional quantum hadrodynamic models [2,3]), or could be expressed as a sum of scalar and vector densities (as in relativistic point-couplings models [9]), or could be a nonlinear function of $\phi$ (e.g., see Refs. [29–31]).

The parameters of the density functional for generalized models have been determined by detailed fits to a set of nuclear properties that should be accurately reproduced according to DFT [7,11]. Except when a large isoscalar tensor coupling is included, the scalar and vector potentials $\Phi$ and $W$ are always larger than 300 MeV in the interior of a nucleus. These potentials produce a hierarchy of energy contributions that follow the NDA predictions, as illustrated by the large unfilled symbols in Fig. 1. This agreement persists when correlation corrections are included explicitly [32], and provides strong evidence that nuclear observables demand naturally sized parameters.
Loophole: The addition of an isoscalar tensor coupling in the energy functional allows excellent fits to nuclear properties while reducing the size of the scalar and vector potentials slightly, to roughly 250 MeV [33–35]. It should also be noted that relativistic formulations of DFT at present lack the rigor of conventional DFT [27,36]; a re-examination from the EFT perspective may improve the situation.

2. Natural size of leading contribution to binding energy per nucleon. Coefficients in successful relativistic mean-field models are consistent with naive dimensional analysis (NDA) and naturalness, as expected in low-energy effective field theories of QCD [4,7,11]. If one applies naturalness arguments to the terms in a relativistic energy functional for nuclear matter and nuclei, the leading scalar and vector terms at equilibrium density $\rho_0$ are each predicted to be of order $\rho_0^2/f_\pi^2 \approx 150$ MeV [14], independent of $\Lambda$. (The $n = 2$ energy estimate in Fig. 1 is lower because it uses an average density in $^{208}$Pb rather than the peak density in the interior.) The scalar and vector potentials $\Phi$ and $W$ in Eq. (1) are each twice the corresponding energy contributions [11], so they are predicted to be roughly 300 MeV in the center of a nucleus.

Loophole: Naturalness may give only order-of-magnitude estimates and there are numerical factors (e.g., combinatoric factors) that may not be correctly accounted for. On the other hand, the estimates of contributions to the binding energy, recently extended to all terms in the energy functional, appear to be quite robust [14] (see Fig. 1).

3. One-boson-exchange potentials. The nucleon-nucleon (NN) scattering matrix can be calculated by unitarizing a kernel for the NN force. The Lorentz structure of the kernel follows from covariance, without mentioning degrees of freedom, but it can be efficiently characterized in terms of boson exchanges in different physical channels. This is a very natural procedure from the point of view of dispersion theory [37].

Each channel is characterized by strength and range parameters and a cutoff. A physical interpretation of each is not needed since the states are virtual in NN scattering. The parameters are directly related to prominent resonances in some channels (vector), but not in others (scalar). Every accurate fit of the parameters to NN observables using the most general (covariant) kernel has led to an interaction with large, isoscalar, scalar and vector contributions of comparable magnitude, but opposite in sign [38]. In the nuclear medium, these scalar and vector NN amplitudes translate into strong single-particle potentials, of order several hundred MeV at equilibrium density. These strong potentials persist when short-range correlations are included explicitly [38].

Loophole: There may be alternative (covariant) decompositions of the kernel that do not result in large scalar and vector components (but we are unaware of any!).

4. Nuclear saturation and observed spin-orbit splittings. If one adopts a covariant formulation of the energy functional, the Lorentz transformation properties of a scalar component induce a velocity dependence in the interaction. When the functional is fit to nuclear saturation in nuclear matter, one automatically produces a spin-orbit force and its observable consequences in a finite system (e.g., nuclear shell structure) [24]. Furthermore, the strength of the spin-orbit interaction with natural-sized scalar and
vector potentials agrees with the empirical strength (see Fig. 2 with \( M_0^*/M \approx 0.60 \)). In contrast, the spin-orbit contribution in nonrelativistic energy functionals must be adjusted by hand \[39\].

To our knowledge, there are no simple alternative explanations for the origin of the full spin-orbit strength. Negele and Vautherin \[40,41\] tried to take Brueckner calculations of light nuclei and extract the spin-orbit force from the splittings, but found only a fraction of the empirical magnitude, equal to the result obtained by applying Thomas precession to the nonrelativistic central potential. The most sophisticated modern calculations get only half of the empirical spin-orbit splittings in light nuclei without including three-nucleon forces, and only two-thirds of the splittings using current three-nucleon-interaction models \[42–44\].

**Loophole:** An isoscalar tensor term can be used to partially reduce the scalar and vector potentials while maintaining a large spin-orbit splitting (the filled symbols in Fig. 2) \[34\].

5. **Proton–nucleus scattering spin observables.** In impulse approximation calculations of medium-energy proton–nucleus scattering spin observables, relativistic treatments with large scalar and vector optical potentials accurately reproduce the data, while nonrelativistic treatments are deficient \[49–51\]. To get agreement at a similar level in a nonrelativistic formulation, one has to go beyond the simplest impulse approximation to include a full-folding treatment \[52\] and medium effects \[53\] (e.g., with a \( G \)-matrix interaction). Furthermore, while the radial shapes of the scalar and vector
FIG. 3. The real parts of the scalar ($S$) and vector ($V$) optical potentials and the corresponding nonrelativistic central and transformed vector-tensor ($V', T'$) potentials for proton scattering from $^{40}$Ca at two energies. [The sign convention for the scalar potential $S$ is opposite to that of $\Phi$ from Eq. (1).] The optical potentials are derived from a global fit over a wide range in energy [54,55].

potentials simply look like the nuclear (baryon) densities with an energy-dependent overall scale, the geometries of the nonrelativistic optical potentials are much less intuitive and change qualitatively with different incident energies (see Fig. 3). Thus the treatment is clean when natural scales are manifest but becomes more complicated when they are hidden.

Loophole: Large scalar and vector optical potentials can be transformed away in favor of smaller potentials of different Lorentz structure [56]. However, the transformed potentials no longer have simple radial shapes (see Fig. 3) [56].

6. Energy dependence of the nucleon-nucleus optical potential. The real part of the empirical optical potential for nucleon–nucleus scattering up to 100 MeV incident kinetic energy $\epsilon$ has a well-determined, nearly linear energy dependence of $-0.3\epsilon$ [57]. This energy dependence is directly predicted in a relativistic mean-field formulation to be $-(W/M)\epsilon$ [2], which is quantitatively correct for a vector potential of natural size. In contrast, the energy dependence in conventional nonrelativistic treatments arises from the non-locality of the exchange corrections in a Hartree–Fock or Brueckner–Hartree–Fock approximation to the mean-field part of the optical potential. Explicit studies of relativistic calculations at different approximation levels show that the energy dependence is dominated by the direct contribution and that exchange corrections are small [58,59].

Loophole: A direct connection between energy dependence from the Lorentz structure of the interaction in relativistic formulations and from exchange corrections in
7. **Pseudo-spin symmetry.** There is an observed near-degeneracy among sets of energy levels in medium and heavy nuclei, which have been called *pseudo-spin doublets* [45]. This degeneracy relies on having a specific relationship between the nonrelativistic central and spin-orbit potentials. Ginocchio has shown that this relationship follows from an $SU(2)$ symmetry of a covariant single-particle hamiltonian if the nucleon scalar and vector potentials are equal in magnitude [46,47]. Such a hamiltonian with covariant Kohn–Sham potentials $\Phi$ and $W$ results from the extremization of relativistic energy functionals.

In the exact symmetry limit, with $\Phi = -W$, there are no bound positive-energy states, so nuclei do not exist. However, an approximate pseudo-spin symmetry leading to approximate pseudo-spin doublets exists for $\Phi \approx -W$ [46]. Each potential must be individually large, since their (near) cancellation must leave a sufficient residual central potential for nuclear binding.

*Loophole:* The symmetry is significantly broken for empirical relativistic potentials and the consequences of this breaking are not understood, so the evidence for pseudo-spin symmetry is not entirely convincing. The observed doublets could be accidental or have an unrelated origin [48].

8. **Correlated two-pion exchange, chiral symmetry, and scalar strength.** The scalar-isoscalar part of the NN kernel below 1 GeV can be studied in an essentially model-independent way in terms of $\pi-\pi$ scattering in this channel [60–62]. Chiral symmetry and unitarity constrain the threshold behavior. The natural strength of the $\pi-\pi$ interaction implies that the amplitude increases from zero as fast as the unitarity bound. The predicted integrated strength is consistent with a large scalar potential [63,64]. Thus we can understand the origin of the large scale in the scalar channel from QCD symmetry constraints, unitarity, and naturalness.

*Loophole:* We do not know of a loophole here.

9. **Cancellations and fine-tuning of nuclear matter.** The small binding energy of nuclear matter would appear to be a counter argument to the claim that the natural scale for nuclei is several hundred MeV. It would be valid, however, only if nuclear matter were an ordinary, nonrelativistic Fermi system. The existence of a minimum in the energy per particle suggests that different orders in the expansion of the energy in powers of the Fermi momentum $k_F$ must be comparable. A logical conclusion is that this should occur only near the underlying mass scale, where all terms contribute roughly equally, and that the binding energy should be roughly of this scale. Yet the empirical equilibrium conditions are not consistent with this conclusion.

In fact, nuclear matter appears to be an exceptionally fine-tuned system, with an equilibrium density far lower than expected for an ordinary Fermi liquid [65,66]. Covariant formulations offer a compelling explanation: there is an interplay of different orders in the energy expansion, but it is highly restricted. In particular, repulsion from the $k_F^5$ and $k_F^6$ terms becomes important compared to the attraction from the $k_F^3$ piece well below an underlying scale of order several hundred MeV. Furthermore, this happens...
because the coefficient of the $k_F^3$ term is “unnaturally” small, roughly half the size one would expect from NDA estimates. In covariant models, this is a direct result of cancellations between Lorentz scalar and vector contributions that are each of natural size. The cancellations leading to a small $k_F^3$ term do not recur in higher orders.

This scenario can be tested using $k_F$ expansions for the energy from phenomenologically successful nonrelativistic and relativistic mean-field models. If the coefficient of the $k_F^3$ term in one of these expansions is doubled or tripled in size, equilibrium does occur at much higher density and the system is bound by 120 to 300 MeV or more (see Fig. 4). No other term in the expansion exhibits such a sensitivity. In nonrelativistic models, the cancellation at $k_F^3$ has no direct explanation. If imposing the cancellation were desirable, one would expect cancellations to occur at higher orders in the expansion. However, an analysis of nonrelativistic Skyrme energy functionals finds energy contributions that are consistent with NDA counting and a hidden scale at leading order only (comparable to the filled symbols at $n = 2$ in Fig. 4) [12]. Furthermore, we know of no alternative dimensional analysis based on binding-energy scales that can account for the size of these energy contributions.

**Loophole:** The cancellation in the leading term is only at the 50% level, which could still be considered natural, without resorting to explanations based on scalar–vector fine tuning. In any case, based on the arguments of Jackson [65], the extremely low empirical equilibrium density of nuclear matter is not consistent with a typical, nonrelativistic, velocity-independent NN potential.
10. **Ambiguity in nuclear matter saturation.** If different nonrelativistic potentials, each fit to NN scattering, are used to calculate the equilibrium binding energy of nuclear matter, the results fall along a line (the “Coester line”) with a spread of 15 MeV or more. This spread, which has usually been attributed to “off-shell” variations in the NN potentials, actually arises because the nuclear matter calculation requires an interaction that is *also* calibrated to three-body (and, in principle, many-body) *on-shell* amplitudes. This has not been done in calculations leading to the Coester line, since only two-body data was used as input in these nonrelativistic calculations. The magnitude of the variation in equilibrium binding energies would be difficult to understand if the underlying scale of the two-body interaction were only 50 MeV.

Large covariant two-body potentials in a relativistic formulation, however, imply sizable three-body contributions in the corresponding nonrelativistic calculation [67,4]. These contributions are consistent with the spread of the Coester line. One would expect a smaller spread in relativistic-model predictions of the equilibrium point, and this is observed in practice [38,68]. Moreover, two-hole-line Dirac–Brueckner–Hartree–Fock calculations using potentials with natural scales can reproduce both NN scattering observables and the nuclear matter equilibrium point simultaneously [68].

*Loophole:* There have been fewer systematic studies of relativistic predictions compared to nonrelativistic predictions, so the relativistic spread may be underestimated.

11. **QCD sum rules for nucleons at finite density.** The QCD sum-rule method relates ground-state matrix elements of QCD operators, such as the quark condensate, to spectral properties of hadrons (e.g., masses) [69,71]. Adapted to finite density, it relates the density dependence of condensates [72,73] to relative residues at the nucleon quasiparticle poles, which can be used to predict on-shell scalar and vector self-energies [74]. The mass scales of QCD are directly incorporated into the analysis through the condensates.

The key feature of the finite-density sum rule analysis is the *covariant* decomposition of a correlator of nucleon interpolating fields. The quasiparticle pole position is unchanged within the coarse resolution of the sum rule approach, but the self-energies extracted from the correlator residues are sizable. This is consistent with weak binding but large covariant potentials. A detailed sum-rule analysis predicts in-medium scalar and vector self-energies of close to 300 MeV (albeit with large error bars) [75–77].

*Loophole:* Many provisional assumptions must be made to carry out the QCD sum-rule analysis [76].

### III. EPILOG

In summary, we have argued that a covariant formulation of nuclear physics has the advantage of manifesting the underlying scales of QCD. The common signatures of these scales are large nucleon scalar and vector self-energies. This connection is shown through both theoretical and empirical considerations of naturalness in covariant analyses of NN scattering and nuclear properties. The manifestation of scales translates in many instances into simpler, more efficient, or more natural explanations of nuclear phenomena than in
nonrelativistic formulations. Examples include the spin-orbit force, the nucleon–nucleon potential, the energy dependence of the proton–nucleus optical potential, pseudo-spin doublets, and the cancellations observed in energy functionals of nuclear matter. The pieces of evidence supporting a representation with large nucleon scalar and vector potentials, while not definitive when considered individually, collectively comprise a compelling positive argument.

The evidence shows that the natural scales are not introduced “artificially” in a covariant formalism, and that the small binding energy (2%) of nuclear matter arises because it is a finely tuned fermionic system.

Of course, the argument would be moot if there were direct experimental evidence that rules out the possibility of large potentials. We are unaware of any such evidence. At one time it was thought that predictions in relativistic models for isoscalar magnetic moments of odd-$A$ nuclei are strongly enhanced compared to the data, which are close to the Schmidt predictions [79]. Naively, the baryon current of a nucleus with a valence nucleon of momentum $p$ outside a closed shell is $p/M^*$, compared to the Schmidt current $p/M$. However, if the calculation is forced to respect Lorentz covariance and the first law of thermodynamics, the nuclear current is constrained to be $p/\mu$, where $\mu \approx M$ is the chemical potential [80]. Thus there is no enhancement in a consistent relativistic framework. The situation for currents at low $q > 0$ is still an open problem, and should be re-examined in the context of modern EFT-inspired models.

We have emphasized throughout that relativistic and nonrelativistic formulations are not mutually exclusive alternatives: both should work, although possibly in very different ways. Parallel EFT model calculations of the phenomena discussed here, such as the energy dependence of the optical potential, would more firmly establish the connections between relativistic and nonrelativistic explanations. While we have focused on the naturalness of covariant models, there is also the pragmatic question of the convergence of relativistic and nonrelativistic EFT expansions. Large nucleon fields can mean that a Foldy–Wouthuysen reduction may converge slowly, even though $p/M$ is small, because this is also an expansion in the ratio of potential strength to the nucleon mass. The relative convergence rates, particularly for spin properties, merit further examination.

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