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Can long-range nuclear properties Be influenced by short range interactions? A chiral dynamics estimate

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ABSTRACT

Recent experiments and many-body calculations indicate that approximately 20% of the nucleons in medium and heavy nuclei ($A \geq 12$) are part of short-range correlated (SRC) primarily neutron-proton (np) pairs. We find that using chiral dynamics to account for the formation of np pairs due to the effects of iterated and irreducible two-pion exchange leads to values consistent with the 20% level. We further apply chiral dynamics to study how these correlations influence the calculations of nuclear charge radii, that traditionally truncate their effect, to find that they are capable of introducing non-negligible effects.

1. Introduction

Electric charge distributions are a fundamental measure of the arrangement of protons in nuclei [1]. The variation of charge distributions of elements along isotopic chains is of particular interest due to its sensitivity to both single particle shell closure and binding effects, as well as properties of the nucleon-nucleon (NN) interaction. In addition, differences between the neutron and proton matter radii in neutron rich nuclei are extensively used to constrain the nuclear symmetry energy and its slope around saturation density, and thus have significant implications for calculations of various neutron star properties, including their equation of state [2–4].

Modern charge radius calculations go far beyond the single particle approximation. Ab initio many-body calculations can be done using various techniques [5–7], but are generally very calculationally demanding, especially for medium and heavy nuclei. The recent development of chiral effective field theory (EFT) inspired soft interactions that offer systematic evaluation of the accuracy of the calculation, and methods using similarity renormalization group (SRG) evolution techniques to reduce the size of the model space are especially useful as they significantly simplify calculations of energy levels. While generally successful, these calculations obtain a systematic underestimate of nuclear charge radii and their variation along isotopic chains [8–10]. This is a known, but not yet explained feature these calculations.

However, both procedures mentioned above are often implemented in a manner that truncates high momentum can reduce the high-momentum components of the nuclear wave function that could be important in computing matrix elements of observable quantities. Here we discuss the impact of neutron-proton Short-Range Correlations (np-SRC) [11–13] on nuclear charge radii.

Over the last decade considerable evidence has accumulated regarding the attractive nature of the short-ranged neutron-proton interaction in the spin triplet channel. Measurements of relatively high-momentum transfer inclusive electron-scattering eactions indicate that about 20% of the nucleons in medium and heavy nuclei ($A \geq 12$) have momentum greater than the nuclear Fermi momentum ($k_F \approx 275$ MeV/c) [14–18]. In the momentum range of 300–600 MeV/c, these high-momentum nucleons were observed to be predominantly members of np-SRC pairs, defined by having large relative and smaller center-of-mass momenta relative to k_F [11,12,19–24]. This is an operational momentum-space definition of the term 'short-range'.

Calculations indicate that the origin of these correlated np-SRC pairs lies in the action of a strong short-ranged tensor interaction [25–27]. These experiments and interpretive calculations are based on the idea that at high-momentum transfers the reaction factorizes, allowing cancellation of reaction mechanism effects in cross-section ratios of different nuclei and the use of the im-

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pulse approximation (with suitable modest corrections) in other cases [11,28]. In effective field theory language, this corresponds to using a high-resolution scale in the similarity renormalization group SRG transformations [29].

In the case of neutron-rich nuclei, recent measurements [30] indicate that, from Al to Pb, the fraction of correlated neutrons (i.e., the probability for a neutron to belong to an *np*-SRC pair) is approximately constant while that of the protons grows with nuclear asymmetry approximately as N/Z (where N and Z are the numbers of neutrons and protons respectively). This is a first indication of a possible significant impact of *np*-SRC on the proton distributions in neutron rich nuclei.

The effects of tensor-induced *np*-SRC pairs in nuclei were shown to have significant impact on issues such as the internal structure of bound nucleons (the EMC effect) [11,31–33], neutron-star structure and the nuclear symmetry energy at supra-nuclear densities [28,34–36], the isospin dependence of nuclear correlation functions [37]. However, it is natural to expect that due to the tensor interaction's short-ranged nature, its impact on long range (i.e., low-energy) observables can be neglected.

This expectation is examined here by focusing on the particular problem highlighted in Ref. [8]: the computed difference in charge radii between ^{52}Ca and ^{48} Ca is smaller than the measured value. The ab initio calculations in that work are based on several interactions that include NNLO$_{\text{sat}}$, which is fit to scattering data up to 35 MeV and to certain nuclear data from nuclei up to $A=24$ [38], and the interactions SRG1 and SRG2. The latter is derived from the nucleon-nucleon interaction of Ref. [39] by performing an evolution to lower resolution scales via the similarity renormalization group (SRG) [29]. Ref. [8] speculates that the reason for the discrepancy between theory and experiment is a lack in the description of deformed intruder states associated with complex configurations. The NNLO$_{\text{sat}}$ interaction does give the correct ^{40}Ca radius and includes short-range correlations for like nucleon pairs implicitly through its optimization procedure.

Here we study another possible reason for the discrepancy that stems from the use of soft interactions. We view all of the interactions employed in Ref. [8] as soft interactions that reduce the influence of short-range correlations. We argue that including omitted effects of *np*-SRC pairs between protons and neutrons in the outer shells of neutron-rich nuclei may change the computed value of the proton MS charge radius for some neutron-rich nuclei. Note that the use of soft interactions, caused by using form factors that reduce the probability for high-momentum transfer should be accompanied by including modified electromagnetic currents as demanded by current conservation. If instead the SRG is used, it should be accompanied by corresponding unitary transformations on the operators. If these modifications to current operators are done completely accurate calculations may be possible.

We begin by using the simplest possible illustration of the possible impact of SRCs on computed charge radii. This is based on a two-state system and is intended only to explain the basic idea. We then use chiral dynamics to estimate the probability of short-range correlations, and further study how these correlations may influence calculations of nuclear charge radii.

2. Schematic model

Consider the evaluation of an operator $\mathcal{O}$ in a framework in which SRC effects can be truncated. We examine the effect of this truncation on the computation of relevant matrix elements.

The consistent application [40,41] of SRG evolution in a many-body calculation requires that the Hamiltonian, H, as well as all other operators, be transformed according to $\mathcal{O} \to U\mathcal{O}U^\dagger$. Here U is a unitary operator, chosen to simplify the evaluation of energies by reducing the matrix elements of H between low- and high- momentum subspaces. The aim is to obtain a block-diagonal Hamiltonian. Such transformations have no impact on observables and include the effects of short-range physics. However, in the case of proton MS charge radius calculations, several works [8] further simplify the calculation by evaluating the expectation value of the *un-transformed* mean square charge radius operator on the *transformed* wave functions.

To understand the general effect of using such un-transformed operators we consider a simple two-state model with two components, $|P\rangle$ and $|Q\rangle$, respectively representing low-lying shell model states and high-lying states within the model space. The Q-space is intended to represent the states that enter into the many-body wave function due to the short-range correlations. Thus the Q-space dominates the high-momentum part of the ground state one-body density [42].

Since we are concerned with nuclear charge radii, the simple model must be further defined by the matrix elements of the charge radius squared operator, R^2. This operator is of long range and is not expected to allow much connection between the P and Q spaces. Therefore, this model is defined by the simple statement: $\langle P|R^2|Q\rangle = 0$. The motivation for this statement comes from the single-particle harmonic oscillator model: the action of the square of the radius changes the principal quantum number by at most one unit. One may arrange model spaces satisfying this condition by using superpositions of harmonic oscillator wave functions. A consequence of this is that $\langle Q|R^2|Q\rangle - \langle P|R^2|P\rangle > 0$.

The Hamiltonian for a two-state system is given by

$$H = \begin{bmatrix} -\epsilon & V \\ V & \epsilon \end{bmatrix} \tag{1}$$

where 2ϵ is the energy splitting between $|P\rangle$ and $|Q\rangle$ and V is the short-distance coupling between them. The exact ground state $|GS\rangle$ can be computed and the occupation probability of the Q space is given by $\mathcal{P}_Q \equiv V^2/[(\epsilon+\Delta)^2+V^2]$, with $\Delta \equiv \sqrt{\epsilon^2+V^2}$. $\mathcal{P}_Q$ in this model corresponds to the probability that a proton belongs to a short range correlated pair. The mean-square charge radius is then given by:

$$\langle GS|R^2|GS\rangle = \langle P|R^2|P\rangle + (\langle Q|R^2|Q\rangle - \langle P|R^2|P\rangle)\mathcal{P}_Q \tag{2}$$

with the second term representing the influence of the high-lying states.

We interpret the result Eq. (2) in terms of the SRG. For a two-state system the complete SRG transformation simply amounts to diagonalizing the Hamiltonian. The resulting renormalization-group improved Hamiltonian $\tilde{H}$ is a diagonal matrix with elements given by $\pm\Delta$. The unitary transformation sets the matrix elements of $\tilde{H}$ between the low and high momentum sub-spaces to zero. Applying the same unitary transformation to the operator R^2, one would obtain the same result as Eq. (2). However, the procedure of Ref. [8], and others, for example, [9,10], corresponds to simply using

$$\langle GS|UR^2U^\dagger|GS\rangle \approx \langle GS|R^2|GS\rangle = \langle P|R^2|P\rangle, \tag{3}$$

which contrasts with the complete calculation of Eq. (2). For the given model, $(\langle Q|R^2|Q\rangle - \langle P|R^2|P\rangle) > 0$, so that the omission of the unitary transformation on the R^2 operator leads to a reduction in the matrix element. In realistic situations the correction term $(\langle Q|R^2|Q\rangle - \langle P|R^2|P\rangle)\mathcal{P}_Q$ would be the difference between two large numbers, so it could be positive or negative.

The two-component model presented above shows the possible qualitative effect on the computed mean-square radius of truncating SRCs. However, it cannot be used to make a quantitative prediction.

3. Chiral dynamics estimate

We now turn to a more complete calculation to estimate the magnitude of the effect for the specific case of adding a neutron to the $1f_{5/2} - 2p_{3/2}$ shell around a ^{48}Ca core. The additional neutron is mainly located in the outer edge of the nucleus. In the pure shell model, this neutron would not affect the proton MS charge radius. However, it is natural to wonder if the attractive, short-range neutron-proton tensor interaction that creates *np*-SRC pairs will cause the protons to move closer to the additional neutron, thereby increasing the charge radius.

The calculation starts with a ^{48}Ca wave function that has been obtained using an interaction that explicitly includes the effects of high-momentum components, and considers the effect of a missing short-ranged potential V on an *np* product wave function $|n,\alpha)$, where n and α represent the neutron and proton orbitals respectively. For numerical work, in this exploratory effort, we ignore the spin orbit force and use harmonic oscillator single-nucleon wave functions, with frequency, $\Omega = 10.3$ MeV, that yields the measured charge radius of 3.48 fm, and the corresponding length parameter, $b^2 = 1/(M\Omega) = 4.02$ fm^2. The interaction V is meant to represent the effects including the short-range strength masked by the SRG procedure, and also corrections to the effects of using a very soft nucleon-nucleon interaction. The effect of V on the wave function is given by

$$|n,\alpha\rangle = C^{-1/2}\left[|n,\alpha) + \frac{1}{\Delta E} Q\, G|n,\alpha)\right], \tag{4}$$

where G is the Bruckner G-matrix that sums the interactions V on the pair and includes the effects of short-range correlations. Note that $|\rangle$ represents the full wave function while $|)$ represents the product state. The energy denominator $\Delta E \equiv E_n + E_\alpha - H_0$, with H_0 the Hamiltonian in the absence of V, Q the projection operator that places the neutron and proton above the Fermi sea and $C_{n\alpha}$ is the normalization constant:

$$C_{n\alpha} = 1 + I_{n\alpha}, \tag{5}$$

with $I_{n\alpha} \equiv \sum_{m,\beta>E_F} \frac{(n,\alpha|G|m\beta)(m,\beta|G|n,\alpha)}{(E_n+E_\alpha-E_m-E_\beta)^2}$.

Defining the proton MS radius as the expectation value of the operator R_p^2, we want to know the quantity

$$\langle n,\alpha|R_p^2|n,\alpha\rangle = C_{n\alpha}^{-1}[(n,\alpha|R_p^2|n,\alpha) + (n,\alpha|G\, Q\, \frac{1}{\Delta E} R_p^2 \frac{1}{\Delta E} Q\, G|n,\alpha)], \tag{6}$$

obtained by using the fact that the one-body operator R_p^2 does not connect the states $|n\alpha)$ and $|m\beta)$ that differ by two orbitals. Using the definitions:

$$R_{n\alpha}^2 \equiv \frac{1}{I_{n\alpha}}(n,\alpha|G\, Q\, \frac{1}{\Delta E} R_p^2 \frac{1}{\Delta E} Q\, G|n,\alpha) \tag{7}$$

and

$$R_\alpha^2 \equiv (\alpha|R_p^2|\alpha), \tag{8}$$

one finds

$$\langle n,\alpha|R_p^2|n,\alpha\rangle = R_\alpha^2 + \mathcal{P}_{n\alpha}^{SRC}(R_{n\alpha}^2 - R_\alpha^2), \tag{9}$$

with $\mathcal{P}_{n\alpha}^{SRC} = \frac{I_{n\alpha}}{1+I_{n\alpha}} \approx 0.2$ is the measured SRC probability [14–17]. Probabilities of this size have been obtained by both ancient and modern computations [6,43–48]. The effect of SRCs is embodied in the second term of Eq. (9), as in Eq. (2). Note the similarity between the two equations. Given that $\mathcal{P}_{n\alpha}^{SRC}$ cannot be zero, the effect of SRCs must either increase or decrease the computed mean-square charge radius. In some cases, there could be a cancellation between the two parts of the correction term, but this should not be expected to occur for all configurations.

We next show that the $\sim 20\%$ value of $\mathcal{P}_{n\alpha}^{SRC}$ is consistent with the chiral dynamics treatment of Refs. [49,50]. In that work the chiral dynamics interaction, dominated by the iterated effects of the one pion exchange potential (OPEP) is shown to be the cause of nuclear binding. Furthermore, the reduction of this effect with increasing nuclear density through the effects of the Pauli principle on the intermediate nucleon-nucleon state is responsible for nuclear saturation. The ideas of Refs. [49,50] account for the qualitative features of nuclear physics with startling simplicity.

The key point for us is that the dominant source of attraction comes from a short distance effect, well-represented by zero-range delta function interaction (denoted here as V_{00}) proportional to a cut-off parameter Λ, that is consistent with the requirements of chiral symmetry. This interaction accounts for an attraction "in the hundred MeV range (per nucleon) for physically reasonable values of the cut-off, $0.5 < \Lambda < 1.0$ GeV." These authors also note that the two pion exchange interaction contains a factor that favors the isospin 0 two-nucleon state by a factor of 9 over the isospin 1 state. The *np* dominance discussed above is a natural consequence of the chiral dynamics interaction.

The calculation of the iterated OPEP was repeated in Appendix A of Ref. [11]. In agreement with [49,50], that work shows that the iteration of the spin-triplet one-pion exchange (OPE) potential (including the transitions $^3S \to {}^3D \to {}^3S$) results in a strong attractive effective short-range interaction that acts in the relative S state (see also [51,52]). The strength is of the correct magnitude to roughly account for the deuteron D-state probability, and therefore may be expected to roughly account for the probability that an *np* pair is in a short range correlation.

Refs. [49,50] explains that V_{00} should *not* be iterated with itself or with 1π exchange. Therefore the iterated OPE term V_{00} approximately corresponds to the $G-$matrix of Eq. (4). That reference gives

$$\begin{aligned} V_{00}(\mathbf{r}) &= -8\pi^2 M\Lambda(\frac{g_A}{4\pi f_\pi})^4(1 - \frac{(3g_A^2+1)(g_A^2-1)}{10g_A^4}) \\ &\quad \times (1 - 2.18\frac{k_F}{M})(3 - 2\tau_1\cdot\tau_2)\delta(\mathbf{r}) \\ &\equiv V_0(3 - 2\tau_1\cdot\tau_2)\delta(\mathbf{r}), \end{aligned} \tag{10}$$

where M is the nucleon mass, g_A the axial vector coupling constant, and the pion decay constant $f_\pi = 92.4$ MeV. The effect of the Pauli principle is encoded in the term proportional to k_F. This expression includes the smaller repulsive effects of the irreducible two-pion exchange graphs.

The interaction causes a change in the wave function:

$$|\delta\Phi_{n,\alpha}) \equiv \frac{Q}{\Delta E} V_{00}|n,\alpha), \tag{11}$$

which accounts for the second term of Eq. (4). To proceed, we need the operator $\frac{Q}{\Delta E}$. We use its value in nuclear matter under the reference spectrum approximation [53], which is qualitatively valid for use along with short-ranged interactions [54]. Then in the coordinate-space representation ($\mathbf{r}_{1,2} = \mathbf{R} \pm \mathbf{r}/2$) this is approximated by the expression:

$$\langle \mathbf{R},\mathbf{r}|\frac{Q}{\Delta E}|\mathbf{R}',\mathbf{r}'\rangle = -\int \frac{d^3K}{(2\pi)^3}\frac{d^3k}{(2\pi)^3} \times \frac{e^{i\mathbf{K}\cdot(\mathbf{R}-\mathbf{R}')} e^{i\mathbf{k}\cdot(\mathbf{r}-\mathbf{r}')}}{2A_2 + W + \frac{K^2}{4M^*} + \frac{k^2}{M^*}}, \tag{12}$$

where $M^* = 0.6M$, $A_2 \approx 100$ MeV, and W is a starting energy [53]. The quantity k_F is the effective Fermi momentum for a given nucleus, here taken as 1.36 fm^{-1}. The short-ranged nature of the interaction is expected to excite that part of the phase space that involves regions of relative low K and relatively high k. Thus, the integral is simplified by replacing K^2 by its average value of $(6/5)k_F^2/M$, where k_F is the effective Fermi momentum for a given nucleus. Then defining $\gamma^2 \equiv M^*(2A_2 + W + (3/10)k_F^2$, we find that

$$\langle \mathbf{R}, \mathbf{r}| \frac{Q}{\Delta E} |\mathbf{R}', \mathbf{r}'\rangle \approx \delta(\mathbf{R} - \mathbf{R}') f(|\mathbf{r}' - \mathbf{r}|), \tag{13}$$

with $f(r) = \frac{M^*}{4\pi r} e^{-\gamma r}$. Then

$$\langle \mathbf{R}, \mathbf{r}|\delta\Phi_{n,\alpha}\rangle \approx f(r)V_0(3 - 2\tau_1 \cdot \tau_2)\phi_n(\mathbf{R})\phi_\alpha(\mathbf{R}). \tag{14}$$

Then

$$\sum_\alpha{}' I_{n\alpha} \approx \sum_\alpha{}' \int d^3R|\phi_n(\mathbf{R})\phi_\alpha(\mathbf{R})|^2 41 \frac{(M^* V_0)^2}{8\pi\gamma} \tag{15}$$

where $\sum_\alpha'$ denotes an average over the bound proton levels. The factor 41 arises from the average of the contributions of $9^2 = 81$ (from the $T = 0$ component of an np pair) and 1 (rom the $T = 1$ component). Given the change in wave function of Eq. (11) one finds the result that

$$R_{n\alpha}^2 \approx \frac{\int d^3R R^2 |\phi_n(R)\phi_\alpha(R)|^2}{\int d^3R|\phi_n(R)\phi_\alpha(R)|^2}. \tag{16}$$

This amounts to using the known Zero-Range Approximation, previously shown to successfully reproduce SRC effects [52].

We next apply this idea to the specific case of adding neutrons to ^{48}Ca, with the added neutron in either the $n = 0f_{5/2}$ or $n = 1p_{3/2}$ state. We will use the average over the L_z substates. Given parameters mentioned above, we find that

$$\mathcal{P}_{n\alpha}^{SRC} \approx 0.2 \pm 0.02 \tag{17}$$

for all of the orbitals considered. The dependence on the starting energy W is weak because it is much smaller than $2A_2 = 200$ MeV. Then the effects of short-range correlations on the mean-square charge radius of an orbital n are given by:

$$\Delta R^2(n) \equiv \sum_\alpha{}' \mathcal{P}_{n\alpha}^{SRC}(R_{n\alpha}^2 - R_\alpha^2) \tag{18}$$

Numerical evaluation leads to

$$\Delta R^2(0f_{5/2}) = 0.17 \pm 0.12 \text{ fm}^2, \;\; \Delta R^2(1p_{3/2}) = -0.8 \text{ fm}^2. \tag{19}$$

The variation seen for $\Delta R^2(0f_{5/2})$ results from increasing the b-parameter by an amount up to 10%. This is done because this state is weakly (if at all) bound. The value of $\Delta R^2(1p_{3/2})$ is relatively insensitive to such changes. Its negative nature arises from the node in $1p_{3/2}$ state wave function which appears in the nuclear surface. This calculation may appear somewhat crude, but is reasonably well-constrained by using $\mathcal{P}_{n\alpha}^{SRC} \approx 0.2$ and the measured charge radius of the ^{48}Ca core state. The effect under consideration is not obviously zero, and the specific values we find are large enough to be taken seriously. Thus we suggest that the effect of short range correlations on computed charge radii should be considered in more detailed calculations that include many configurations and aim at high precision.

We note that the ab initio triton calculation of [55] finds that ignoring the effect of the unitary transformation on the charge radius squared operator leads to an overestimate of the value by about 0.04 fm, not dissimilar in percentage to our results.

4. Discussion

Ref. [8] explains various possible reasons (in addition to the effects of deformed intruder states) for the differences between the experimental and computed values of charge radii. The calculations are based on the single-reference coupled-cluster method, which is ideally suited for nuclei with at most one or two nucleons outside a closed (sub-) shell. Many calculations in the literature considerably underestimate the large charge radius of ^{52}Ca. Dynamical quadrupole and octupole effects could be responsible, but seem to be too small. These authors mention core breaking effects. Their *ab iniitio* calculations do show "a weak, but gradual erosion of the proton core as neutrons are added." Thus our statement is that including the effects of short range correlations could make the erosion of the proton core stronger and influence the resulting computed charge radii. Doing the necessary *ab initio* calculation is beyond the scope of this paper, but we do suggest that such effects should be considered in more detailed calculations of charge radii that aim at high precision.

We next discuss the motivation for pursuing such calculations. The experimental data accumulated in the last decade, in conjunction with un-truncated ab initio and effective calculations, allows quantifying the abundance and properties of SRC pairs in nuclei with unprecedented detail. Recent measurements of asymmetric nuclei indicate that SRC pairs are dominated by np pairs even in very neutron rich nuclei [30]. This implies that the protons are more correlated than neutrons in neutron rich nuclei.

Modern calculations relate the thickness of the neutron skin of ^{208}Pb to the nuclear equation of state and hence to neutron star properties [2–4]. A high priority experiment at Jefferson Lab is planned to measure the neutron skin thickness using parity violating electron scattering [56]. However, hitherto neglected short-range effects which reduce the neutron skin thickness should be included to accurately relate the neutron skin thickness to the nuclear EOS.

The indicated larger probability of protons to be part of SRC pairs in neutron rich nuclei, in combination with the larger average neutron radius, indicates that short-range correlations can have an impact on long-range nuclear properties such as the nuclear MS charge radius. The present work shows that the 20% probability for an np pair to strongly correlated is a natural consequence of the chiral dynamics of Refs. [49,50]. This effect is dominated by the tensor force which is large in the state with deuteron quantum numbers. Moreover, we find that including the effects of np-SRCs seems to be necessary to achieve a calculation of high precision. This is somewhat surprising because it is a long-range effect of a short-range, typically truncated, part of the NN interaction. We hope that the idea presented here can be confirmed or ruled out by more advanced computations.

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