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Some aspects of the quenching of single-particle strength in atomic nuclei

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In this article, we discuss some aspects of the quenching of the single-particle strength with emphasis on the isospin dependence of long- and short-range correlations. A phenomenological analysis that connects recent Jefferson Laboratory studies with data on spectroscopic factors, is contrasted with the results of the Dispersive Optical Model approach. We consider some consequences of the model on the nature of the dressed nucleons in the nuclear medium, their effective masses, as well as other aspects of nuclear structure such as charge radii, effective charges, and spin-spin correlations. Qualitative estimates indicate that short-range correlations must play a significant role on those aspects. Despite the fact that our conclusions are perhaps speculative at this stage, we trust that the results will stimulate further experimental and theoretical work, specifically on exotic nuclei far from stability.

KEYWORDS

single-particle strength, long- and short-range correlations, nuclear reactions, isospin dependence, effective mass, neutron matter, charge radii and effective charges, spin-spin correlations

1 Introduction

The year 2024 marks the 75^{th} anniversary of the publication of the seminal papers by Maria Goeppert-Mayer and Hans Jensen on the nuclear shell model [1, 2]; their work together with the collective model [3] established the pillars of our understanding of nuclear structure. Despite the fact that atomic nuclei consist of strongly interacting nucleons forming a dense quantum system, the notion of independent particle motion in a mean-field has been highly successful and has provided the framework to explain many nuclear properties, notably the so-called magic numbers. However, as Goeppert-Mayer remarked in her Nobel Lecture [4] *"The assumption of the occurrence of clear individual orbits of neutrons and protons in the nucleus is open to grave doubts"*, and went on to say *"It still remains surprising that the model works so well"*[1].

An appealing argument has been given by Mottelson [6] based on the quantality parameter:

$$\Lambda = \frac{\hbar^2/Ma^2}{V_0},$$

1 The validity of the shell model is discussed in detail in Ref. [5].

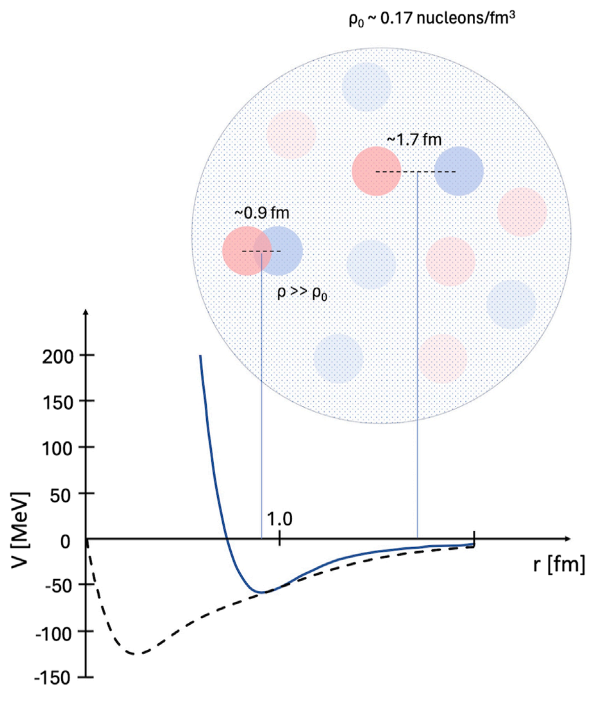

FIGURE 1
Central (solid line) and tensor (dashed line) AV18 potentials for the $S = 1, T = 0$ channel [8] and a schematic representation of a nucleus showing the average nucleon-nucleon separation and that in a short-range correlated pair.

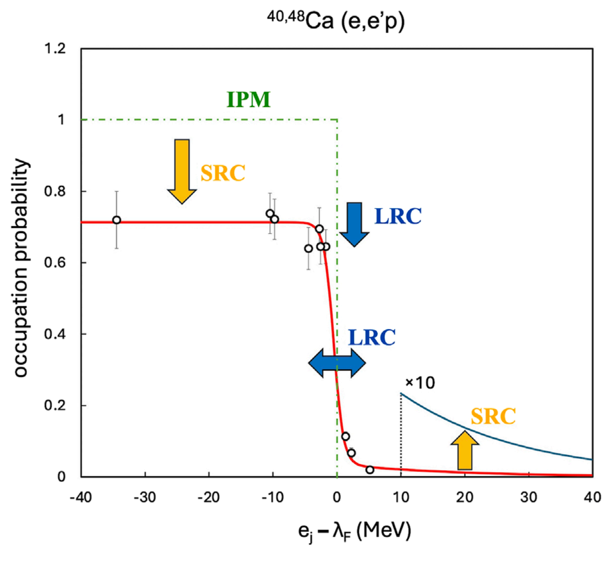

FIGURE 2
Occupation probabilities in ^{40,48}Ca as determined by $(e,e'p)$ reactions data. Deviations from the IPM (dashed green) due to LRC (blue) and SRC (yellow) are indicated by the arrows (see text).

with a the inter-constituents distance, which measures the ratio of the zero point motion kinetic energy to the strength of the interaction (V_0). With the typical values shown in Figure 1, the quantality parameter for nuclei is of order $\Lambda \approx 0.4$, similar to those in ^{3}He and ^{4}He which are liquids at zero temperature (for comparison, values for solids are $\Lambda < 0.07$). Thus, nuclei should behave like a quantum Fermi liquid [7], with *quasi-particles* taking the role of the particles in the Independent Particle Model (IPM).

Considering the nucleus in the simplest approximation of a non-interacting Fermi gas, the occupation probability distribution of orbitals n_j with momentum p is a step function, i.e., $n_j = 1$ for $p \le p_F$ and $n_j = 0$ for $p > p_F$, with p_F the Fermi momentum. In a Fermi liquid, where correlations between nucleons are considered, the mean-field approximation gets modified, diluting the pure independent-particle picture due to excitations across p_F, as illustrated in Figure 2. To some extent, the effects of the correlations could be embedded in the concept of a *quasi-particle (qp)*, with energy:

$$e(qp) \approx \frac{(p^2 - p_F^2)}{2m} + V(p) \approx v_F(p - p_F)$$

from which it follows that the qp acquires an effective mass:

$$m^* = \frac{p_F}{v_F} = \frac{m}{1 + m\partial^2 V/\partial p^2}$$

Due to the Pauli principle the phase-space for scattering, which goes as $(p - p_F)^2$, is drastically reduced giving the quasi-particle a lifetime much longer than the characteristic orbit transit time $\Delta t \sim 1/\omega_0$, with ω_0 a typical harmonic oscillator frequency. Thus, the conclusion that emerges is that the independent particles of the shell or collective models should be interpreted as *"dressed"* nucleons.

Crucial evidence for the departure from the IPM comes from high-energy electron scattering showing that the nuclear ground-state wavefunction must have a marked admixture of high-momentum components. The high-momentum tail, typically parameterized as $exp(-p^2/p_0^2)$ with $\frac{p_0^2}{2m} \approx 19$ MeV [9, 10], can be understood as the result of nucleon-nucleon (*NN*) short-range correlations (SRC) introduced by the strong nuclear force, and corresponds to single-particle excitations, $\Delta E \sim \Delta p^2/2m \gtrsim 60$ MeV. In reference to the geometrical picture depicted in Figure 1, a nucleon finds itself within a relative distance of 1 fm about 20% $(\approx (1/1.7)^3)$ of the time. Furthermore, the strong attraction due to the tensor force in the spin - triplet $^3S_1$ channel [11] suggests that at short distances, nucleon pairs are correlated in the same way as they are in the deuteron or in free scattering processes [10].

In the following, we discuss the implications of the concepts above to some aspects of the structure of atomic nuclei with an emphasis on the evolution with isospin (neutron-proton asymmetry).

2 Quenching of spectroscopic factors

Direct reactions continue to play a major role in our understanding of the nuclear elementary modes of excitation, particularly in the characterization of the single-particle degrees of freedom and their correlations. A reaction is called direct if it proceeds directly from the initial to the final state without the formation of an intermediate compound state and, to a good approximation, the cross section can be factorized into a nuclear-structure term and a reaction term corresponding to that of a single-particle state. Thus, these reactions have been used to test models of nuclear structure by comparing spectroscopic overlaps between initial and final nuclear states. The spectroscopic overlaps are represented by spectroscopic factors, derived from the experimentally measured cross section divided by the calculated one for a single-particle state with the same energy and quantum numbers (effectively reduced cross sections).

In more detail we have for the case of a particle-adding reaction:

$$d\sigma^{(+)}\left(j, I_i \to I_f\right) = \frac{1}{2j+1}\frac{2I_f+1}{2I_i+1}\mathscr{S}_{if}^{(+)}d\sigma_{sp}^{(+)}(j)$$

where

$$\mathscr{S}_{if}^{(+)} = \frac{1}{2I_f+1}\langle I_f \| a^\dagger(j)\| I_i\rangle^2$$

is the spectroscopic factor giving the structure information and $d\sigma_{sp}^{(+)}(j)$ a single-particle reaction cross section, with similar expressions for particle-removing reactions. Depending on the type of reaction being studied, the single-particle cross section can be calculated in different approximations, for example: distorted-wave Born approximation (DWBA), distorted-wave impulse approximation (DWIA), Eikonal approximation, *etc.* (see Refs. [12–17] and references therein).

Using the commutation rules and tensor properties of the creation and annihilation operators $a^\dagger(jm)$ and $a(jm)$ one can obtain the Macfarlane-French sum rules [18]:

$$\sum_{I_f}\frac{2I_f+1}{2I_i+1}\mathscr{S}_{if}^{(+)} = 2j+1-n(j) = \text{Number of vacancies}$$

$$\sum_{I_f}\mathscr{S}_{if}^{(-)} = n(j) = \text{Number of particles}$$

An important consequence of the equations above is that in cases where both addition and removal reactions could me measured, such as (d,p) and (p,d), there is a total sum rule that measures the orbit degeneracy, independent of the details of how the particles and vacancies are distributed:

$$\sum_{I_f}\frac{2I_f+1}{2I_i+1}\mathscr{S}_{if}^{(+)} + \sum_{I_f}\mathscr{S}_{if}^{-} = 2j+1 \quad (1)$$

In addition to the high-momentum tails observed in high-energy electron scattering, the depletion of the single-proton strength as observed in $(e,e'p)$ reactions in the quasi-free scattering regime [19, 20] is perhaps one of the best indicators for the departure from a mean-field approximation to the structure of nuclei. Experimental data for 16 stable targets point to a quenching of proton spectroscopic factors of 0.55 (0.07 rms) with respect to the IPM expectations[2] expressed as:

$$R = \frac{\mathscr{S}_{if}^{(-)}}{n(j)} \approx 0.6 \quad (2)$$

2 At this point it is important to note that the quenching extracted from $(e,e'p)$ measurements may depend on the momentum transfer, Q^2 [21, 22]. Although the Q^2 dependence of the quenching needs to be better understood, here we analyze the (well established) low-Q^2 data, where the scale resolution should be sensitive to probe the quenching due to both SRC and LRC [21].

Recently, there has been some debate regarding the meaning of spectroscopic factors, as these are not true observables [23, 24]. To address this question, Schiffer and collaborators [25] studied neutron-adding, neutron-removal, and proton-adding transfer reactions on the stable even Ni isotopes, with particular attention to the cross-section determinations. Spectroscopic factors derived from a consistent analysis of the data, in terms of the DWBA, were used to extract valence-orbit occupancies (vacancies) following from the sum rules discussed above. The deduced occupancies are consistent at the level of 5% indicating that, in the absence of a full *ab initio* calculation of structure and reaction cross sections, spectroscopic factors provide an empirically meaningful quantity to compare with theory. The use of shape deformation parameters, ϵ_λ, in the interpretation of collective nuclei comes to mind as a similar case.

Following on that work, the Argonne group carried out an extensive survey and self-consistent analysis of single-nucleon transfer reactions [26]. Summed spectroscopic strengths (Equation 1) were used to determine the factor (Equation 2) by which the observed cross sections, corrected for the reaction mechanism, differ from expectations. Across the 124 cases they analyzed, including various proton- and neutron-transfer reactions and with angular momentum transfer $\ell = 0$–7, spectroscopic factors are quenched with respect to the values expected from mean-field theory by a constant factor of 0.55, with an rms spread of 0.10, and consistent with that determined in $(e,e'p)$. The factor appears to be independent of whether the reaction is nucleon adding or removing, whether a neutron or proton is transferred, the mass of the nucleus, the reaction type, and angular-momentum transfer. This provides compelling evidence for a uniform quenching of single-particle motion in the nuclear medium.

The topic continues to be of much interest in the field [17] and open questions remain in regard to the evolution of *NN* correlations in nuclei with large neutron-proton asymmetry which are becoming accessible by radioactive beam studies of transfer, knockout, and quasi-free scattering (QFS) reactions. In these exotic systems, the effects of weak binding and coupling to the continuum might also play an important role.

An intriguing (rather controversial) result receiving attention is the (apparent) quenching observed in one-proton (and one-neutron) removal reactions carried out at intermediate energies around 100 MeV/nucleon. The study of Refs. [27, 28] showed an unexpected dependence of the quenching, as a function of the difference (ΔS) in proton and neutron separation energies, $S_p - S_n$ ($S_n - S_p$), of the initial system, at odds with the results obtained in transfer and QFS $(p,2p)$ reactions [17]. Whether the origin of this dependence is due to the effect of correlations or deficiencies in the reaction model is still a matter of debate.

2.1 Long-range and short-range correlations

The in-medium effects are captured by the concept of a *quasi-particle*. At any given moment, only 60% – 70% of the states below the Fermi momentum are occupied, with 30% – 40% of the nucleons participating in more complex configurations [19, 20, 26, 29–34].

The NN correlations that modify the mean-field approximation picture are often distinguished into long-range correlations (LRC) and short-range correlations (SRC), referring to their spatial separation and the part of the NN potential they are most sensitive to [30, 35, 36]. Therefore, both LRC and SRC deplete the occupancy of single-particle states, with LRC primarily mixing states near the nuclear Fermi momentum and SRC populating states well above it. It is important to note that within the context of this work, LRC are defined as (surface) pairing (PC) and particle-vibration coupling (PVC). While generally in low-energy nuclear structure one refers to pairing correlations as the short-range part of the force, as compared to the quadrupole force which is of longer range, here pairing is not considered part of the SRC associated with high-momentum components.

In Figure 2, we summarize the situation with the cases of ^{40,48}Ca that have been extensively studied. On one hand the sharp cutoff at the Fermi surface, expected for a non-interacting system, is seen to be broaden by the effect of the LRC admixing n-particle–n-hole configurations, typically of order ± the pairing gap, Δ, around λ_F. On the other hand, SRCs (tensor force) are thought to induce the high-momentum tail via the formation of correlated high-momentum isospin $T = 0$, spin $S = 1$ neutron-proton (*np*) pairs, a *quasi-deuteron*. In fact, results from Jefferson Lab (JLab) presented in Ref. [37] indicate that ≈90% of the nucleons with high-momentum are correlated in those *np* configurations.

2.2 Isospin dependence

The isospin dependence of LRC and SRC, and their competition in very asymmetric nuclei is a question that requires further studies. By explicitly incorporating the observed [38] increase of the high-momentum component of the protons in neutron-rich nuclei, we recently proposed a phenomenological approach to examine the role of both SRC and LRC in the quenching of the single-particle strength (SP) in atomic nuclei, specifically their evolution in asymmetric nuclei and neutron matter [39]. In our approach, we start by proposing that the wave-function of the *quasi-particle*, representing a *dressed* nucleon in the nuclear medium can be written in the linear form:

$$|qp\rangle = K_{SP}|SP\rangle + K_{LRC}|LRC\rangle + K_{SRC}|SRC\rangle. \tag{3}$$

This conjecture and the lack of interference terms stem from the underlying assumption that the SP, LRC, and SRC states are all orthogonal to each other. This is supported by the fact that SRC induce mixing to states of very high momentum and energy in the nuclear spectral function and there should be a small overlap with the SP and LRC components [29, 40, 41]. In near doubly magic nuclei, for which both pairing and deformation manifest themselves as vibrations, the individual terms in Equation 3 can be justified in first order perturbation as one-particle–one-hole (1p1h) (PVC) and two-particle–two-hole (2p2h) (PC) excitations. From the general arguments given in Ref. [39], we adopted the following expressions for the isospin dependence of PVC and PC:

$$K^2_{\mathrm{PVC}} = \alpha\left(1 + \frac{33}{51}\frac{N-Z}{A}\right)^2,$$

$$K^2_{PC} = \beta\left(1 - 6.07\left(\frac{N-Z}{A}\right)^2\right)^2.$$

The findings in Ref. [38] from JLab exclusive $(e, e'p)$ measurements of the correlated proton and neutron momenta, readily suggest the phenomenological expressions,

$$K^2_{SRC,minority} = \gamma\left(1 + SL^{minority}_{SRC}|N-Z|/A\right), \tag{4}$$

$$K^2_{SRC,majority} = \gamma\left(1 - SL^{majority}_{SRC}|N-Z|/A\right), \tag{5}$$

with the slope parameters $SL^{minority}_{SRC} = 2.8 \pm 0.7$ and $SL^{majority}_{SRC} = 0.3 \pm 0.2$ giving the isospin-dependence of the SRC contribution. Majority and minority define the protons, neutrons in asymmetric systems; protons are the majority at $(N-Z)/A < 0$ and neutrons are the majority at $(N-Z)/A > 0$. The results of our fit of the experimental data on doubly magic nuclei give: $\alpha = 10\% \pm 2\%$, $\beta = 3\%$[3], and $\gamma = 22\% \pm 8\%$. The different contributions are shown in Figure 3. The quenched single-particle strength, R (Equation 2), is expressed in terms of the independent components as

$$R = 1 - \left(K^2_{SRC} + K^2_{\mathrm{PVC}} + K^2_{PC}\right). \tag{6}$$

We end this section by comparing our predictions with the results of Refs. [27, 28]. For this purpose, we use the equations given in Ref. [42] to convert A, Z and N into $S_p - S_n$. The two trends are shown as shaded areas in Figure 4. As seen, our results give a less pronounced dependence on ΔS (in excellent agreement with, e.g., [43–46]); although not conclusive, it may point to a deficiency in the nucleon knockout reaction model rather than structure effects.

2.3 Comparison with the dispersive optical model

Dickhoff and collaborators have led extensive studies on the application of the dispersive-optical-model (DOM) to describe simultaneously a wealth of structure and reaction experimental data (see Ref. [47] for a review). Of particular relevance here is their study of the neutron-proton asymmetry dependence of correlations in nuclei [48]. In that work, elastic-scattering measurements, total and reaction cross-section measurements, $(e, e'p)$ data, and single-particle energies for magic and doubly-magic nuclei were analyzed within the DOM framework to generate optical-model potentials that can be related to spectroscopic factors and occupation probabilities. Their results show that,

3 The value of $\beta = 3\%$ has been estimated based on lowest order pairing vibrations that introduce 2p2h admixtures in the unperturbed (0p0h) ground-state configurations and has not been fitted to experimental data, hence there is no uncertainty associated with it.

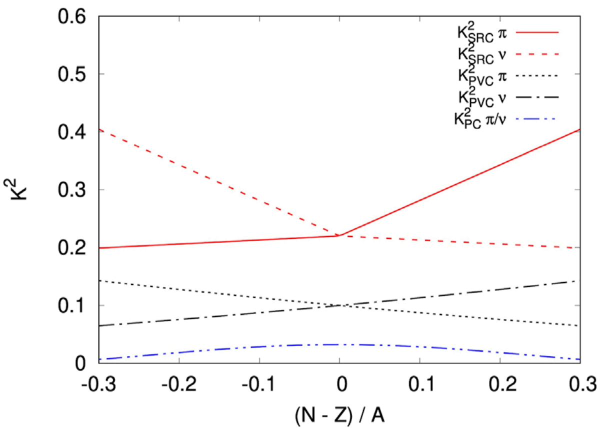

FIGURE 3
Square amplitude (K^2) for each correlation term (SRC, PVC, PC) as a function of neutron–proton asymmetry, derived from [38, 39].

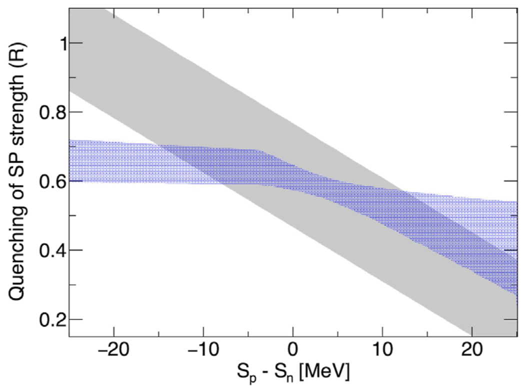

FIGURE 4
Quenching of proton single-particle strength (R) measured in nucleon-removal reactions (gray-shaded area) [27, 28] as a function of the difference in separation energies. Our predictions are shown with the blue-shaded (patterned) area (within 2σ).

for stable nuclei with $N \geq Z$, the imaginary surface potential for protons exhibits a strong dependence on the neutron-proton asymmetry, leading to a modest dependence of the spectroscopic factors on asymmetry. The appealing aspect of the DOM approach is that both LRC and SRC are described by surface and volume imaginary potentials, respectively. It is of interest to compare the predicted DOM results for the $g_{9/2}$ proton spectroscopic factors in stable Sn isotopes with our calculations. This is done in Figure 5, showing remarkable agreement between the two predictions, which adds additional support to our phenomenological model. Furthermore, in the DOM analysis of all considered nuclei, the neutron imaginary potential displays very little dependence on the neutron-proton asymmetry, also in line with our findings for $N \geq Z$ nuclei (Figure 3).

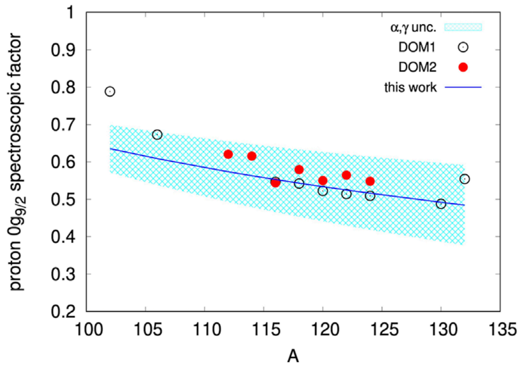

FIGURE 5
Comparison of dispersive-optical-model calculations [48] of the proton $0g_{9/2}$ spectroscopic factors (relative to IPM values) for Sn isotopes–obtained with fits where the depth of the Hartree-Fock potential was adjusted to reproduce the Fermi energy (DOM2) and where the depth was adjusted to reduce the correct $0g_{9/2}$ level energy (DOM1) – to our predictions. The shaded area reflects the uncertainty in our predictions originating from the uncertainties in the SRC ($\delta\gamma = 8\%$) and PVC ($\delta\alpha = 2\%$) contributions. Pairing correlations have been fixed at $\beta = 3\%$.

3 The nature of the dressed nucleons

As discussed earlier, the arguments put forward by Brueckner [10] suggest that in the presence of SRC components in the *NN* interaction, a "bare" nucleon becomes "dressed" in a virtual *quasi-deuteron* cloud about 20% of the time, as measured by the coefficient γ of Equations 4, 5. The implications of SRC and the *quasi-deuteron* concept have been discussed and elaborated in many works, e.g. [49–54], which we are not in a position to discuss here. Rather, we focus on the qualitative (phenomenological) approach to discuss the potential impact of the *qp* nature, induced by SRC, in low-energy observables for which, *a priori*, the properties of the finite system are quite essential.

In terms of the underlying independent single-particle shell structure, we could qualitatively interpret the effect as follows: a high-momentum proton (neutron) scatters from a neutron (proton) in a j–orbit forming a *quasi-deuteron* in a higher j' level while leaving behind a hole (j^{-1}) below the Fermi level. In more detail,

$$|\tilde{j_\pi}\rangle \approx \mathcal{A}_j|j_\pi\rangle + n_{j_\nu}\sum_{j'}^{n_{j'}} b_{jj'}|j_\nu^{-1}\rangle \otimes |j'_\pi j'_\nu\rangle^{1^+}.$$

If we further assume that $b_{jj'} = b_j$, then we can rewrite the equation above as:

$$|\tilde{j_\pi}\rangle \approx \mathcal{A}_j|j_\pi\rangle + \mathcal{B}_j|j_\nu^{-1}\rangle \otimes \left(\frac{\sum_{j'}^{n_{j'}}|j'_\pi j'_\nu\rangle^{1^+}}{n_{j'}}\right). \quad (7)$$

with $\mathcal{B}_j = b_j n_{j_\nu} n_{j'}$, and where the last term in parenthesis can be interpreted as an effective *qd*. The high-momentum components of the nucleon wavefunction requiring single-particle excitations of the order of $\gtrsim 60$MeV will correspond to a *quasi-deuteron* generated from harmonic oscillator j' orbitals associated with changes in the principal oscillator quantum number, $\Delta N \sim \Delta E/\hbar\omega_0$. In reference to Figure 1, a typical shell model mixing matrix element in the triplet-even channel, using harmonic oscillator wavefunctions, can be estimated [55]:

$$\langle V_{\ ^3S_1} \rangle \approx 10\,\mathrm{MeV}/A^{2/3},$$

giving a mixing amplitude in Equation 7 of

$$b_j \sim \langle V_{\ ^3S_1} \rangle / (2\Delta E) = \frac{10/A^{2/3}}{120}.$$

Assuming a single-j valence shell, we approximate $n_{j_v} \sim 2j+1 \approx 2A^{1/3}$. The number of orbits $n_{j'}$ available to scatter the qd is of order:

$$n_{j'} \approx N_{valence} + \Delta N \approx A^{1/3} + \frac{\Delta E}{\hbar\omega_0} \approx A^{1/3}(1+60/41) \approx 2.5A^{1/3},$$

leading finally to $\mathcal{B}_j \approx 0.42$, in line with the SRC strength amplitude empirically determined from Equations 4, 5, i.e., $\sqrt{\gamma} = 0.47$ [39].

4 Effective mass

The concept of nucleon effective mass, m^*, was originally developed by Brueckner [9] to describe the motion of nucleons in a momentum-dependent potential with the motion of a quasi-nucleon of mass m^* in a momentum-independent potential. The momentum dependence of the neutron and proton mean field is reflected in the nucleon effective masses, with varying theoretical predictions depending on the approach and interaction used, see, e.g., [56]. What is particularly important is the so-called effective mass splitting, i.e., $m_n^* - m_p^*$, in asymmetric nuclear matter. This impacts the equilibrium neutron/proton ratio in primordial nucleosynthesis, properties of neutron stars and mirror nuclei, and the location of the neutron and proton drip-lines, to name a few[4]. Although the nature of the splitting has been largely resolved in neutron-rich asymmetric nuclear matter, with the neutron effective mass being larger than that of the proton, the magnitude of the splitting remains an open question. The latter is determined by the momentum dependence of the isovector part of the single-nucleon potential, while the effective mass of symmetric nuclear matter also plays a role. Thus, probing the nucleon effective mass from a different perspective can give us insights into the momentum dependence of the nuclear mean field and can address the question of the proton-neutron effective mass splitting.

Bertsch and Kuo [29] have connected the effective mass to the depletion of the single-particle strength. By evaluating the contributions to the single-particle energy in second-order perturbation theory, they obtained the relation:

$$\frac{m}{m^*} - 1 \approx 2\frac{\Sigma V^2}{E_x^2},$$

approximately equal to the depletion of the single-particle strength of the state. By relating to Equations 2, 6, we can rewrite the expression above in terms of R:

$$\frac{m^*}{m} \approx \frac{1}{2-R},$$

from which we predict the neutron and proton effective masses as a function of $(N-Z)/A$, shown in Figure 6.

4 For an overview on effective masses we point to the review of Bao-An Li and collaborators [57] and references therein.

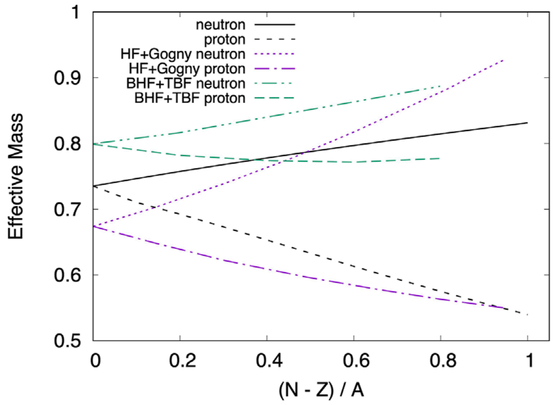

FIGURE 6
Effective mass for protons and neutrons following Ref. [29] and the quenching factor calculated in Ref. [39] (assuming 22% SRC component), and how this compares with calculations using the Hartree-Fock approach and a modified Gogny effective interaction (HF + Gogny) from [59], and calculations using the Brueckner-Hartree-Fock approach with Argonne V18 two-body interaction and a microscopic three-body force (BHF + TBF) from [60].

Our results are compared with the values obtained in Ref. [58] from a single-nucleon potential derived within the Hartree-Fock approach using a modified Gogny effective interaction (MDI) [59]. We also compare with the nuclear matter predictions on the effective mass (at nuclear saturation density) in a Brueckner-Hartree-Fock (BHF) nuclear many-body approach [60]. In this model, which gives satisfactory nuclear matter bulk properties, the nucleon force includes a two-body component from the Argonne V18 potential and a three-body term constructed from the meson-exchange-current approach. As seen, both predictions give different nucleon effective masses, reflecting their dependence on the interaction used. It is interesting to note that in order to reproduce the nuclear matter predictions, we would need a SRC component of 11% in the reduction of the single-particle strength, in contrast to the established value of ≈20%.

As discussed in [39] we can also speculate about the nature of a *quasi-proton* (nuclear polaron [61]) in neutron matter (nM). For infinite matter at saturation density we can neglect surface and pairing coupling terms, both expected to be small, and take the limit of $A \to \infty$ and $(N-Z)/A \to 1$. We predict a proton quenching factor of $R_{nM}^p = 1 - \gamma(1 - SL_{SRC}^p) \sim 0.16$ and an effective mass, $m_p^*(nM) \approx 0.54$, in good agreement with the nuclear matter calculations of Refs. [57, 58].

In the following, we turn our attention to finite nuclei and the implications of the phenomenological model to aspects of nuclear structure such as charge radii, effective charges, and spin-spin correlations.

5 Charge radii

The nuclear charge radius is a measure of the distribution of protons in the nucleus and it constitutes one of the fundamental

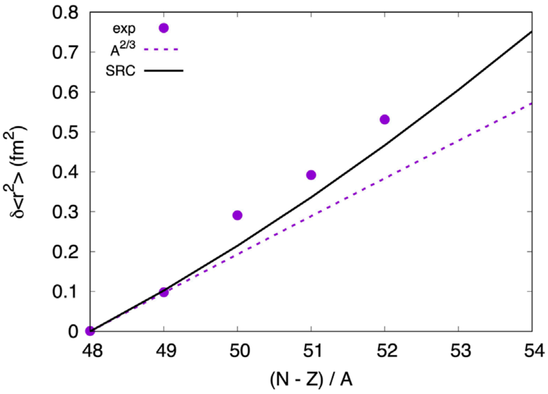

FIGURE 7
Change in the nuclear mean-square charge radii, $\delta\langle r^2\rangle$, of neutron-rich Ca isotopes with respect to ^{48}Ca [62] and how this compares with the expected increase following the size of the nucleus ($A^{2/3}$). This discrepancy could be qualitatively compensated with the inclusion of SRCs as explained in the text.

nuclear properties that, together with masses, can challenge nuclear models. A laser spectroscopy measurement [62] reported anomalously large charge radii in ^{50,52}Ca relative to ^{48}Ca, beyond what state-of-the-art *ab initio* calculations could reproduce. This result could indicate the occurrence of proton excitations (core-breaking) across the $Z = 20$ gap in the neutron-rich Ca isotopes, challenging the doubly-magic nature of ^{52}Ca with implications beyond the scope of this article. A recent study employing quasi-free one-neutron knockout from ^{52}Ca [63] showed that the rms radius of the neutron $p_{3/2}$ orbital is significantly larger than that of the $f_{7/2}$ orbital, suggesting that the large charge radii in the Ca isotopes could be attributed to the extended spatial distribution of p neutron orbitals. Another interpretation, however, was discussed by Miller and collaborators [64], who suggested that the increase in the charge radii could be attributed to SRC with the deficiency of *ab initio* calculations reproducing this anomaly coming from the use of soft potentials that do not capture the effects of SRC in charge radii; indeed, in neutron-rich nuclei we anticipate protons spending more time in the high-momentum part of the nucleon momentum density distribution, impacting the distribution of charges and hence the charge radii.

A simple estimate of the effect due to SRC follows from the consideration that protons in the *quasi-deuteron* configuration are associated with orbits with higher principal oscillator numbers that induce a change in the proton radius

$$\delta\langle r^2\rangle \approx \gamma r_0^2 \Delta N\left(1 + SL^p_{SRC}|N - Z|/A\right),$$

where $\Delta N \sim \Delta E/\hbar\omega_0$ and with an isospin dependence that resembles the experimental trend, as shown in Figure 7. Indeed, SRCs can induce an increase in the nuclear mean-square charge radius, $\delta\langle r^2\rangle$, beyond what is expected following the size of the nucleus ($A^{2/3}$). This result demonstrates the impact that SRCs can have on properties like charge radii and highlights the importance of including them in the theoretical description of atomic nuclei.

6 Effective charges

It is interesting to comment that the same mechanism will contribute to the nucleons' effective charges. In the shell model, core polarization effects result in $e^{\pi}_{eff} \sim 1 + \delta e$ and $e^{\nu}_{eff} \sim \delta e$, with a typical value of $\delta e \sim 0.5$ [65]. Specific values for different mass regions are usually fitted to reproduce quadrupole electromagnetic properties. A contribution from SRC can be estimated along the same line as above:

$$\delta e_{SRC} \approx \gamma \frac{\Delta N}{A^{2/3}}\left(1 + SL^p_{SRC}|N - Z|/A\right),$$

giving a value of the order of 0.1 near ^{40}Ca. This contribution should be present even in the absence of any core-polarization effect.

7 Ground-state spin-spin correlations

This section explores the possible effect of SRCs to the ground-state spin-spin correlations in order to provide a plausible explanation for the reported discrepancy between experimental and shel-model results.

Within the context of understanding the role played by isoscalar pairing in the ground states of $N \approx Z$ nuclei [66], the Osaka group has led a series of studies [67, 68] to probe neutron–proton spin–spin correlations in the ground states of $N = Z$ nuclei in the *sd* shell. The relevant observable is the scalar product between the total spins of the neutrons and protons, $\langle\vec{S}_{\rm n}\cdot\vec{S}_{\rm p}\rangle$, which can be measured by spin $M1$ excitations produced by inelastic hadronic scattering at medium energies.

The $M1$ operator consists of spin and orbital angular-momentum terms which can be of isoscalar (IS: $\Delta T = 0$) and isovector (IV: $\Delta T = 1$) nature. The IS and IV spin-$M1$ reduced nuclear matrix elements (ME) for transitions from the ground state $|gs\rangle$ of an even-even nucleus to an excited state $|f\rangle$ are defined by

$$M_f(\vec{\sigma}) = \langle f\| \sum_{k=1}^{A} \vec{\sigma}_k \|gs\rangle \text{ and } M_f(\vec{\sigma}\tau_z) = \langle f\| \sum_{k=1}^{A} \vec{\sigma}_k \tau_{z,k} \|gs\rangle.$$

These can be determined by measuring the (p,p') differential cross-section at 0°, which is proportional to the squared matrix elements above. The conversion from cross sections to absolute ME is done through a unit cross section and a kinematic factor, similar to the case of Gamow-Teller (GT) transitions [69]. Once the ME are determined,

$$\langle\vec{S}_n\cdot\vec{S}_p\rangle \approx \Delta_{spin}(E_x) = \frac{1}{16}\sum_{E_f<E_x}\left(|M_f(\vec{\sigma})|^2 - |M_f(\vec{\sigma}\tau_z)|^2\right),$$

where the sums are typically up to $E_x \approx 16$ MeV. Since the values in the two-particle system are distinctively different:

$$\langle\vec{s}_{\rm n}\cdot\vec{s}_{\rm p}\rangle = \begin{cases} +1/4, & \text{for IS np pair (deuteron)} \\ -3/4, & \text{for IV np pair} \end{cases}$$

$\langle\vec{S}_{\rm n}\cdot\vec{S}_{\rm p}\rangle$ will also depend strongly on the type of pairs being scattered across the Fermi surface.

In the experiments carried out at the RCNP facility in Osaka, high energy-resolution proton inelastic scattering at $E_{\rm p} = 295$ MeV was studied in ^{24}Mg, ^{28}Si, ^{32}S and ^{36}Ar [67]. The

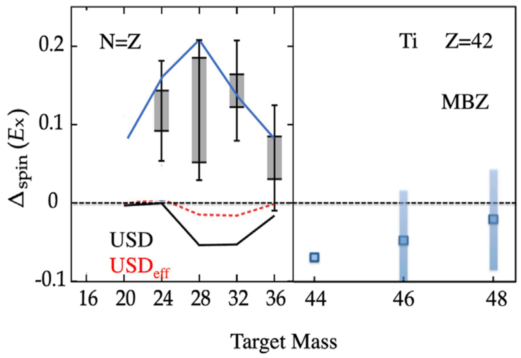

FIGURE 8
Left panel: Spin-spin correlations for $N = Z$ nuclei and shell model results with the USD (black line) and a modified USD$_{eff}$ (red dashed line) interactions. The blue line gives an upper limit estimate of the correction due to SRC, given in Equation 8. Right panel: Predicted shell-model results with the MBZ interaction for ^{46,48}Ti with an estimate of the experimental uncertainty anticipated for the iThemba measurement. Figure adapted from [67].

results in Figure 8, show positive values of $\langle \vec{S}_n \cdot \vec{S}_p \rangle$ for the *sd* shell suggesting a predominance of *quasi-deuterons*, at variance with USD shell-model calculations that are unable to reproduce the experimental results.

In Ref. [70] a formalism was developed to calculate the matrix elements of the $\vec{S}_n \cdot \vec{S}_p$ operator in a variety of coupling schemes and apply it to the solution of a schematic model consisting of nucleons in a single-l shell. The study showed that for all possible parameter values in the model Hamiltonian the expectation value $\langle \vec{S}_n \cdot \vec{S}_p \rangle$ is found to be ≤ 0 in the ground state of all even–even $N = Z$ nuclei, and the spin–orbit term in the nuclear mean field leads to more negative values.

What could be the reason for the positive values? Is it possible that we are observing the effects of the deuteron cloud dressing the nucleons related to the SRC quenching of spectroscopic factors? In fact, we can estimate a correction to the USD results based on the value of γ discussed earlier. Taking either ^{16}O or ^{40}Ca as the closest spin saturated cores for the *sd*-shell, the number of valence *quasi-deuterons* present in the paired ground states could contribute up to a positive value of $\approx \frac{1}{4}$ to the USD values,

$$\delta\Delta_{spin}(E_x) \lesssim \gamma(1-\gamma)\,\frac{1}{4}N_{sd}^{qd}, \tag{8}$$

bringing the estimates closer to the experimental measurements as shown in Figure 8. It seems clear that further theoretical and experimental work is required to fully answer remaining questions as to the microscopic origin of the spin–spin correlations. In particular, a compelling experimental direction to follow would be to study their isospin dependence. An approved experiment at iThemba [71] will extend the studies of Ref. [67] measuring the spin-spin correlations in the ground states of ^{46,48}Ti (see right panel in Figure 8), for which the shell model using the MBZ interaction [72] predicts negative values. For $N > Z$ targets, a combination of (p,p') and (d,d') scattering is required to disentangle the IS and IV components of the $M1$ operator.

8 Conclusion

The quenching of single-particle strength in atomic nuclei continues to be an active area of research in nuclear physics. Modern advances in direct reactions, particularly suited to probe nucleon occupancies, are providing new insights for a quantitative understanding of this phenomenon, intimately related to the fundamental nature of nucleons in the nuclear medium. In an attempt to connect recent studies on SRC from Jefferson Laboratory with data on spectroscopic factors, we have proposed a phenomenological model discussed in Sec. 2 that includes the combined effects of SRC and LRC (PVC and PC). Our results are in agreement with those of the DOM.

We have explored potential implications of our phenomenological analysis on some other aspects of nuclear structure, with special emphasis on the evolution with isospin. In particular, we discussed the subjects of effective masses, charge radii and effective charges, and spin-spin correlations. We showed that our estimates for the asymmetry dependence of effective masses due to SRC are consistent with microscopic calculations. More qualitative estimates of charge radii and effective charges, and spin-spin correlations reveal observable effects due to SRC on these properties.

While perhaps rather speculative at this stage, our conclusions suggest the significant role that SRC play in the nature of dressed nucleons in the nuclear medium, and we trust that our results will stimulate additional work. On the experimental side, existing accelerator facilities and new detector systems with increased sensitivity and resolving power are positioning us to access exotic beams to study exclusive direct reactions, in reverse kinematics, to explore the isospin degree of freedom and shed further light on the topic. On the theory side, new *ab initio* developments and the large increase in computer power becoming available are shaping a path to a predictive model of nuclei and their reactions. Achieving that ultimate goal will require a strong synergy between experiment and theory to design the best possible experiments that will inform of important improvements in the model. In turn, new theoretical insights will lead to new experimental programs that will be, again, contrasted with theory. One cannot but look forward to these exciting developments.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: None. Requests to access these datasets should be directed to Augusto O. Macchiavelli macchiavelao@ornl.gov.

Author contributions

AOM: Writing–original draft, Writing–review and editing. SP: Writing–original draft, Writing–review and editing. MP: Writing–original draft, Writing–review and editing.

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Conflict of interest

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