Transverse electron scattering form factors at low momentum transfer: Sensitivity to in-medium modifications of vector mesons?

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Form factor measurements of $M2$ and $M4$ transitions to the lowest $J^\pi=2^-$ and 4^- states, respectively, in ^{48}Ca with inelastic electron scattering at 180° are reported for momentum transfers $q\simeq 0.4-0.8$ fm^{-1}. These form factors complement previous measurements at higher q which have been treated by Lallena [Phys. Rev. C **48**, 344 (1993)], as a test case to derive information on in-medium modifications of the ρ-meson mass. He deduced within the random-phase approximation (RPA) an effective mass $m_\rho^* \simeq 0.9-0.95\ m_\rho$ assuming simultaneous scaling of the π coupling constant (Brown-Rho scaling). The validity of the analysis is critically assessed by comparing the measured form factors to second random-phase approximation (SRPA) calculations with a $\pi+\rho$ exchange interaction. The dependence of the form factors on the choice of the interaction and corrections such as mesonic exchange currents (MEC) are found to be of comparable magnitude to effects from a dropping of m_ρ, and in-medium effects hence cannot be clearly inferred from the data. To quantify the latter would require first the construction of an interaction which is capable of describing simultaneously and optimally a large variety of low-energy nuclear properties in ^{48}Ca. Remaining discrepancies in such a description could then be studied with the aim to single out in-medium effects of the type advocated by Lallena.

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I. INTRODUCTION

The modification of hadrons embedded in the nuclear medium constitutes a central problem of modern nuclear physics. It is experimentally addressed, e.g., in high-energy heavy-ion reactions [1,2] and electron scattering [3], but also in β decay where properties like the axial charge of the weak nucleon axial vector current in nuclei might be modified [4]. Although it seems at first sight remote, electron scattering at low energies and momentum transfers might also provide access to this problem. As an example, medium effects influence the pion coupling constant f_π and the ρ-meson mass and lead to a reduction of the isovector tensor interaction together with a simultaneous enhancement of the spin-orbit force [5,6]. The necessity of such corrections has been demonstrated, e.g., in studies of magnetic dipole transitions in light [7] and heavy [8] nuclei. Isovector transverse electron scattering is sensitive to changes of the tensor part of the NN interaction. Therefore, form factors of magnetic transitions can be expected to be modified appreciably.

Such effects were studied by Lallena [9] for the form factors of low-lying unnatural parity transitions in ^{48}Ca. The analysis focused on transitions to the lowest $J^\pi=4^-$ and $J^\pi=2^-$ states at $E_x=6.11$ and 6.89 MeV, respectively, investigated experimentally by Wise *et al.* [10]. The calculations of Lallena were carried out in the framework of RPA using the Jülich-Stony Brook residual interaction [11] modified to permit variations of f_π and m_ρ, thereby simulating the medium corrections. One conclusion of Ref. [9] was that a consistent description can be obtained assuming a scaling of the effective vector meson masses with the reduction of the pion coupling constant f_π in the nuclear medium. Such a behavior, predicted by Brown and Rho [12] and now called ''Brown-Rho scaling,'' can be understood from a partial restoration of chiral symmetry at finite baryon densities taking into account the scaling properties of QCD [2,13].

The possibility of inferring nuclear medium properties from electron scattering at low momentum transfer would provide exciting experimental prospects. Some cautionary remarks are necessary, however, since quantitative calculations of form factors represent a considerable task, even in the most advanced microscopic models. The results may depend on the specific choice of the residual interaction as well as non-nucleonic degrees of freedom (e.g., MEC corrections). It should also be noted that hadron scattering should, in principle, be able to probe medium effects but recent investigations of stretched states in ^{16}O and ^{28}Si with polarized proton scattering seem to question the need for any introduction of an effective ρ-meson mass [14,15].

The motivation of the present work has been twofold. First, it is shown that recent electron scattering experiments at 180° at low momentum transfers [16–19] yield new information on magnetic transitions in ^{48}Ca including the ones discussed in [9]. These results provide crucial constraints for any interpretation in the framework of medium corrections mentioned above. Second, in order to disentangle the role of in-medium modifications searched for from uncertainties due to peculiarities of the particular used model, independent SRPA [20] calculations based on the M3Y interaction [21,22] and $\pi+\rho$ exchange are performed which provide a successful description of the magnetic dipole and quadrupole response in medium and heavy nuclei [17,19] already without the medium modifications introduced in [9].

II. DATA

Measurements have been performed at the 180° scattering facility [23,24] of the superconducting Darmstadt electron linear accelerator S-DALINAC coupled to a large solid-angle, large momentum-acceptance spectrometer [25]. An isotopically enriched (>97%) target of ^{48}Ca (10 mg/cm^2)

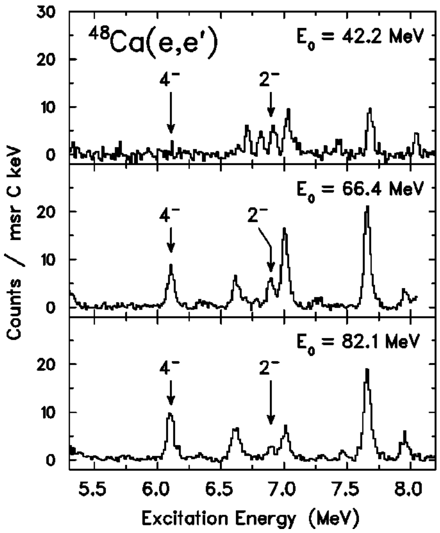

FIG. 1. Background subtracted spectra of of the ^{48}Ca(e,e') reaction at 180° for various incident energies in the excitation energy range $E_x=5.5-8$ MeV. The $J^\pi=2^-$ and 4^- states of interest are indicated by arrows.

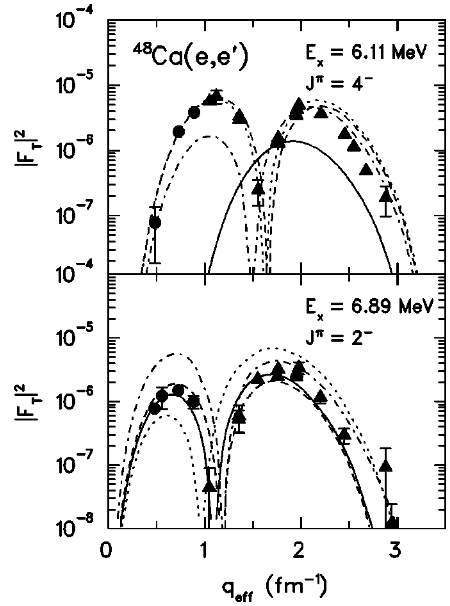

FIG. 2. Form factors of the $M4$ and $M2$ transitions to the low lying $J^\pi=4^-$ and $J^\pi=2^-$ states at $E_x=6.11$ and 6.89 MeV in ^{48}Ca measured in inelastic electron scattering at the S-DALINAC (circles) and Bates [10] (triangles). The curves represent calculations [9] with the interaction (1) for values $\epsilon=1$ (solid line), 1.2 (dashed line), 1.6 (dotted line), and 2 (dashed-dotted line).

was bombarded with electron beams of typically $1-3$ μA. Spectra were taken at four incident electron energies of $E_0=42.4$, 50.0, 66.4, and 82.2 MeV corresponding to a momentum transfer range $q\simeq 0.4-0.8$ fm^{-1}. The energy resolution, mainly limited by the target thickness, ranged from 50 to 70 keV. The spectrometer settings covered an excitation energy range $E_x=4-15$ MeV. Experimental details are described in [16,18].

Figure 1 presents spectra of the excitation region $E_x\simeq 5.5-8$ MeV measured at $E_0=42.4$, 66.4, and 82.2 MeV. The two transitions of interest are clearly visible in all cases and well separated from other excitations. It is thus straightforward to integrate the lines and to derive the corresponding form factors [16]. These are shown in Fig. 2 as a function of the effective momentum transfer together with the data at higher q ($q>1$ fm^{-1}) from [10]. It may be noted that the inclusion of the new data permits us to resolve the ambiguity of the earlier work [10] in the multipolarity assignment ($M2$,$M5$) of the transition populating the $E_x=6.89$ MeV level.

III. ANALYSIS WITH A LANDAU-MIGDAL-TYPE INTERACTION

In the following, we briefly summarize the form factor calculations of Lallena [9] and the impact of the new low-q data for a derivation of the ρ-meson effective mass. The approach starts from the Jülich-Stony Brook interaction [11] which is composed of a zero-range part of the Landau-Migdal type plus long-range π and ρ exchange potentials

$$V_{res}=C_0(g_0\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}+g_0'\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2})+\frac{1}{\epsilon}V_\pi+\epsilon V_\rho(\epsilon). \tag{1}$$

The calculations allow for a simultaneous variation of the π and ρ potential expressed in Eq. (1) by the parameter

$$\epsilon=\left(\frac{m}{m^*}\right)^2, \tag{2}$$

where m^* denotes the effective mass. The chosen form of Eq. (1) assumes a simultaneous scaling of the pion coupling constant f_π and the ρ-meson mass based on a ‘‘universal scaling’’ law for the effective nucleon (m_N) and meson (m_σ, m_ρ, m_ω) masses in the nuclear medium

$$\frac{m_N^*}{m_N}\approx\frac{m_\sigma^*}{m_\sigma}\approx\frac{m_\rho^*}{m_\rho}\approx\frac{m_\omega^*}{m_\omega}\approx\frac{f_\pi^*}{f_\pi} \tag{3}$$

proposed by Brown and Rho (Brown-Rho scaling) [12]. For $\epsilon=1$ the original interaction of [11] is attained. The strength parameters g_0 and g_0' of the interaction were fixed to reproduce the energies and transition strengths in ^{208}Pb [26].

The experimental form factors in Fig. 2 are compared to calculations with the interaction (1) for $\epsilon=1$ (solid line), 1.2 (dashed line), 1.6 (dotted line), and 2 (dashed-dotted line). Strong effects due to the variation of ϵ are visible. The new low-q data on ^{48}Ca from our 180° experiments described in the previous section clearly provide an upper constraint of $\epsilon\approx 1.2$ by the behavior of the $M2$ transition around the first maximum of the form factor. Since results for the $M4$ transition also confirm the need for a value $\epsilon>1$ already inferred from the higher-q data [9] and since they are reasonably compatible with $\epsilon\approx 1.2$ too, a small but finite reduction of the ρ-meson mass $m_\rho^\star \approx 0.9-0.95\, m_\rho$ might be deduced from an analysis employing an interaction of the type (1).

IV. ANALYSIS WITH A $\pi+\rho$ EXCHANGE INTERACTION

However, as pointed out in the Introduction, we ask ourselves if the data can be described equally well by a different interaction as the one in the previous section and in particular without invoking a change of m_ρ in the medium. Therefore, the form factors are independently analyzed in the framework of SRPA using a M3Y interaction which was shown to account successfully for the global $M1$ and $M2$ response in ^{48}Ca [17]. In contrast to [17], single-particle wave functions were determined in the Woods-Saxon parametrization of [27]. The depths and radii of the potentials were varied (under the condition of a constant volume integral) to reproduce the experimentally known single-particle energies. The resulting proton potential yields a mean-square charge radius $\langle r \rangle_p = 3.47$ fm in excellent agreement with experiment [28]. From the neutron potential $\langle r \rangle_n = 3.76$ fm is obtained. Inelastic hadron scattering experiments (see [29] and references therein) suggest a neutron radius in ^{48}Ca larger than the proton radius by about $0.2-0.3$ fm consistent with the above value.

In order to keep the analysis transparent, we restrict ourselves to a simplified interaction which consists of the central and tensor pieces for π and ρ exchange of the original M3Y interaction [22]

$$V_{central}(q) = \left(\frac{f}{m_\pi}\right)^2 \left[\frac{1}{3} \boldsymbol{\sigma_1}\cdot \boldsymbol{\sigma_2} \boldsymbol{\tau_1}\cdot \boldsymbol{\tau_2} \frac{m_\pi^2}{q^2+m_\pi^2} + \epsilon K_1 \boldsymbol{\sigma_1}\cdot \boldsymbol{\sigma_2} \boldsymbol{\tau_1}\cdot \boldsymbol{\tau_2} \frac{m_\rho^2}{q^2+m_\rho^2} \right],$$

$$V_{tensor}(q) = -\left(\frac{f}{m_\pi}\right)^2 \frac{\boldsymbol{\tau_1}\boldsymbol{\tau_2}}{3} (3\, \boldsymbol{\sigma_1}\cdot q\, \boldsymbol{\sigma_2}\cdot q - \boldsymbol{\sigma_1}\cdot \boldsymbol{\sigma_2}\, q^2) \times \left[\frac{1}{q^2+m_\pi^2} + \epsilon K_2 \frac{1}{q^2+m_\rho^2} \right], \tag{4}$$

where the constants f, $K1$, and $K2$ are given in [22]. Variations of ϵ are restricted to the ρ meson. Note that for $\epsilon=1$ and $q=0$ the interactions (1) and (4) coincide in the spin-isospin channel.

Before application to our problem the interaction (4) is tested on the much-studied (see, e.g., [30] and references therein) form factor of the prominent $M1$ spin-flip transition in ^{48}Ca [31], given in Fig. 3. A good description is obtained rather independent of the choice of ϵ. A variation between 1 (solid line) and 1.6 (dotted line) leads to small changes of less than 10% at the first maximum of the form factor only, and both calculations are compatible with the data at higher q. It may be noted that a calculation with the full M3Y interaction is practically indistinguishable from the $\epsilon=1.0$ result. A quenching factor of $g_s^{eff}=0.67 g_s^{free}$ is included to achieve quantitative agreement. This is in reasonable correspondence with recent large-scale shell model calculations of the $M1$ strength in the $N=28$ isotones [32] and fp-shell Gamow-Teller transitions [33]. Furthermore, the results of [17] demonstrate that the quenching factors agree for $M1$ and $M2$ strengths in ^{48}Ca. Therefore, it seems reasonable to include it as a global correction to the spin part of all magnetic transition operators.

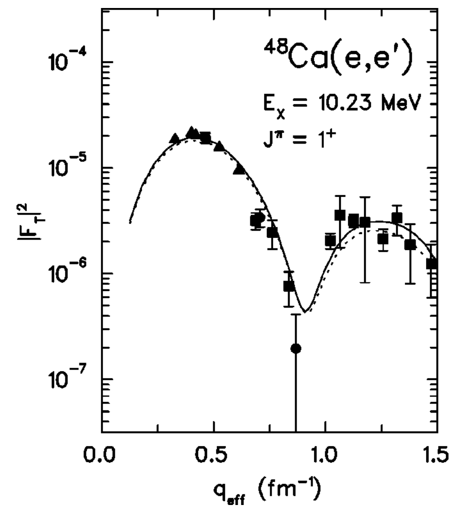

FIG. 3. Form factor of the prominent $M1$ spin-flip transition at $E_x = 10.23$ MeV in ^{48}Ca [31] compared to calculations with the interaction (4) for $\epsilon=1$ (solid line) and 1.6 (dotted line).

Proceeding to the transitions of interest, the influence of the ρ-meson mass is first tested on the strength distributions. As an example, Fig. 4 displays the variation of the $B(M2)$ strength between 4 and 9 MeV excitation energy for different values of ϵ. In the bottom part, the experimental distribution folded with a Lorentzian of comparable width to the SRPA

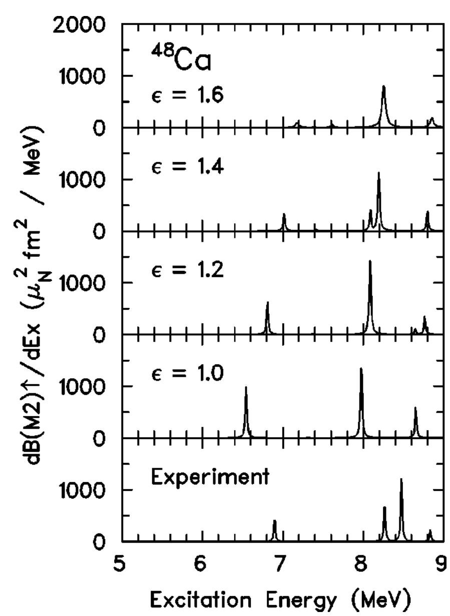

FIG. 4. $B(M2)\uparrow$ strength distribution in ^{48}Ca for $E_x = 4-9$ MeV calculated with SRPA and the interaction (4). Results are shown for $\epsilon=1$, 1.2, 1.4, and 1.6. The experimental strength distribution folded with a Lorentzian of a width comparable to the SRPA calculations is presented at the bottom for comparison.

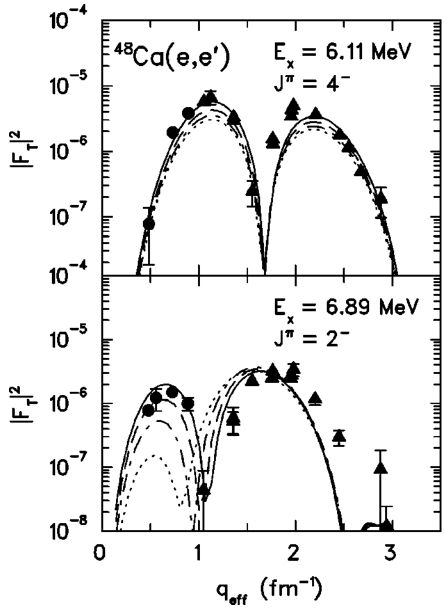

FIG. 5. Same as Fig. 2, but calculations with the interaction (4) for values $\epsilon=1$ (solid line), 1.2 (dashed line), 1.4 (dashed-dotted line), and 1.6 (dotted line).

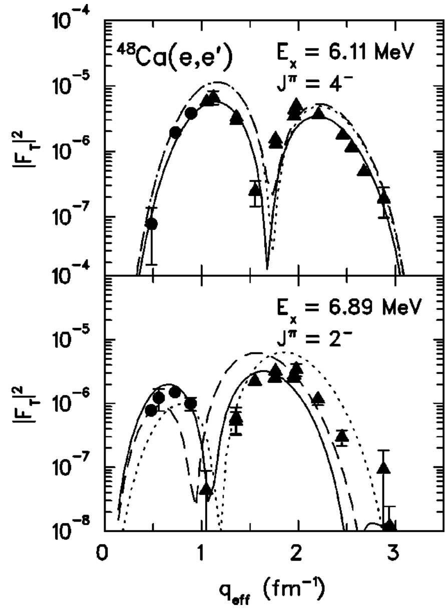

FIG. 6. Dependence of the form factors of the $M4$ and $M2$ transitions to the low lying $J^{\pi}=4^{-}$ and $J^{\pi}=2^{-}$ states at $E_x=6.11$ and 6.89 MeV in ^{48}Ca on the choice of the interaction. Solid line: $\pi+\rho$ exchange, Eq. (4). Dashed line: M3Y [21,22] with exchange terms. Dotted line: M3Y without exchange terms.

results is presented. The calculations generally resemble quite well the experimental findings of an isolated transition below $E_x=7$ MeV and a group between $E_x=8$ and 9 MeV. (One may note that a further transition at 6.69 MeV is experimentally observed for which a $M2$ character cannot be excluded.) For $\epsilon=1.0$, the two most prominent transitions around 6.5 and 8 MeV are of dominant one particle–one hole (1p-1h) structure and can be interpreted to arise mainly from the interference of the $\nu(2p_{1/2}1d_{3/2}^{-1})$ and $\pi(1f_{7/2}1d_{3/2}^{-1})$ configurations (constructive for the lower, destructive for the upper state). The inclusion of two particle–two hole (2p-2h) states leads to small, but noticeable effects. With increasing ϵ (dropping ρ mass) a slight overall shift towards higher energies is observed, while the strength of the lowest transition decreases, mainly due to stronger mixing with another close-lying (but much weaker) excitation. Similar results are obtained for the low-energy $M4$ strength not shown here with two close-lying states resulting from the mixing of the $\pi(1f_{7/2}2s_{1/2}^{-1})$ and $\pi(1f_{7/2}1d_{3/2}^{-1})$ couplings. The lower-lying transition is identified with the experimental excitation of the 6.11 MeV level.

Calculations for the experimental $M4$ and $M2$ form factors of the 6.11 and 6.89 MeV states, respectively, with this approach are summarized in Fig. 5 for values $\epsilon=1$ (solid line), 1.2 (dashed line), 1.4 (dashed-dotted line), and 1.6 (dotted line). The main effect on the $M4$ transition is a global reduction for all q. However, independent of the choice of ϵ the experimental position of the second form factor maximum is predicted at momentum transfers somewhat too high. The best description for the $M4$ transition is obtained for an ϵ value close to 1, while the optimum ϵ value at the first maximum of the $M2$ form factor would be between 1.0 and 1.2. However, the $M2$ predictions show a pronounced dependence on the effective m_ρ in the momentum transfer range $q\simeq 0.6-1.5$ fm^{-1} favoring $\epsilon=1.0$. At higher q independent of ϵ the form factor falls off too steeply.

One obvious difference to the results of Lallena is a much less dramatic dependence on the variation of ϵ. The overall reduction observed in both transitions with decreasing m_ρ can be traced back to a modification of the spin-isospin coupling constant because of short-range correlations, as shown, e.g., by Baym and Brown [34]. One may speculate that these differences mainly arise from the inclusion of MEC effects due to pion and seagull terms by Lallena [9]. The good description of the prominent $M1$ form factor without any need for MEC contributions is somewhat contradictory to the rather strong role of those contributions played within the model described in Sec. II [35].

Finally, we study in Fig. 6 the sensitivity of the presented results to the choice of the interaction. The solid lines are again the result using interaction (4) with $\epsilon=1$, while the dashed lines correspond to the M3Y interaction as applied in [17], where exchange terms are neglected. The dotted lines show calculations restricted to the spin-isospin channel of the M3Y interactions, but including exchange terms. The predictions for the $M4$ transition depend mainly on the ratio of the relevant 1p-1h components. The increase of the form factors for the latter two interactions is related to the ratio of the $\pi(1f_{7/2}2s_{1/2}^{-1})$ to the $\pi(1f_{7/2}1d_{3/2}^{-1})$ amplitude. The $M2$ form factors exhibit an additional sensitivity to the momentum transfer at the first minimum. The main structure is in all cases defined by the $\pi(1f_{7/2}1d_{3/2}^{-1})$ and $\nu(2p_{1/2}1d_{3/2}^{-1})$ configurations. Using the M3Y interaction without exchange terms, the modification with respect to the $\pi+\rho$ force is mainly caused by additional admixture of the $\nu(2p_{1/2}1d_{5/2}^{-1})$ transition. Using the spin-isospin part of the M3Y, instead the $\pi(1f_{7/2}1d_{5/2}^{-1})$ transition comes into play leading to a global shift towards higher momentum transfers. It is evident that the differences induced by the choice of a particular interaction are of comparable magnitude to the variations of $m_\rho^\star$ (cf. Fig. 5), and there is no obvious way to distinguish them.

V. CONCLUDING REMARKS

The present work aimed at an investigation of the role of in-medium vector mesons (in particular the ρ meson) for transverse inelastic electron scattering form factors in nuclei at low excitation energies. Sizable effects have been predicted by Lallena in a study of the lowest $M2$ and $M4$ transitions in ^{48}Ca [9]. Here, new experimental information at low momentum transfers is presented which provides important constraints on such an analysis. A consistent description of the data can be achieved with a small, but finite effective ρ-meson mass $m_\rho^\star \approx 0.9-0.95\ m_\rho$ and a simultaneous scaling of the π coupling constant, i.e., assuming Brown-Rho scaling [12].

However, our main emphasis was a critical test of the model dependence of such conclusions. Results from a $\pi+\rho$ exchange force constructed from the M3Y interaction also provide a reasonable description of the data, but suggest that no dropping of the in-medium ρ-meson mass is needed in line with the findings of [14,15]. The comparison of the two models reveals that modifications of the results due to the particular choice of the residual interactions as well as extra corrections such as meson exchange currents are indistinguishable from the sought medium effects.

One general limitation of the approaches discussed here is the neglect of a density dependence of the effective mass as predicted by QCD sum rules [36]. This might restrict the feasibility of the results to some average surface value corresponding to q values around $1.5-2\ \mathrm{fm}^{-2}$. It would be highly desirable to include density-dependent effects in future work as attempted, e.g., in [37] for the description of quasifree hadronic reaction variables.

At present, one must conclude that, while magnetic form factors at low momentum transfers exhibit considerable sensitivity to in-medium modifications of vector mesons, the freedom in fixing parameters of the residual interaction or including corrections such as MEC lead to effects of comparable magnitude inextricably intertwined. Thus, while inelastic electron scattering transverse from factors in nuclei are a potentially interesting opportunity to investigate in-medium properties of vector mesons, first an optimum interaction successfully describing a large variety of low-energy nuclear properties has to be determined before a quantitative analysis may be possible.

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