Ab initio computation of the longitudinal response function in $^{40}$Ca

J. E. Sobczyk,1 B. Acharya,1 S. Bacca,1,2 and G. Hagen3,4

1Institut für Kernphysik and PRISMA+ Cluster of Excellence, Johannes Gutenberg-Universität, 55128 Mainz, Germany
2Helmholtz-Institut Mainz, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany
3Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
4Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA

We present a consistent ab initio computation of the longitudinal response function $R_L$ in $^{40}$Ca using the coupled-cluster and Lorentz integral transform methods starting from chiral nucleon-nucleon and three-nucleon interactions. We validate our approach by comparing our results for $R_L$ in $^4$He and the Coulomb sum rule in $^{40}$Ca against experimental data and other calculations. For $R_L$ in $^{40}$Ca we obtain a very good agreement with experiment in the quasi-elastic peak up to intermediate momentum transfers, and we find that final state interactions are essential for an accurate description of the data. This work presents a milestone towards ab initio computations of neutrino-nucleus cross sections relevant for experimental long-baseline neutrino programs.

Understanding a wide variety of nuclear phenomena in terms of constituent nucleons is a major ongoing initiative in nuclear theory [1]. Theoretical predictions that start from the forces among nucleons and their interactions with external probes as described by chiral effective field theory are arguably the doorway to connect experimental observations with the underlying fundamental theory of quantum chromo-dynamics [2–5]. This approach is key to interpret existing data, provide guidance for future experiments, and support interdisciplinary efforts at the interface with nuclear physics, such as neutrino physics [6].

Neutrino oscillation experiments aim at addressing some of the biggest unanswered questions in physics by measuring the charge conjugation-parity violating phase in the lepton sector of the Standard Model of particle physics. For the current neutrino oscillation experiments the systematic errors are at the order of $\sim 10\%$ and largely influenced by considerable cross-section uncertainties. Next generation experiments set their precision goal much higher. The T2HK [7] and DUNE [8] experiments aim at achieving much smaller statistical fluctuations, comparable with present systematic errors. It is therefore crucial to control the systematics, whose major part comes from the limited precision of theoretical modeling of neutrino-nucleus cross sections. Furthermore, the exposure needed to achieve a desired sensitivity also depends on the ability of reducing systematic errors. The models which are presently in use, particularly the ones implemented in the Monte Carlo event generators, should be benchmarked with the predictions given by ab initio models of nuclear dynamics for relevant nuclei such as $^{12}$C, $^{16}$O and $^{40}$Ar.

Due to recent developments of accurate quantum many-body methods with controlled approximations, ever-increasing computing power, and advancements in the description of nuclear interactions and electroweak currents, we are now entering an era where the ab initio description of lepton-nucleus scattering is becoming possible. The Green’s Function Monte Carlo (GFMC) method was used to calculate nuclear responses of $^4$He and $^{12}$C [9, 10], and was recently able to make direct comparisons with the neutrino-nucleus experimental cross sections [11, 12]. Using the same dynamical ingredients, other simplified methods are being developed to reduce the computational load and address the quasi-elastic peak [13]. In another set of studies, the lepton-nucleus scattering cross sections of $^4$He, $^{16}$O and $^{40}$Ar were obtained using spectral functions calculated in the self-consistent Green’s function method with final-state interactions included using mean-field potentials [14, 15].

In this Letter, we lay out the tools for an ab initio method that accurately accounts for final state interactions, consistently with the treatment of initial state interactions, and demonstrate its advantages by comparing to available longitudinal electron scattering data for $^{40}$Ca. We base our approach on the coupled-cluster (CC) method [16–25], which stands out as one of the most suitable and promising methods for calculations involving medium-mass and heavy nuclei due to the polynomial scaling of its computational cost with the mass number $A$. Initially applied to closed-shell nuclei (see Ref. [25] for a review), it has since been extended to accurately describe doubly open-shell neighbors such as $^{40}$Ar [26, 27], and more recently starting from an axially deformed reference state entire isotope chains [28, 29]. Combining CC with the Lorentz integral transform method [30, 31], the LIT-CC approach extends the reach of this theory to processes involving excitation of bound nuclear states to the continuum. Originally applied to calculate low-energy nuclear dipole responses [32, 33], recently it was extended to compute the Coulomb sum rule for $^4$He and $^{16}$O [34]. By devising a method to project out the spurious center-of-mass (CoM) excitations, Ref. [34] has also tackled the major technical challenge of removing CoM contaminations in calculations utilizing translationally non-invariant nuclear electroweak operators. These developments open the door to go beyond the sum rule...
calculations and gain deeper insights into the dynamics of the nucleus by computing the nuclear response functions. With the goal of eventually applying the theory to neutrino-nucleus scattering, where experimental data are scarce or imprecise, we first benchmark our results for inelastic electron-scattering by comparing them with existing data for $^{40}$Ca.

The inclusive cross section of this process can be expressed in terms of two response functions: the longitudinal, $R_L(\omega, q)$, and the transverse, $R_T(\omega, q)$, where $\omega$ is the energy transferred from the electron to the nucleus. These are induced by the charge and the current operator, respectively, and can be experimentally disentangled using the so-called Rosenbluth separation. We study the longitudinal response in this work and defer the transverse response, which receives large two-nucleon electromagnetic current contributions [12], to a future work. Formally, the longitudinal response function can be defined as

$$R_L(\omega, q) = \sum_f \langle \Psi_f | \rho(q) | \Psi_0 \rangle^2 \delta \left( E_f + \frac{q^2}{2M} - E_0 - \omega \right),$$

where $M$ is the mass of the target nucleus, and $|\Psi_{0/f}\rangle$ and $E_{0/f}$ respectively denote the initial/final-state nuclear wave functions and energies, which we compute using nucleon-nucleon and three-nucleon forces from chiral effective field theory. In order to estimate the sensitivity of our results on the employed Hamiltonian we use two different chiral interactions, namely NNLO$_{\text{sat}}$ [35] and $\Delta$NNLO$_{\text{GO}}(450)$ [36]. These interactions are both given at next-to-next-to-leading order in the chiral expansion and employ a regulator cutoff of 450 MeV/$c$, but they differ in that $\Delta$NNLO$_{\text{GO}}(450)$ includes explicit $\Delta$-isobars in its construction while NNLO$_{\text{sat}}$ does not. These interactions are well suited for our study of $^4$He and $^{40}$Ca as they have been shown to provide an accurate description of radii and binding energies of light and medium-mass nuclei nuclei, and the saturation point of symmetric nuclear matter [35, 36].

The charge density operator considered in this work is

$$\rho(q) = \frac{e}{2} \sum_{i=1}^A \left( G_E^S(Q^2) + \tau_i^3 G_E^V(Q^2) \right) \exp(iq \cdot r_i),$$

where $e$ is the proton charge, while $r_i$ and $\tau_i^3$ are the coordinate and the third isospin component of nucleon $i$. We use the parametrization of Ref. [37] for the nucleon isoscalar/isovector electric form factors, $G_E^S/V(Q^2)$. The Darwin-Foldy and the spin-orbit relativistic corrections, as well as the two-nucleon current contributions, are not included in Eq. (2) since we strive for consistency between the power-counting and truncation in the chiral expansions of the current and the interactions. Specifically, corrections to Eq. (2) are at least four orders higher in the chiral expansion when the inverse of the nucleon mass is counted as two chiral orders [38], which is beyond the order at which the interactions we use are truncated.

The sum over $\Psi_f$ in Eq. (1) poses a serious computational challenge, since it involves an integration over the continuum states, when $\omega$ is above the particle emission threshold $\omega_h$. To overcome this issue, we use the LIT method, where through the application of a Lorentzian-kernel transform

$$E_L(\sigma, q) = \sigma f \int d\omega \frac{R_L(\omega, q)}{(\omega - \sigma R)^2 + \sigma^2} = \langle \tilde{\Psi}_0^{\sigma, q} | \tilde{\Psi}_0^{\sigma, q} \rangle$$

(3)

with $\sigma f \neq 0$, one reduces the problem to solving

$$(H - E_0 - \sigma)|\tilde{\Psi}_0^{\sigma, q}\rangle = \rho(q)|\Psi_0\rangle,$$

(4)

where $H$ denotes the nuclear Hamiltonian. Effectively, $\tilde{\Psi}_0^{\sigma, q}$ is the solution of a bound-state “Schrödinger-like” equation with a source term, which can be solved also in coupled-cluster theory.

The CC method allows for the inclusion of many-body correlations as a controlled expansion by writing the nuclear wave function as $|\Psi\rangle = e^T|\Phi_0\rangle$. Here $|\Phi_0\rangle$ is a suitably chosen reference state, and $T = T_1 + T_2 + \ldots$ is a linear expansion in particle-hole excitations typically truncated at some low excitation rank. In this work we truncate $T = T_1 + T_2$ which is known as the coupled-cluster singles and doubles (CCSD) method. Inserting the CCSD wave function into the many-body Schrödinger equation and projecting from the left with $e^{-T}$, it is seen that the reference state $|\Phi_0\rangle$ is the ground-state of the similarity transformed normal-ordered Hamiltonian $\tilde{H}_N = e^{-T}H_Ne^T$. In the LIT-CC formulation one has to employ the equation-of-motion coupled-cluster technique (EOM-CC) [39] with a source term (see r.h.s. of Eq. (4)) and the similarity transformed normal-ordered operator $\tilde{\Theta}_N \equiv e^{-T}\Theta_Ne^T$ [40]. Here, $\Theta$ are the rank-$J$ multipole of the electromagnetic charge operator given by Eq. (2). To obtain the LIT, we perform EOM-CC calculations for each multipole $|\rho(q)\rangle^T$, and perform the sum over all multipoles at the end (see also Ref. [41]).

The response function $R_L(\omega, q)$ for a given value of $q$ is then obtained by inverting the integral transform from Eq. (3). To perform the inversions, which require the solution of an ill-posed problem, we perform the expansion $R_L(\omega) = \sum_{h=0}^N c_i \omega^{n_h} e^{-\beta}$ and seek for stable solutions by varying the non-linear parameter $\beta$ (as well as $n_h$) in a certain range. The inversion procedure involves the determination of the coefficients $c_i$ of the $N$ basis functions by a least-squares fit [31]. We impose $R(\omega)$ to be zero for $\omega \leq \omega_h$, using the values we obtain for a given nuclear Hamiltonian in the CCSD approximation. We estimate the uncertainty associated with the inversion procedure by inverting LITs with three different values of $\sigma f = 5, 10$ and 20 MeV and by varying $N$ from 6 to 9.

In all our results we employ a model space consisting of 15 major oscillator shells ($e_{\text{max}} = 2n+l = 14$) with an additional cut on the matrix elements of the three-nucleon
force given by $\epsilon_{\text{max}} = 2n_1 + l_1 + 2n_2 + l_2 + 2n_3 + l_3 \leq 16$. We checked that we can reach a satisfactory convergence of $\mathcal{L}_L$ in terms of the single-particle model space size $\epsilon_{\text{max}}$. The latter can be tested, e.g., by studying the residual dependence on the underlying harmonic oscillator frequency $\hbar \Omega$. In particular, for LITs with $\sigma = 20$ MeV we estimate the convergence in the quasi-elastic peak to be at the 2% level for $q \leq 350$ MeV/c and of 4% for $q \geq 400$ MeV/c, by varying $\hbar \Omega$ in the range 18 to 22 MeV.

**Benchmark on the $^4$He nucleus**— We begin by presenting our results for $R_L$ in the case of $^4$He at $q = 300$ MeV/c. In Fig. 1, we show calculations performed with the NNLO$_{\text{sat}}$ interaction in the CCSD scheme for an underlying harmonic oscillator frequency of $\hbar \Omega = 16$ MeV. Here the small band reflects only the uncertainty associated with the LIT inversion. For comparison, we also show calculations performed with the hyperspherical harmonics method (HH) [45] using the AV18/UIX potential and Green Function Monte Carlo (GFMC) [43] calculations that used the AV18/UI7 potential. We obtain very good agreement with the experimental data as well as with other theoretical calculations. This comparison corroborates our method and further validates the protocol we developed in Ref. [34] to remove center of mass contamination.

**Benchmark on the $^{40}$Ca nucleus**— Following the same steps as in Ref. [34], we calculate the Coulomb sum rule for $^{40}$Ca using the NNLO$_{\text{sat}}$ interaction. We observe that the CoM contamination is negligible for $q > 200$ MeV/c, and is overall much smaller than in the previously considered cases of $^4$He and $^{16}$O [34]. In Fig. 2 we compare it to the cluster variational Monte Carlo (CVMC) results from Ref. [46] which used the AV18/UIX potential and included Darwin-Foldy and spin-orbit corrections. Results are compatible at low-$q$ due to the larger uncertainty in the CVMC curve, and show the same increasing trend for $q > 100$ MeV/c with small differences. We have verified that the difference at $q = 500$ MeV/c is mainly due to relativistic effects which we omitted in order to be consistent with the chiral order we work at. Most importantly, both theoretical predictions are in agreement with experimental data [47] in the range between 300 and 375 MeV/c and are higher than the data above $q = 400$ MeV/c, likely because experimental data are obtained by integrating $R_L$ up to a finite $\omega$, and not up to infinity as is done in the theoretical calculations. We consider this a successful benchmark of our method and point out that only a mild Hamiltonian dependence is observed.

**The $^{40}$Ca longitudinal response function**— We now turn to our $ab$ initio calculation of $R_L$ in $^{40}$Ca where the full final state interaction is considered. We choose $^{40}$Ca because we can compare our calculations with existing data, and it is also a stepping stone for coupled-cluster computations of neutrino scattering on $^{40}$Ar. For both NNLO$_{\text{sat}}$ and $\Delta$NNLO$_{\text{GO}}(450)$ we perform computations of $R_L$ at the momentum transfers $q = 200, 300, 350$ and $400$ MeV/c. In CCSD, the obtained ground-state energies $E_0$ (proton separation energies $\omega_{\text{sat}}$) are 300.1 (6.32) MeV and 322.12 (6.12) MeV for the NNLO$_{\text{sat}}$ and the $\Delta$NNLO$_{\text{GO}}(450)$ potential, respectively.

First, we find two bound excited $J^\pi = 3^-, 5^-$ states lying respectively at 4.5(3.8) MeV and 4.7(4.0) MeV with the NNLOsat($\Delta$NNLO$_{\text{GO}}(450)$) interactions, which are in reasonable agreement with experimental data at 3.7 MeV ($J^\pi = 3^-$) and at 4.5 MeV ($J^\pi = 5^-$). We plot their strengths as a line in Fig. 3, and we observe that it decreases with $q$. Second, for the continuum response we show a band that reflects the uncertainty associated with the LIT inversion and the model space, as we vary the harmonic oscillator frequency $\hbar \Omega$ from 18 to 20 and 22 MeV. As can be seen in Fig. 3, for each momentum transfer we observe a mild dependence on the interaction, the latter being stronger at $q = 200$ MeV/c. Comparing to the available experimental data from Ref. [47], we find a generally very good agreement, which is best for $q = 300$ MeV/c. At $q = 400$ MeV/c, we see a quenching of the quasi-elastic peak and an enhancement in the tail with

---

**FIG. 1.** Longitudinal response function for $^4$He at $q = 300$ MeV/c. HH results taken from Ref. [42], GFMC results from Ref. [43], and experimental data from Ref. [44].

**FIG. 2.** $^{40}$Ca results for Coulomb sum rule for N2LO$_{\text{sat}}$ and $\hbar \omega = 22$ MeV compared with CVMC results of Ref. [46] and experimental data taken from Ref. [47].
respect to experiment. We speculate that this could potentially be explained by relativistic boost effects \cite{43} or by the fact that, especially at high $q$ and high $\omega$, we are reaching the limits of applicability of chiral effective field theory set by the regulator cutoff 450 MeV/c.

Finally, to quantify the effect of the final state interaction, we will contrast the LIT-CC results with those of the simple plane wave impulse approximation (PWIA). The point-proton longitudinal response function is obtained in PWIA assuming one outgoing free proton with mass $m$ and a spectator (A-1)-system with mass $M_s$,

$$R_{PWIA}^{L}(\omega, q) = \int dp \, n(p) \delta \left( \omega - \frac{(p + q)^2}{2m} - \frac{p^2}{2M_s} - \omega_{th} \right),$$

and then augmented with nucleon electric form factors. Here $n(p)$ represents the proton momentum distribution calculated from coupled-cluster theory using the NNLO$_{sat}$ interaction, where CoM corrections are found to be negligible \cite{48}. Unlike the LIT-CC results, the PWIA curves shown in Fig. 3 are in poor agreement with the data: (i) they miss the quasi-elastic peak position by up to 20 MeV, (ii) they overestimate considerably the quasi-elastic peak size by up to 40\% and (iii) and they do not fully account for the asymmetric shape of the response. The differences between the LIT-CC and the PWIA results are very strong at lower $\omega$, where we observe that even for the highest momentum transfers here considered $q = 400$ MeV/c, we describe the experimental data very well. This highlights the importance of consistently including the final state interaction.

In order to provide a prediction for future measurements as opposed to a sole postdiction of existing data, we have calculated also the $q = 200$ MeV/c kinematics, where no data exist yet. While this low-$q$ range may be less important for neutrino physics, this is where we have the largest uncertainty band (range of low-$q$ and low-$\omega$). New precise data could provide important tests of the \textit{ab initio} nuclear structure theory. An experimental program in this direction is presently under development in Mainz \cite{49}.

Conclusions— We performed an \textit{ab initio} calculation of the longitudinal response function of $^{40}$Ca and obtained very good agreement with existing data. Our results are a proof of principle that the LIT-CC method is suitable to deliver responses for lepton-nucleus scattering at the momentum transfers relevant for neutrino oscillation experiments. Consequently, we extended the reach of consistent \textit{ab initio} calculations of electromagnetic responses at intermediate momentum transfers into a region of medium-mass nuclei, which until now was limited to systems with $A \leq 12$.

Our framework allows for quantification of uncertainties stemming from truncations of model space, chiral effective-field-theory, and coupled-cluster expansions. In this work, we estimated errors that arise from the inversion procedure, and studied the dependencies on the
We thank Nir Barnea and Thomas Papenbrock for useful comments and discussions. This work was supported by the Deutsche Forschungsgemeinschaft (DFG) through the Collaborative Research Center [The Low-Energy Frontier of the Standard Model (SFB 1044)], and through the Cluster of Excellence “Precision Physics, Fundamental Interactions, and Structure of Matter” (PRISMA+ EXC 2118/1) funded by the DFG within the German Excellence Strategy (Project ID 39083149), by the Office of Nuclear Physics, U.S. Department of Energy, under grants desc0018223 (NUCLEI SciDAC-4 collaboration) and by the Field Work Proposal ERKBP72 at Oak Ridge National Laboratory (ORNL). Computer time was provided by the Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program and by the Field Work Proposal ERKBP72 at Oak Ridge National Laboratory (ORNL). This research used resources of the Oak Ridge Leadership Computing Facility located at ORNL, which is supported by the Office of Science of the Department of Energy under Contract No. DE-AC05-00OR22725.

[1] Heiko Hergert, “A guided tour of ab initio nuclear many-body theory,” Frontiers in Physics 8, 379 (2020), and references therein.

[2] U. van Kolck, “Few-nucleon forces from chiral Lagrangians,” Phys. Rev. C 49, 2932–2941 (1994).

[3] P. F. Bedaque and U. van Kolck, “Effective field theory for few-nucleon systems,” Annual Review of Nuclear and Particle Science 52, 339–396 (2002), nucl-th/0203055.

[4] E. Epelbaum, H.-W. Hammer, and Ulf-G. Meißner, “Modern theory of nuclear forces,” Rev. Mod. Phys. 81, 1773–1825 (2009).

[5] R. Machleidt and D.R. Entem, “Chiral effective field theory and nuclear forces,” Physics Reports 503, 1 – 75 (2011).

[6] L. Alvarez-Ruso et al. (NuSTEC), “NuSTEC White Paper: Status and challenges of neutrino-nucleus scattering,” Prog. Part. Nucl. Phys. 100, 1–68 (2018), arXiv:1706.03621 [hep-ph].

[7] K. Abe et al. (Hyper-Kamiokande Proto-Collaboration), “Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande,” PTEP 2015, 053C02 (2015).

[8] R. Acciarri et al. (DUNE), “Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE),” (2015), arXiv:1512.06148 [physics.ins-det].

[9] A. Lovato, S. Gandolfi, J. Carlson, Steven C. Pieper, and R. Schiavilla, “Neutral weak current two-body contributions in inclusive scattering from $^{12}$C,” Phys. Rev. Lett. 112, 182502 (2014).

[10] A. Lovato, S. Gandolfi, J. Carlson, Steven C. Pieper, and R. Schiavilla, “Electromagnetic and neutral-weak response functions of $^4$He and $^{12}$C,” Phys. Rev. C 91, 062501 (2015), arXiv:1501.01981 [nucl-th].

[11] A. Lovato, S. Gandolfi, J. Carlson, Ewing Lusk, Steven C. Pieper, and R. Schiavilla, “Quantum Monte Carlo calculation of neutral-current $\nu - ^{12}$C inclusive quasielastic scattering,” Phys. Rev. C 97, 022502 (2018), arXiv:1711.02047 [nucl-th].

[12] A. Lovato, J. Carlson, S. Gandolfi, N. Rocco, and R. Schiavilla, “Ab initio study of ($\nu e$, $e^-\bar{\nu}$) and ($e\nu$, $e^+\nu$) inclusive scattering in $^{12}$C: Confronting the miniboone and t2k ccqe data,” Phys. Rev. X 10, 031068 (2020).

[13] S. Pastore, J. Carlson, S. Gandolfi, R. Schiavilla, and R. B. Wiringa, “Quasielastic lepton scattering and back-to-back nucleons in the short-time approximation,” Phys. Rev. C 101, 044612 (2020).

[14] N. Rocco and C. Barbieri, “Inclusive electron-nucleus cross section within the Self Consistent Green’s Function approach,” Phys. Rev. C 98, 025501 (2018), arXiv:1803.00825 [nucl-th].

[15] C. Barbieri, N. Rocco, and V. Somà, “Lepton scattering from $^{40}$Ar and $^{94}$Ti in the quasielastic peak region,” arXiv:1907.01122 [nucl-th].

[16] F. Coester, “Bound states of a many-particle system,” Nuclear Physics 7, 421 – 424 (1958).

[17] F. Coester and H. Kümmler, “Short-range correlations in nuclear wave functions,” Nuclear Physics 17, 477 – 485 (1960).

[18] H. Kümmel, K. H. Lührmann, and J. G. Zabolitzyk, “Many-fermion theory in expS- (or coupled cluster) form,” Physics Reports 36, 1 – 63 (1978).

[19] B. Mihaila and J. H. Heisenberg, “Microscopic Calculation of the Inclusive Electron Scattering Structure Function in $^{16}$O,” Phys. Rev. Lett. 84, 1403–1406 (2000).

[20] D. J. Dean and M. Hjorth-Jensen, “Coupled-cluster approach to nuclear physics,” Phys. Rev. C 69, 054320 (2004).

[21] M. Wloch, D. J. Dean, J. R. Gour, M. Hjorth-Jensen, K. Kowalski, T. Papenbrock, and P. Piechuch, “Ab-Initio coupled-cluster study of $^{18}$O,” Phys. Rev. Lett. 94, 212501 (2005).

[22] G. Hagen, T. Papenbrock, D. J. Dean, and M. Hjorth-Jensen, “Medium-mass nuclei from chiral nucleon-nucleon interactions,” Phys. Rev. Lett. 101, 092502 (2008).

[23] G. Hagen, T. Papenbrock, D. J. Dean, and M. Hjorth-Jensen, “Ab initio coupled-cluster approach to nuclear structure with modern nucleon-nucleon interactions,” Phys. Rev. C 82, 034330 (2010).

[24] Sven Binder, Joachim Langhammer, Angelo Calci, and Robert Roth, “Ab initio path to heavy nuclei,” Phys. Lett. B 736, 119 – 123 (2014).

[25] G. Hagen, T. Papenbrock, M. Hjorth-Jensen, and D. J. Dean, “Coupled-cluster computations of atomic nuclei,” Rep. Prog. Phys. 77, 096302 (2014).

[26] H. N. Liu, A. Obertelli, P. Doornenbal, C. A. Bertulani, G. Hagen, J. D. Holt, G. R. Jansen, T. D. Morris, A. Schwenk, R. Stroberg, N. Achouri, H. Baba, F. Browne, D. Calvet, F. Château, S. Chen, N. Chiga, A. Corsi, M. L. Cortés, A. Delbart, J.-M.
C. G. Payne, A. Giganon, C. Hilaire, T. Isobe, T. Kobayashi, Y. Kubota, V. Lapoux, T. Motobayashi, I. Murray, H. Otsubo, V. Panin, N. Paul, W. Rodriguez, H. Sakurai, M. Sasano, D. Steppenbeck, L. Stuhl, Y. L. Sun, Y. Togano, T. Uesaka, K. Winmer, K. Yoneda, O. Aktas, T. Aumann, L. X. Chung, F. Flavigny, S. Franchoo, I. Gašparič, R.-B. Gerst, J. Gibelin, K. I. Hahn, D. Kim, T. Koivai, Y. Kondo, P. Koseoglou, J. Lee, C. Lehr, B. D. Linh, T. Lokotto, M. MacCormick, K. Moschner, T. Nakamura, S. Y. Park, D. Rossi, E. Sahin, D. Sohler, P.-A. Söderström, S. Takeuchi, H. Törnvist, V. Vaquero, V. Wagner, S. Wang, V. Werner, X. Xu, H. Yamada, D. Yan, Z. Yang, M. Yasuda, and L. Zanetti, “How robust is the n = 34 subshell closure? first spectroscopy of $^{52}$Ar,” Phys. Rev. Lett. 122, 072502 (2019).

27. C. G. Payne, S. Bacca, G. Hagen, W. Jiang, and T. Papenbrock, “Coherent elastic neutrino-nucleus scattering on $^{36}$Ar from first principles,” Phys. Rev. C 100, 061301 (2019), arXiv:1908.09739 [nucl-th].

28. S. J. Novario, G. Hagen, G. R. Jansen, and T. Papenbrock, “Charge radii of exotic neon and magnesium isotopes,” Phys. Rev. C 102, 051303 (2020).

29. A. Koszorús, F. X. Yang, W. G. Jiang, S. J. Novario, S. W. Bai, J. Billowes, C. L. Binnwers, M. L. Bissell, T. E. Cocolios, B. S. Cooper, R. P. de Groote, A. Ekström, K. T. Flanagan, C. Forsén, S. Franchoo, R. F. García Ruiz, F. P. Gustafsson, G. Hagen, G. R. Jansen, A. Kanellakopoulos, M. Kortelainen, W. Nazarewicz, G. Neyens, T. Papenbrock, P. G. Reinhard, C. M. Ricketts, B. K. Sahoo, A. R. Vernon, and S. G. Wilkins, “Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of n = 32,” Nature Physics (2021), 10.1038/s41567-020-01136-5.

30. Viktor D. Efros, Winfried Leidemann, and Giuseppina Orlandini, “Response functions from integral transforms with a lorentz kernel,” Phys. Lett. B 338, 130 – 133 (1994).

31. V D Efros, W Leidemann, G Orlandini, and N Barnea, “The lorentz integral transform (lit) method and its applications to perturbation-induced reactions,” Journal of Physics G: Nuclear and Particle Physics 34, R459 (2007).

32. S. Bacca, N. Barnea, G. Hagen, G. Orlandini, and T. Papenbrock, “First principles description of the giant dipole resonance in $^{16}$O,” Phys. Rev. Lett. 111, 122502 (2013).

33. S. Bacca, N. Barnea, G. Hagen, M. Miorelli, G. Orlandini, and T. Papenbrock, “Giant and pigny dipole resonances in $^4$He, $^{16}$O, and $^{40}$Ca from chiral nucleon-nucleon interactions,” ArXiv e-prints (2014), arXiv:1410.2258 [nucl-th].

34. J. E. Sobczyk, B. Acharya, S. Bacca, and G. Hagen, “Coulomb sum rule for $^4$He and $^{16}$O from coupled-cluster theory,” Phys. Rev. C 102, 064312 (2020), arXiv:2009.01761 [nucl-th].

35. A. Ekström, G. R. Jansen, K. A. Wendt, G. Hagen, T. Papenbrock, B. D. Carlsson, C. Forssén, M. Hjorth-Jensen, P. Navrátil, and W. Nazarewicz, “Accurate nuclear radii and binding energies from a chiral interaction,” Phys. Rev. C 91, 051301 (2015), arXiv:1502.04682 [nucl-th].

36. W. G. Jiang, A. Ekström, C. Forssén, G. Hagen, G. R. Jansen, and T. Papenbrock, “Accurate bulk properties of nuclei from a = 2 to ∞ from potentials with Δ isobars,” Phys. Rev. C 102, 054301 (2020).

37. J.J. Kelly, “Simple parametrization of nucleon form factors,” Phys. Rev. C 70, 068202 (2004).

38. H. Krebs, E. Epelbaum, and U. G. Meißner, “Nuclear Electromagnetic Currents to Fourth Order in Chiral Effective Field Theory,” Few Body Syst. 60, 31 (2019), arXiv:1902.06839 [nucl-th].

39. John F. Stanton and Rodney J. Bartlett, “The equation of motion coupled-cluster method, a systematic biorthogonal approach to molecular excitation energies, transition probabilities, and excited state properties,” J. Chem. Phys. 98, 7029–7039 (1993).

40. M. Miorelli, S. Bacca, G. Hagen, and T. Papenbrock, “Computing the dipole polarizability of $^{48}$Ca with increased precision,” Phys. Rev. C 98, 041324 (2018).

41. Bijaya Acharya and Sonia Bacca, “Neutrino-deuteron scattering: Uncertainty quantification and new $L_{1,1}$ constraints,” Phys. Rev. C 101, 015505 (2020).

42. Nir Barnea, Winfried Leidemann, and Giuseppina Orlandini, “State-dependent effective interaction for the hyperspherical formalism with noncentral forces,” Nuclear Physics A 693, 565 – 578 (2001).

43. Noemi Rocco, Winfried Leidemann, Alessandro Lovato, and Giuseppina Orlandini, “Relativistic effects in ab-initio electron-nucleus scattering,” Phys. Rev. C 97, 055501 (2018), arXiv:1801.07111 [nucl-th].

44. J. Carlson, J. Jourdan, R. Schiavilla, and I. Sick, “Longitudinal and transverse quasielastic response functions of light nuclei,” Phys. Rev. C 65, 024002 (2002).

45. Sonia Bacca, Nir Barnea, Winfried Leidemann, and Giuseppina Orlandini, “Role of the final-state interaction and three-body force on the longitudinal response function of $^4$He,” Phys. Rev. Lett. 102, 162501 (2009).

46. D. Lonardoni, A. Lovato, Steven C. Pieper, and R. B. Wiringa, “Variational calculation of the ground state of closed-shell nuclei up to a = 40,” Phys. Rev. C 96, 024326 (2017).

47. C. F. Williamson et al., “Quasielastic electron scattering from Ca-40,” Phys. Rev. C 56, 3152–3172 (1997).

48. J. E. Sobczyk, B. Acharya, S. Bacca, G. Hagen, and T. Papenbrock, in preparation.

49. L. Doria and M. Mihovilovic, private communication.