

Combined Theoretical Analysis of the Parity-Violating Asymmetry for ^{48}Ca and ^{208}Pb

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The recent experimental determination of the parity violating asymmetry A_{PV} in ^{48}Ca and ^{208}Pb at Jefferson Lab is important for our understanding on how neutrons and protons arrange themselves inside the atomic nucleus. To better understand the impact of these measurements, we present a rigorous theoretical investigation of A_{PV} in ^{48}Ca and ^{208}Pb and assess the associated uncertainties. We complement our study by inspecting the static electric dipole polarizability in these nuclei. The analysis is carried out within nuclear energy density functional theory with quantified input. We conclude that the simultaneous accurate description of A_{PV} in ^{48}Ca and ^{208}Pb cannot be achieved by our models that accommodate a pool of global nuclear properties, such as masses and charge radii, throughout the nuclear chart, and describe—within one standard deviation—the experimental dipole polarizabilities α_D in these nuclei.

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Introduction.—Polarized elastic electron scattering and polarized proton scattering have been recently used at Jefferson Lab [1,2] and RCNP in Osaka [3,4] to measure, respectively, A_{PV} and α_D in ^{48}Ca and ^{208}Pb . These nuclei are the two stable doubly magic systems that have substantial neutron-to-proton asymmetry measured in terms of the neutron excess $N - Z$. Large neutron excess increases the neutron skin thickness, decreases A_{PV} , and increases α_D , and many aspects of theoretical description get simplified in doubly magic nuclei, which makes them particularly attractive for theory. Moreover, to connect properties of the atomic nucleus to the nuclear matter equation of state (EOS), it is preferable to study heavy systems such as ^{208}Pb whose properties are dominated by volume effects.

Since the electron scattering, governed by the electro-weak force, is relatively well understood, it promises a clear interpretation of results. In this respect, it should be noted that in order to extract information on the neutron skin thickness R_{skin} and the symmetry energy parameters J and L of the EOS from the observed A_{PV} at a single kinematic condition, nuclear models must be used. The dependence of the results on a nuclear model \mathcal{M} enters through (i) the description of the parity-violating response [5] and (ii) the nuclear model of electroweak charge distribution of the atomic nucleus. This model dependence results in uncertainties which need to be considered when carrying out the extraction $A_{\text{PV}} \xrightarrow{\mathcal{M}} R_{\text{skin}}, J, L$ [6]. In the case of α_D , the model dependence in the analysis stems from distorted wave impulse approximation analysis of proton scattering data, including assumed optical potential model [7], and possible contaminations of the $E1$ nuclear response from

(i) other nuclear multipolarities and (ii) quasideuteron excitations.

The PREX-2 Collaboration [1] result has stimulated a number of studies with often contradictory results on the impact of A_{PV} on various nuclear observables and astrophysical data. For example, in Refs. [1,8], a particular set of covariant energy density functionals (EDFs) was used to infer information on R_{skin}, J , and L as well as on some neutron star properties. Using the same family of EDFs, Ref. [9] analyzed implications of the PREX-2 Collaboration on α_D and concluded that there exists a tension between the value of R_{skin} reported by PREX-2 Collaboration and measured value of α_D . On the other hand, the reaction cross sections for proton and alpha scattering [10–12] were found to be consistent with the large value of R_{skin} deduced by PREX-2 Collaboration. In Ref. [6], A_{PV} was analyzed by taking special care of model uncertainties and correlations with other observables such as α_D . According to this Letter, the significant $1-\sigma$ uncertainty of PREX-2 Collaboration value of A_{PV} precludes the use of this observable as a constraint on the isovector sector of current EDFs. Other studies [13–23] also found it difficult to accommodate the PREX-2 Collaboration values of R_{skin} and L . We note that some of these references consider the value of R_{skin} reported in Ref. [1] as a *measured* quantity, ignoring the aspect of the model-dependent extraction $A_{\text{PV}} \xrightarrow{\mathcal{M}} R_{\text{skin}}$.

In this Letter, we carry out a comprehensive theoretical investigation of A_{PV} and α_D within nuclear density functional theory (DFT) [24] supplemented by statistical uncertainty quantification and correlation analysis. In this

TABLE I. Parameters and results of the CREX Collaboration experiment [2].

Mean scattering angle:	$\bar{\theta}_{\text{Ca}}$	4.51 ± 0.02
Transferred momentum:	$\langle Q^2 \rangle$	$0.0297 \pm 0.0002 \text{ GeV}^2$
	q	$0.8733 \pm 0 \text{ fm}^{-1}$
Beam energy:	E_{beam}	$2182 \pm 0.5 \text{ MeV}$
Weak charge:	Q_W	26.0 ± 0.1
Parity violating asymmetry:	$A_{\text{PV}}^{(\text{Ca})}$	$2668 \pm 106 \text{ ppb}$
Weak form factor at Q^2 :	$F_W^{(\text{Ca})}$	$0.1304 \pm 0.0072\%$

way, we assess the impact of A_{PV} in ^{208}Pb and ^{48}Ca on EDFs developments and on the nuclear matter symmetry energy at saturation.

Parity violating asymmetry.—Polarized elastic electron scattering gives access to the parity violating asymmetry A_{PV} , an observable that probes the weak charge density distribution in atomic nuclei provided the electromagnetic charge density is known [5,25]. Via theoretical models, A_{PV} has been used to extract information on the neutron skin thickness and on the symmetry-energy parameters J and L (see, e.g., [6,8,26]). For an accurate analysis of the measured A_{PV} , different contributions must be considered. In medium mass and heavy nuclei such as ^{48}Ca or ^{208}Pb , Coulomb distortions must be accounted for [27]. Accurate nucleon electromagnetic and weak form factors are essential [25]. A correct understanding of the beam polarization is also crucial. In this respect, the analyzing power obtained in the PREX-2 Collaboration experiment is quite puzzling [28–32]. At high incident electron-beam energies, inelastically scattered electrons from low-energy excited states or even from the giant dipole resonance of the studied target may impact results [2,33]. Effects from QED corrections to the Coulomb field felt by the incident electrons as well as radiative processes such as bremsstrahlung have not been estimated in this context. For small enough scattering angles, even atomic electrons may display some impact on A_{PV} . Finally, the currently neglected higher-order contributions to A_{PV} , such as magnetic effects, or two-body currents, may play some role (see also Supplemental Material [34]).

We show in Table I the parameters and results of CREX Collaboration [2]. Nucleonic moments which are also needed for processing the data are given in Table S1 of Supplemental Material [34]. In this study, we have performed calculations of A_{PV} in ^{48}Ca using the same parameters and conditions as in experiment, including the reported acceptance function. Our calculations strictly follow those of Ref. [6] for A_{PV} in ^{208}Pb based on quantified EDFs. For more details, see Supplemental Material [34].

Dipole polarizability.—The dipole polarizability α_D quantifies the restoring force of the nucleus if an external electric dipole field tries to pull away protons from neutrons. Hence, this quantity characterizes the isovector

channel via the average symmetry potential felt by nucleons. Experimentally, α_D can be deduced using real photons from the total photoabsorption cross section [43] or, equivalently, using virtual photons in polarized proton scattering [3,4]. Theoretically, α_D can be computed from integrating the inverse-energy weighted dipole strength distribution [44–51]. The results presented here are based on the latter approach by using the same EDFs employed to calculate A_{PV} . Within this framework, the product of α_D and J has been shown to be linearly correlated with the neutron skin thickness or, similarly, with the L parameter in neutron rich medium and heavy nuclei [47,49].

Parametrizations and observables.—We base our study on three different types of EDFs. This serves to assess the impact of the form of a functional. One EDF is of the nonrelativistic standard Skyrme type, labeled SV [52]; the second EDF, labeled RD, is a generalized Skyrme type that contains a richer density dependence in terms of rational approximants [53]; and the third one is a point-coupling relativistic mean-field EDF, labeled PC [54], optimized using the same data set as SV min [55]. All three functional families are optimized with respect to the same set of ground-state data, energies, charge radii, surface thickness, etc., in more than 60 semimagic, spherical nuclei [52]. In addition, in Supplemental Material, we explore the impact of model extensions by considering a Skyrme parametrization SV-ext that contains a richer density dependence than SV-min but implemented differently than in RD.

The basic parametrizations in each family are obtained from a fit to the given data set. They are named SV-min [52], RD-min [53], and PC-min [55]. All of them provide high quality in the reproduction of ground-state nuclear properties. We emphasize that none of these EDFs included the data on A_{PV} or α_D in the fit. In order to assess the information content of A_{PV} and α_D , we also develop new parametrizations which add the recent experimental data for A_{PV} and/or α_D in ^{48}Ca and/or ^{208}Pb to the fitting protocol of the SV and RD functionals as shown in Table II. To avoid that those extended fits drive into unphysical regions, we constrain additionally three basic nuclear matter properties (NMP): incompressibility K ; isoscalar effective mass m^*/m ; and sum rule enhancement factor κ_{TRK} (isovector effective mass). These NMP are fixed such that the new parametrizations reproduce the giant monopole resonance, giant dipole resonance, and giant quadrupole resonance in ^{208}Pb with the same quality as the original SV-min and RD-min parametrizations.

Model parameters and nuclear matter properties.—The three functionals use to some extent different types of parameters. To make them better comparable, we express all model parameters related to bulk properties in terms of nuclear matter properties (NMP) which characterize the energy per particle ($e = E/A$) of infinite symmetric nuclear matter at zero temperature around nuclear saturation density ρ_{eq} . These can be grouped into isoscalar and

TABLE II. Summary of the EDFs used in the present Letter and their fit observables. All EDF parametrization use the set of ground state data from [52]. The various test parametrizations use additional constraining data on α_D and A_{PV} in ^{48}Ca and ^{208}Pb as indicated. The parametrization SV-min* was introduced in Ref. [6].

Parametrization	$\alpha_D(\text{Ca})$	$A_{PV}(\text{Ca})$	$\alpha_D(\text{Pb})$	$A_{PV}(\text{Pb})$
SV-min	—	—	—	—
SV-APV $^2\alpha^2$	+	+	+	+
SV-APV $^1\alpha^2$	+	+	+	—
SV- α^2	+	—	+	—
SV-min*	—	—	+	+
RD-min	—	—	—	—
RD-APV $^2\alpha^2$	+	+	+	+
RD-APV $^1\alpha^2$	+	+	+	—
RD- α^2	+	—	+	—
PC-min	—	—	—	—

isovector NMP. The isoscalar NMP are equilibrium energy e_{eq} , equilibrium density ρ_{eq} , incompressibility K , and isoscalar effective mass m^*/m . The isovector NMP are symmetry energy J , slope of symmetry energy L , and sum rule enhancement factor κ_{TRK} (equivalent to isovector effective mass). The symmetry energy slope L , being proportional to the pressure of pure neutron matter at saturation, is a crucial input for neutron star models.

Correlation analysis.—A linear-regression interpretation of the χ^2 fits of the parametrizations allows us to deduce uncertainties of model parameters or observables and correlations between them [56–58]. A useful dimensionless measure of correlation is the coefficient of determination (COD) between two parameters and/or observables [59]. In Fig. 1 the COD matrix for the bulk model parameters (those which can be expressed in terms of NMP) and the key observables of this study: α_D , A_{PV} , and R_{skin} are shown. Specifically, we show the result for two different parametrizations, SV-min and PC-min. (The results for RD-min are very similar to those of SV-min.) Except for J and L , other model parameters are practically uncorrelated with the observables of interest while the isovector NMP J and L show strong correlations with A_{PV} , α_D , and R_{skin} . This shows that these quantities are all isovector indicators [44]. At least for ^{208}Pb , we see a 99% correlation between R_{skin} and A_{PV} , which means that A_{PV} contains the information about R_{skin} for the models considered here. As expected, the correlations between R_{skin} and symmetry energy parameters deteriorates when going from ^{208}Pb to ^{48}Ca due to stronger surface effects in ^{48}Ca .

We also see that PC-min produces stronger isovector correlations than SV-min. The reason is that the relativistic PC functional, as most other relativistic functionals, is poorly parametrized in the isovector channel which means that the isovector observables *must be* strongly correlated

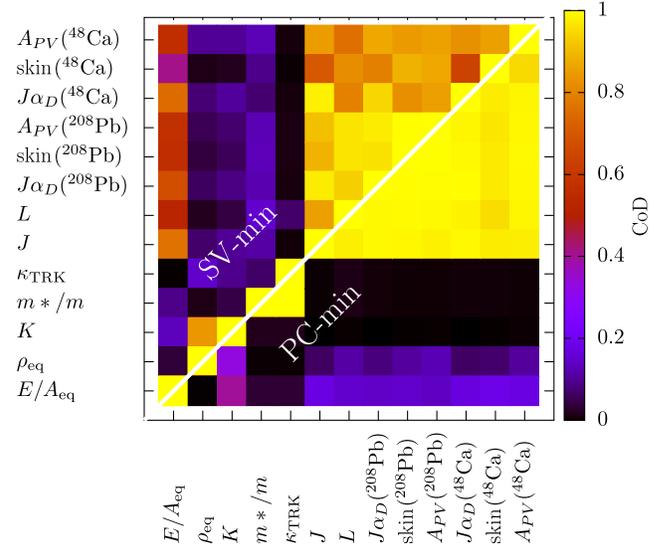


FIG. 1. Matrix of coefficients of determination (COD) between model parameters and observables for SV-min (upper triangle) and PC-min (lower triangle). Not shown are the CODs with spin-orbit parameters which are negligible and with surface parameters which are small.

[44]. For instance, the EDF FSUGold2 [60] used in the PREX-2 Collaboration analysis [8], employs only two isovector parameters. For Skyrme functionals, on the other hand, the parametrization of the isovector channel is as rich as for the isoscalar channel, which yields a greater versatility at the price of requiring more isovector observables to properly determine the isovector coupling constants.

Deducing neutron skin and isovector NMP from A_{PV} .—The major objective of PREX-2 Collaboration and CREX Collaboration experiments was to accurately measure A_{PV} to assess the size of R_{skin} . The accompanying theoretical analysis [8] has attempted to deduce isovector bulk NMP from the PREX-2 Collaboration data using a set of relativistic functionals. How reliable is such extraction? We now discuss this question with the help of trend analysis. Figure 2 shows the trends of $J\alpha_D$, L , and R_{skin} with A_{PV} for ^{48}Ca and ^{208}Pb calculated at the experimental conditions of CREX and PREX-2 Collaborations. The gray regions correspond to the experimental 1- σ error bands and the vertical dotted lines mark the mean value reported in [1,2]. As expected, all three quantities show a clear trend with A_{PV} . Mind, however, that a trend alone is not conclusive as one must also inspect the variance of the prediction. This is done here by showing the error ellipsoids for three parametrizations: RD-min, SV-min, and SV-APV $^1\alpha^2$. The ellipsoids seem to align along the linear trend. Variances perpendicular to the trend are larger for ^{48}Ca and very small for ^{208}Pb . The stronger correlations associated with ^{208}Pb had already been seen in Fig. 1. Particularly impressive is the strong correlation between the

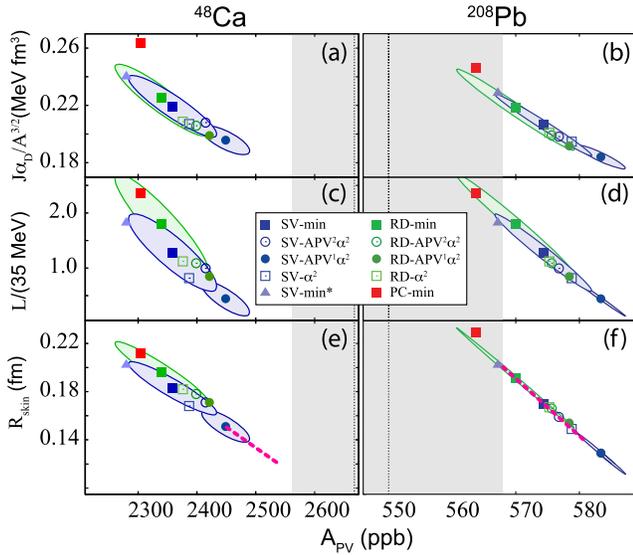


FIG. 2. Trend of R_{skin} , L , and $J\alpha_D$ with A_{PV} for ^{48}Ca (left) ^{208}Pb (right). Different EDFs are distinguished by symbols and colors. For three parametrizations (SV-min, SV-APV $^1\alpha^2$, and RD-min) the error ellipsoids are indicated. Dashed magenta lines in panels (e) and (f) indicate the range of R_{skin} predicted by *ab initio* calculations of Ref. [61] in ^{48}Ca and Ref. [22] in ^{208}Pb assuming the same $A_{\text{PV}} - \alpha_D$ trend as in DFT calculations. The mean values of measured A_{PV} are marked by vertical dotted lines and their $1-\sigma$ errors by gray bands. The values of R_{skin} in ^{48}Ca for PC-min, SV-min, and SV-APV $^1\alpha^2$ are 0.229 ± 0.027 fm, 0.170 ± 0.034 fm, and 0.129 ± 0.017 fm, respectively. The corresponding values of L are 82.5 ± 17.2 MeV, 44.8 ± 24.6 MeV, and 15.5 ± 11.0 MeV.

R_{skin} and A_{PV} in ^{208}Pb illustrated by the needle-shaped error ellipsoids for all three models shown. Only slightly weaker correlations with A_{PV} are seen for L and $J\alpha_D$. We also show in Figs. 2(e) and 2(f) the prediction of R_{skin} from the *ab initio* calculations of Refs. [22,61].

The correlations as such look encouraging. However, the comparison with the data on A_{PV} is disappointing. The theoretical predictions for A_{PV} tend to overestimate ^{208}Pb and clearly underestimate ^{48}Ca . We tried to find a compromise by calibrating our models by imposing constraints on the values of A_{PV} and α_D , see Table II. It is remarkable that the resulting EDFs conform to the linear trend. But doing so, they fail to improve the agreement with both experiments simultaneously. Actually, most of the theoretical results shown do not overlap or barely overlap ($1-\sigma$) with the experimental data on A_{PV} . As an example, the relativistic EDF PC-min that predicts A_{PV} in ^{208}Pb consistent with experiment, spectacularly fails for ^{48}Ca . As discussed above, the isovector sector of PC-min is underdeveloped, and the same can be stated about the relativistic EDFs used in Ref. [8] that were used to extract the value of R_{skin} from the PREX-2 Collaboration measurement.

The *ab initio* calculations for ^{48}Ca [61] predict R_{skin} that is smaller than the EDF models used. As seen in Fig. 2(e),

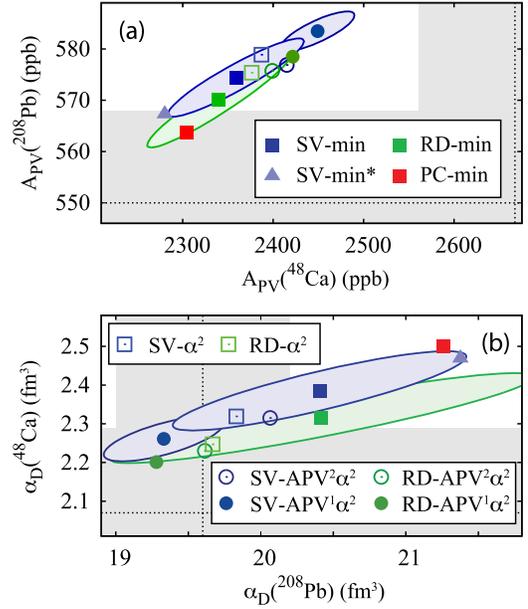


FIG. 3. Trends of measured observables: (a) $A_{\text{PV}}(^{208}\text{Pb})$ versus $A_{\text{PV}}(^{48}\text{Ca})$ and (b) $\alpha_D(^{48}\text{Ca})$ versus $\alpha_D(^{208}\text{Pb})$. Different functionals are distinguished by symbols and colors. For three parametrizations (SV-min, SV-APV $^1\alpha^2$, RD-min), the error ellipsoids are indicated. The experimental means are marked by dotted lines and their errors are marked by gray bands.

this result is more consistent with the CREX Collaboration data. Still, large deviation for the PREX data remains [22]. To make a more definite assessment of *ab initio* results, their predictions for A_{PV} would be desirable.

Trends of A_{PV} and α_D in ^{48}Ca versus ^{208}Pb .—The discussion of Fig. 2 ends with indicating a tension between PREX-2 Collaboration and CREX Collaboration values of A_{PV} viewed through the lens of quantified nuclear models. In Fig. 3 we compare predictions of theoretical models for A_{PV} and α_D in ^{48}Ca and ^{208}Pb . The lower panel shows the results for α_D . The theoretical results line up along a linear trend whose direction aims clearly toward the intersection of the two experimental results. Several models (except for PC-min and SV-min*) are consistent with experimental data for α_D . The upper panel shows similar comparison for A_{PV} . Theoretical results exhibit again a linear trend which, however, bypasses the experimental intersection. The error ellipsoids show slight deviations from the linear trend, but not enough to embrace the data. The wrong direction of the average trend together with the rather narrow error ellipsoids suggest that a simultaneous fit of both A_{PV} values cannot produce a consistent explanation of PREX-2 Collaboration and CREX Collaboration measurements.

Conclusions.—In this Letter, we critically assessed the predictions of the quantified nuclear DFT models in the context of the recent PREX-2 Collaboration and CREX Collaboration measurements of the parity-violating asymmetry A_{PV} . Our results raise questions on (i) the suitability

of the current theory to describe the measured A_{PV} values; (ii) the physical content of the correlations between A_{PV} and various observables and/or parameters; and (iii) the suitability of measured A_{PV} values to deduce R_{skin} , J , and L . Regarding (i) and (ii), the EDFs employed in our study have been used successfully to describe masses, charge radii, giant resonances, and other nuclear properties along the whole nuclear chart, and there is no indication that these EDFs are fundamentally wrong. Indeed, charge radii are typically described by state-of-the-art EDFs within 0.015–0.02 fm average deviations and masses are calculated within 1–2 MeV. Such a global level of agreement with experiment throughout the entire nuclear chart has not been reached by any other microscopic theoretical tool that can also address the nature of excited states. In order to explore the model dependence of the correlations, we have considered a slightly more general functional SV-ext, see Supplemental Material [34]. Because of the extended parameter space, the correlations provided by SV-ext are slightly reduced. Whether the physical correlations discussed in this Letter are valid for a greater class of EDFs, which go well beyond the models used here (see, e.g., Refs. [62–66] for the recent studies on EDF developments) still remains to be investigated.

The results presented in Figs. 2 and 3 suggest a tension between the A_{PV} data and global nuclear EDFs or that the A_{PV} values of CREX and PREX-2 Collaborations are not mutually compatible within the given experimental errors with the current theory. This calls for a critical search of limitations of current nuclear EDFs and interactions used in *ab initio* calculations and/or possible other sources of uncertainty in experiment. We also confirm the conclusion reached in Ref. [6]: the significant uncertainties, specially of PREX-2 Collaboration value of A_{PV} , make it difficult to use this observable as a meaningful constraint on the isovector sector of current EDFs. Until the tension between theory and experiment, or between the two measurements (see, e.g., Ref. [67] for planned MREX experiment at MESA), is resolved, one should exercise extreme caution when interpreting the new A_{PV} measurements in the context of neutron skins or nuclear symmetry energy.

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[1] D. Adhikari *et al.* (PREX Collaboration), Accurate Determination of the Neutron Skin Thickness of ^{208}Pb Through

- Parity-Violation in Electron Scattering, *Phys. Rev. Lett.* **126**, 172502 (2021).
- [2] D. Adhikari *et al.* (CREX Collaboration), Precision Determination of the Neutral Weak form Factor of ^{48}Ca , *Phys. Rev. Lett.* **129**, 042501 (2022).
- [3] A. Tamii *et al.*, Complete Electric Dipole Response and the Neutron Skin in ^{208}Pb , *Phys. Rev. Lett.* **107**, 062502 (2011).
- [4] J. Birkhan *et al.*, Electric Dipole Polarizability of ^{48}Ca and Implications for the Neutron Skin, *Phys. Rev. Lett.* **118**, 252501 (2017).
- [5] T. Donnelly, Parity-violating electron scattering, *Prog. Part. Nucl. Phys.* **24**, 179 (1990).
- [6] P.-G. Reinhard, X. Roca-Maza, and W. Nazarewicz, Information Content of the Parity-Violating Asymmetry in ^{208}Pb , *Phys. Rev. Lett.* **127**, 232501 (2021).
- [7] A. Tamii *et al.*, Measurement of high energy resolution inelastic proton scattering at and close to zero degrees, *Nucl. Instrum. Methods Phys. Res., Sect. A* **605**, 326 (2009).
- [8] B. T. Reed, F. J. Fattoyev, C. J. Horowitz, and J. Piekarewicz, Implications of PREX-2 on the Equation of State of Neutron-Rich Matter, *Phys. Rev. Lett.* **126**, 172503 (2021).
- [9] J. Piekarewicz, Implications of prex-2 on the electric dipole polarizability of neutron-rich nuclei, *Phys. Rev. C* **104**, 024329 (2021).
- [10] T. Wakasa, S. Tagami, J. Matsui, M. Yahiro, and M. Takechi, Reaction cross section of proton scattering consistent with PREX-II, *Results Phys.* **29**, 104749 (2021).
- [11] S. Tagami, T. Wakasa, J. Matsui, M. Yahiro, and M. Takechi, Neutron skin thickness of ^{208}Pb determined from the reaction cross section for proton scattering, *Phys. Rev. C* **104**, 024606 (2021).
- [12] M. Matsuzaki, S. Tagami, and M. Yahiro, Neutron skin thickness of ^{208}Pb , $^{116,120,124}\text{Sn}$, and ^{40}Ca determined from reaction cross sections of ^4He scattering, *Phys. Rev. C* **104**, 054613 (2021).
- [13] B.-A. Li, B.-J. Cai, W.-J. Xie, and N.-B. Zhang, Progress in constraining nuclear symmetry energy using neutron star observables since GW170817, *Universe* **7**, 182 (2021).
- [14] R. Essick, I. Tews, P. Landry, and A. Schwenk, Astrophysical Constraints on the Symmetry Energy and the Neutron Skin of ^{208}Pb with Minimal Modeling Assumptions, *Phys. Rev. Lett.* **127**, 192701 (2021).
- [15] R. Essick, P. Landry, A. Schwenk, and I. Tews, Detailed examination of astrophysical constraints on the symmetry energy and the neutron skin of ^{208}Pb with minimal modeling assumptions, *Phys. Rev. C* **104**, 065804 (2021).
- [16] E. R. Most and C. A. Raithel, Impact of the nuclear symmetry energy on the post-merger phase of a binary neutron star coalescence, *Phys. Rev. D* **104**, 124012 (2021).
- [17] W. G. Newton and G. Crocombe, Nuclear symmetry energy from neutron skins and pure neutron matter in a Bayesian framework, *Phys. Rev. C* **103**, 064323 (2021).
- [18] B. Biswas, Impact of PREX-II and combined radio/NICER/XMM-Newton’s mass–radius measurement of PSR J0740 + 6620 on the dense-matter equation of state, *Astrophys. J.* **921**, 63 (2021).
- [19] J. Lattimer, Neutron stars and the nuclear matter equation of state, *Annu. Rev. Nucl. Part. Sci.* **71**, 433 (2021).

- [20] F. Sammarruca and R. Millerson, Analysis of the neutron matter equation of state and the symmetry energy up to fourth order of chiral effective field theory, *Phys. Rev. C* **104**, 034308 (2021).
- [21] J. T. Zhang, X. L. Tu, P. Sarriguren, K. Yue, Q. Zeng, Z. Y. Sun, M. Wang, Y. H. Zhang, X. H. Zhou, and Y. A. Litvinov, Systematic trends of neutron skin thickness versus relative neutron excess, *Phys. Rev. C* **104**, 034303 (2021).
- [22] B. Hu, W. Jiang, T. Miyagi, Z. Sun, A. Ekstrm, C. Forssn, G. Hagen, J. D. Holt, T. Papenbrock, S. R. Stroberg, and I. Vernon, *Ab initio* predictions link the neutron skin of ^{208}Pb to nuclear forces, *Nat. Phys.* **18**, 1196 (2022).
- [23] Y. Lim and J. W. Holt, Neutron star radii, deformabilities, and moments of inertia from experimental and *ab initio* theory constraints on the ^{208}Pb neutron skin thickness, *Galaxies* **10**, 99 (2022).
- [24] M. Bender, P.-H. Heenen, and P.-G. Reinhard, Self-consistent mean-field models for nuclear structure, *Rev. Mod. Phys.* **75**, 121 (2003).
- [25] C. J. Horowitz, S. J. Pollock, P. A. Souder, and R. Michaels, Parity violating measurements of neutron densities, *Phys. Rev. C* **63**, 025501 (2001).
- [26] X. Roca-Maza, M. Centelles, X. Viñas, and M. Warda, Neutron Skin of ^{208}Pb , Nuclear Symmetry Energy, and the Parity Radius Experiment, *Phys. Rev. Lett.* **106**, 252501 (2011).
- [27] C. J. Horowitz, Parity violating elastic electron scattering and Coulomb distortions, *Phys. Rev. C* **57**, 3430 (1998).
- [28] S. Abrahamyan *et al.* (HAPPEX and PREX Collaborations), New Measurements of the Transverse Beam Asymmetry for Elastic Electron Scattering from Selected Nuclei, *Phys. Rev. Lett.* **109**, 192501 (2012).
- [29] A. Esser *et al.*, First Measurement of the Q^2 Dependence of the Beam-Normal Single Spin Asymmetry for Elastic Scattering Off Carbon, *Phys. Rev. Lett.* **121**, 022503 (2018).
- [30] A. Esser *et al.*, Beam-normal single spin asymmetry in elastic electron scattering off ^{28}Si and ^{90}Zr , *Phys. Lett. B* **808**, 135664 (2020).
- [31] D. Adhikari *et al.* (PREX and CREX Collaborations), New Measurements of the Beam-Normal Single Spin Asymmetry in Elastic Electron Scattering Over a Range of Spin-0 Nuclei, *Phys. Rev. Lett.* **128**, 142501 (2022).
- [32] O. Koshchii, M. Gorchtein, X. Roca-Maza, and H. Spiesberger, Beam-normal single-spin asymmetry in elastic scattering of electrons from a spin-0 nucleus, *Phys. Rev. C* **103**, 064316 (2021).
- [33] C. J. Horowitz, Parity violating elastic electron scattering from ^{27}Al and the Q_{weak} measurement, *Phys. Rev. C* **89**, 045503 (2014).
- [34] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.129.232501> for more details on the A_{PV} calculations, an extended EDF SV-ext and more details on the covariance analysis of A_{PV} , which includes Refs. [1,2,6,35–42].
- [35] H. Atac, M. Constantinou, Z. E. Meziani, M. Paolone, and N. Sparveris, Charge radii of the nucleon from its flavor dependent Dirac form factors, *Eur. Phys. J. A* **57**, 65 (2021).
- [36] M. Tanabashi *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **98**, 030001 (2018).
- [37] C. J. Horowitz and J. Piekarewicz, Impact of spin-orbit currents on the electroweak skin of neutron-rich nuclei, *Phys. Rev. C* **86**, 045503 (2012).
- [38] M. Hoferichter, J. Menéndez, and A. Schwenk, Coherent elastic neutrino-nucleus scattering: EFT analysis and nuclear responses, *Phys. Rev. D* **102**, 074018 (2020).
- [39] A. Acha *et al.* (HAPPEX Collaboration), Precision Measurements of the Nucleon Strange Form Factors at $Q^2 \sim 0.1 \text{ GeV}^2$, *Phys. Rev. Lett.* **98**, 032301 (2007).
- [40] J. Liu, R. D. McKeown, and M. J. Ramsey-Musolf, Global analysis of nucleon strange form factors at low Q^2 , *Phys. Rev. C* **76**, 025202 (2007).
- [41] C. Alexandrou, S. Bacchio, M. Constantinou, J. Finkenrath, K. Hadjiyiannakou, K. Jansen, and G. Koutsou, Nucleon strange electromagnetic form factors, *Phys. Rev. D* **101**, 031501(R) (2020).
- [42] P.-G. Reinhard and W. Nazarewicz, Nuclear charge densities in spherical and deformed nuclei: Toward precise calculations of charge radii, *Phys. Rev. C* **103**, 054310 (2021).
- [43] J. Ahrens, H. Borchert, K. Czock, H. Eppler, H. Gimm, H. Gundrum, M. Krning, P. Riehn, G. Sita Ram, A. Zieger, and B. Ziegler, Total nuclear photon absorption cross sections for some light elements, *Nucl. Phys.* **A251**, 479 (1975).
- [44] P.-G. Reinhard and W. Nazarewicz, Information content of a new observable: The case of the nuclear neutron skin, *Phys. Rev. C* **81**, 051303(R) (2010).
- [45] J. Piekarewicz, B. K. Agrawal, G. Colò, W. Nazarewicz, N. Paar, P.-G. Reinhard, X. Roca-Maza, and D. Vretenar, Electric dipole polarizability and the neutron skin, *Phys. Rev. C* **85**, 041302(R) (2012).
- [46] P.-G. Reinhard and W. Nazarewicz, Information content of the low-energy electric dipole strength: Correlation analysis, *Phys. Rev. C* **87**, 014324 (2013).
- [47] X. Roca-Maza, M. Brenna, G. Colò, M. Centelles, X. Viñas, B. K. Agrawal, N. Paar, D. Vretenar, and J. Piekarewicz, Electric dipole polarizability in ^{208}Pb : Insights from the droplet model, *Phys. Rev. C* **88**, 024316 (2013).
- [48] T. Hashimoto *et al.*, Dipole polarizability of ^{120}Sn and nuclear energy density functionals, *Phys. Rev. C* **92**, 031305 (R) (2015).
- [49] X. Roca-Maza, X. Viñas, M. Centelles, B. K. Agrawal, G. Colò, N. Paar, J. Piekarewicz, and D. Vretenar, Neutron skin thickness from the measured electric dipole polarizability in ^{68}Ni , ^{120}Sn , and ^{208}Pb , *Phys. Rev. C* **92**, 064304 (2015).
- [50] S. Bassauer *et al.*, Evolution of the dipole polarizability in the stable tin isotope chain, *Phys. Lett. B* **810**, 135804 (2020).
- [51] S. Goriely, S. Péru, G. Colò, X. Roca-Maza, I. Gheorghe, D. Filipescu, and H. Utsunomiya, $e1$ moments from a coherent set of measured photoneutron cross sections, *Phys. Rev. C* **102**, 064309 (2020).
- [52] P. Klüpfel, P.-G. Reinhard, T. J. Bürvenich, and J. A. Maruhn, Variations on a theme by Skyrme: A systematic study of adjustments of model parameters, *Phys. Rev. C* **79**, 034310 (2009).
- [53] J. Erler, P. Klüpfel, and P.-G. Reinhard, Exploration of a modified density dependence in the Skyrme functional, *Phys. Rev. C* **82**, 044307 (2010).

- [54] T. Nikšić, D. Vretenar, and P. Ring, Relativistic nuclear energy density functionals: Adjusting parameters to binding energies, *Phys. Rev. C* **78**, 034318 (2008).
- [55] W. Nazarewicz, P. G. Reinhard, W. Satuła, and D. Vretenar, Symmetry energy in nuclear density functional theory, *Eur. Phys. J. A* **50**, 20 (2014).
- [56] P.-G. Reinhard, J. Piekarewicz, W. Nazarewicz, B. K. Agrawal, N. Paar, and X. Roca-Maza, Information content of the weak-charge form factor, *Phys. Rev. C* **88**, 034325 (2013).
- [57] J. Dobaczewski, W. Nazarewicz, and P.-G. Reinhard, Error estimates of theoretical models: A guide, *J. Phys. G* **41**, 074001 (2014).
- [58] J. Erler and P.-G. Reinhard, Error estimates for the Skyrme-Hartree-Fock model, *J. Phys. G* **42**, 034026 (2015).
- [59] P. D. Allison, *Multiple Regression: A Primer* (Sage Publications, Thousand Oaks, CA, 1998).
- [60] W.-C. Chen and J. Piekarewicz, Building relativistic mean field models for finite nuclei and neutron stars, *Phys. Rev. C* **90**, 044305 (2014).
- [61] G. Hagen, A. Ekström, C. Forssén, G. R. Jansen, W. Nazarewicz, T. Papenbrock, K. A. Wendt, S. Bacca, N. Barnea, B. Carlsson, C. Drischler, K. Hebeler, M. Hjorth-Jensen, M. Miorelli, G. Orlandini, A. Schwenk, and J. Simonis, Neutron and weak-charge distributions of the ^{48}Ca nucleus, *Nat. Phys.* **12**, 186 (2016).
- [62] M. Baldo, P. Schuck, and X. Vias, Kohnsham density functional inspired approach to nuclear binding, *Phys. Lett. B* **663**, 390 (2008).
- [63] J. Dobaczewski, *Ab initio* derivation of model energy density functionals, *J. Phys. G* **43**, 04LT01 (2016).
- [64] R. Navarro Pérez, N. Schunck, A. Dyhdalo, R. J. Furnstahl, and S. K. Bogner, Microscopically based energy density functionals for nuclei using the density matrix expansion. II. Full optimization and validation, *Phys. Rev. C* **97**, 054304 (2018).
- [65] P. Papakonstantinou, T.-S. Park, Y. Lim, and C. H. Hyun, Density dependence of the nuclear energy-density functional, *Phys. Rev. C* **97**, 014312 (2018).
- [66] F. Marino, C. Barbieri, A. Carbone, G. Colò, A. Lovato, F. Pederiva, X. Roca-Maza, and E. Vigezzi, Nuclear energy density functionals grounded in *ab initio* calculations, *Phys. Rev. C* **104**, 024315 (2021).
- [67] M. Thiel, C. Sfienti, J. Piekarewicz, C. J. Horowitz, and M. Vanderhaeghen, Neutron skins of atomic nuclei: per aspera ad astra, *J. Phys. G* **46**, 093003 (2019).