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$$P_{\text{b}} > 208$$

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# Information content of the parity-violating asymmetry in $^{208}\text{Pb}$

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The parity violating asymmetry  $A_{\text{PV}}$  in  $^{208}\text{Pb}$ , recently measured by the PREX-2 collaboration, is studied using modern relativistic (covariant) and non-relativistic energy density functionals. We first assess the theoretical uncertainty on  $A_{\text{PV}}$  which is intrinsic to the adopted approach. To this end, we use quantified functionals that are able to accommodate our previous knowledge on nuclear observables such as binding energies, charge radii, and the dipole polarizability  $\alpha_{\text{D}}$  of  $^{208}\text{Pb}$ . We then add the quantified value of  $A_{\text{PV}}$  together with  $\alpha_{\text{D}}$  to our calibration dataset to optimize new functionals. Based on these results, we predict a neutron skin thickness in  $^{208}\text{Pb}$   $r_{\text{skin}} = 0.19 \pm 0.02$  fm and the symmetry-energy slope  $L = 54 \pm 8$  MeV. These values are consistent with other estimates based on astrophysical data and are significantly lower than those recently reported using a particular set of relativistic energy density functionals. We also make a prediction for the  $A_{\text{PV}}$  value in  $^{48}\text{Ca}$  that will be soon available from the CREX measurement.

*Introduction.*— The recent measurement of the parity-violating asymmetry  $A_{\text{PV}}$  at transferred momentum  $q = 0.3978/\text{fm}$  in  $^{208}\text{Pb}$  by the PREX-2 collaboration [1] provided a highly anticipated observable that can inform models of nuclei and nuclear matter. In a separate theoretical paper [2], implications of the PREX-2 result on nuclear properties and the equation of state of neutron-rich matter have been discussed within a specific class of relativistic energy density functionals (EDFs). The authors relate the measured  $A_{\text{PV}}$  to  $r_{\text{skin}}$  and deduce from that a rather large symmetry-energy slope parameter  $L = 106 \pm 37$  MeV and a large neutron skin thickness in  $^{208}\text{Pb}$   $0.21 \lesssim r_{\text{skin}} \lesssim 0.31$  fm. The mean values of these quantities systematically overestimate the currently accepted limits ( $J = [28.5, 34.9]$  MeV,  $L = [30.6, 86.8]$  MeV [3–5], and  $r_{\text{skin}} = [0.13, 0.19]$  fm [6–8]).

We emphasize the fact that the new experimental information provided by PREX-2 collaboration is the  $A_{\text{PV}}$  measured at a specific kinematic condition. Other nuclear quantities of interest reported in [1, 2], such as the neutral weak form-factor, neutron skin thickness, interior weak density, interior baryon density, and symmetry energy parameters, become accessible only via theoretical models.

The question addressed in this Letter is whether the PREX-2 value of  $A_{\text{PV}}$  creates a principle tension with other data and models, as claimed in [2]. The strategy is, first, to study  $A_{\text{PV}}$  directly rather than non-observable quantities, and second, to employ a broad set of structurally different EDFs together with a statistical analysis [9] to estimate the uncertainty on  $A_{\text{PV}}$  intrinsic to each EDF as well as the correlation with other observables. In particular, we consider the relation with the electric dipole polarizability  $\alpha_{\text{D}}$  in  $^{208}\text{Pb}$  which is known to be strongly correlated with  $r_{\text{skin}}$  and weak form factor [10–12] and for which independent experimental data exist [8, 13]. All EDFs under consideration show a clear cor-

relation between  $A_{\text{PV}}$  and  $\alpha_{\text{D}}$  and indicate a possible incompatibility of their current values. We extend the analysis to other observables as neutron skins, bulk symmetry energy and its slope, and we make predictions for  $A_{\text{PV}}$  in  $^{48}\text{Ca}$  at the CREX kinematics [14].

*The parity-violating asymmetry.*—  $A_{\text{PV}}$  can be obtained experimentally from longitudinally polarized elastic electron scattering [15] as

$$A_{\text{PV}}(Q^2) = \frac{d\sigma_{\text{R}}/d\Omega - d\sigma_{\text{L}}/d\Omega}{d\sigma_{\text{R}}/d\Omega + d\sigma_{\text{L}}/d\Omega}, \quad (1)$$

where  $d\sigma_{\text{L}}/d\Omega$  ( $d\sigma_{\text{R}}/d\Omega$ ) is the differential cross section for the scattering of left (right) handed electrons,  $\Omega$  is the solid angle, and  $Q^2$  is the squared transferred four momentum. The scattering cross sections in (1), for a heavy nucleus, must be computed taking into account Coulomb distortions [16, 17]. To this end, we have modified the Dirac partial-wave code ELSEPA [18] to deal with parity non-conserving potentials. Actually, the distribution of scattering angles in the PREX-2 experiment has a non-negligible width which we take into account by considering the PREX-2 acceptance function, see supplemental material (SM) [19] for details.

To gain insight into structure of the parity violating asymmetry, it is useful to inspect the Plane Wave Born Approximation expression for  $A_{\text{PV}}$ : [15]

$$A_{\text{PV}}(Q^2) \approx -\frac{G_{\text{F}}Q^2Q_{\text{N,Z}}^{(\text{W})}}{4\sqrt{2}\pi\alpha Z} \frac{F_{\text{W}}(q)}{F_{\text{C}}(q)}, \quad (2)$$

where  $q = \sqrt{Q^2}$ ,  $G_{\text{F}} = 1.1663787 \cdot 10^{-5}/\text{GeV}^2$  is the Fermi coupling constant,  $F_{\text{W}}$  the weak form factor,  $F_{\text{C}}$  is the charge form factor, and  $Q_{\text{N,Z}}^{(\text{W})}$  is the weak charge of the nucleus with  $N$  neutrons and  $Z$  protons. Both  $F_{\text{W}}$  and  $F_{\text{C}}$  are normalized to one. Since  $F_{\text{C}}$  primarily depends on protons and  $F_{\text{W}}$  on neutrons,  $A_{\text{PV}}$  decreases

linearly with  $r_{\text{skin}}$  at low  $Q^2$ , also when Coulomb distortions are taken into account [17]. Consequently this observable can be used to infer information on  $r_{\text{skin}}$ .

Even if exploited at a single kinematic condition,  $A_{\text{PV}}$  is one of the most promising observables to probe neutrons in nuclei since it is based on the well known electroweak interaction. Other promising observables (cf. Refs. [20–22]) sensitive to the neutron distribution in nuclei include the dipole polarizability  $\alpha_{\text{D}}$  [8, 13], which we shall discuss in this Letter.

*Error budget for  $A_{\text{PV}}$ .*— In Table I, we list the nucleonic parameters that are used for the calculation of the nucleon electromagnetic and weak form factors and  $A_{\text{PV}}$ , see SM [19] for details.

TABLE I. Final choice of the parameters entering the calculation of the weak form factor and  $A_{\text{PV}}$ : the electric proton ( $\langle r_p^2 \rangle$ ) and neutron ( $\langle r_n^2 \rangle$ ) radii; the magnetic dipole moments,  $\mu_p$  and  $\mu_n$ ; the strange quark electric coupling  $\rho_s$  and the strange quark magnetic moment  $\kappa_s$ ; the weak charge of neutrons  $Q_n^{(W)}$  and protons  $Q_p^{(W)}$ ; and the total weak charge of  $^{208}\text{Pb}$   $Q_{126,82}^{(W)}$ .

$\langle r_p^2 \rangle$ (fm <sup>2</sup> )	$0.726 \pm 0.019$	[23]
$\langle r_n^2 \rangle$ (fm <sup>2</sup> )	$-0.1161 \pm 0.0022$	[24]
$\mu_p$	2.792847	[24]
$\mu_n$	-1.9130	[24]
$Q_p^{(W)}$	$0.0713 \pm 0.0001$	[25, 26]
$Q_n^{(W)}$	$-0.9888 \pm 0.0011$	[25, 26]
$\rho_s$	$-0.24 \pm 0.70$	[27, 28]
$\kappa_s$	$-0.017 \pm 0.004$	[29]
$Q_{126,82}^{(W)}$	$-117.9 \pm 0.3$	[1, 30]

Most parameters in Table I are given with errors either from experimental analysis or compilation of different sources. To estimate how these errors propagate to the prediction of  $A_{\text{PV}}$  on a test calculation, we assume a Gaussian profile for the distribution of each parameter to sample the variance in  $A_{\text{PV}}$ . The result is shown in Fig. 1. The first six entries show the impact of each parameter separately. Considerable contributions come only from the strength of the  $s$  quark and, dominantly, from  $Q_{N,Z}^{(W)}$ . The entry “sum 1-6” shows the total uncertainty from the first six entries accumulated by the Gaussian law of error propagation.

There are also uncertainties on the predictions of the theoretical models (see below) stemming from the empirical calibration of the model parameters. The last two entries in Fig. 1 show them (thin blue bars) for two typical model parametrizations discussed below together with the errors from the nucleonic parameters (thick red bars). Both theoretical predictions are compatible, within errors, with the upper edge of the experimental uncertainty of the PREX-2 measurement [1].

*Theoretical models* – There exists a variety of nuclear EDFs in the literature (for a review see, e.g., [31, 32]).

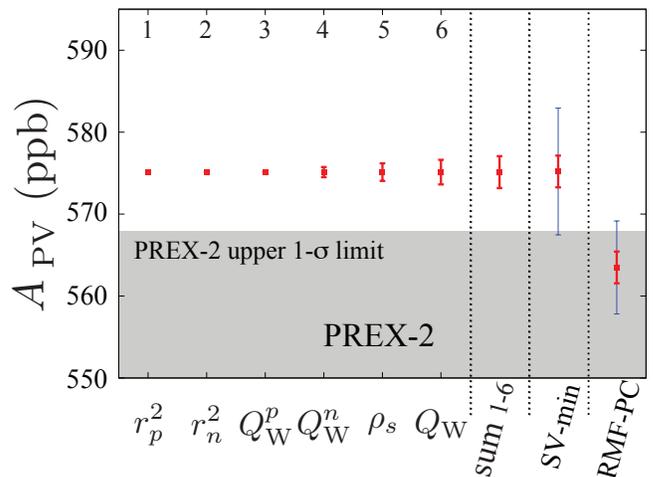


FIG. 1. Uncertainty budget for  $A_{\text{PV}}$ . First six entries labeled 1-6: the effect of the errors on the parameters in Table I on the uncertainty on  $A_{\text{PV}}$ . The resulting total uncertainty due to coupling constants is labeled “sum 1-6”. The quantified predictions of  $A_{\text{PV}}$  with SV-min and RMF-PC models (thin bars), which include statistical model uncertainties related to neutron and proton point densities and the coupling-constant uncertainty. The experimental value of  $A_{\text{PV}}$  is  $550 \pm 17.9$  ppb [1]. The gray band marks the corresponding upper 1-sigma confidence interval.

They differ in their structure and in the way there were calibrated. We use here several families of EDFs having different functional form and provide in similar fashion a set of parametrizations with systematically varied symmetry energy  $J$ , while maintaining isoscalar properties and an overall good quality in their predictions. This is of particular interest when studying an observable like  $A_{\text{PV}}$  which, being related to the differences between the weak and electric charge densities, is predominantly sensitive to the isovector channel of the EDFs [10]. The families of EDFs considered in the survey are: FSU – based on the traditional non-linear Walecka model [33] specially devised to minimally improve its flexibility on the isovector channel [34]; DD and PC – extended RMF models with more flexibility due to density-dependent coupling constants. DD employs the traditional finite-range meson-exchange fields [35] while PC uses point couplings [36]; the series of SV [37] and SAMi [38] parametrizations belong to the widely used non-relativistic Skyrme EDFs; the RD series is a variant of the Skyrme EDFs with a different form of density dependence [39]. Four of the families (SV, RD, PC, and DD) are calibrated to exactly the same large set of ground observables: binding energies, charge radii, diffraction radii, and surface thicknesses in semi-magic, spherical nuclei [37] plus a systematically scanned constraint on symmetry energy  $J$ . The differences between the results of these EDF families show the impact of the EDF form. The calibration is done by means of the standard linear regression, which also provides information on uncertainties and statisti-

cal correlations between observables [9, 12]. The other two families (FSU and SAMi) are calibrated to different datasets with different bias. The SAMi functionals, e.g., have been optimized with the focus on spin-isospin resonances. We include these functionals to probe the impact of calibration strategy. However, we checked that the performance for the reference nucleus,  $^{208}\text{Pb}$ , is roughly comparable for all parametrizations used, see the SM for details [19]. The inter-model comparison helps quantifying the systematic theoretical error.

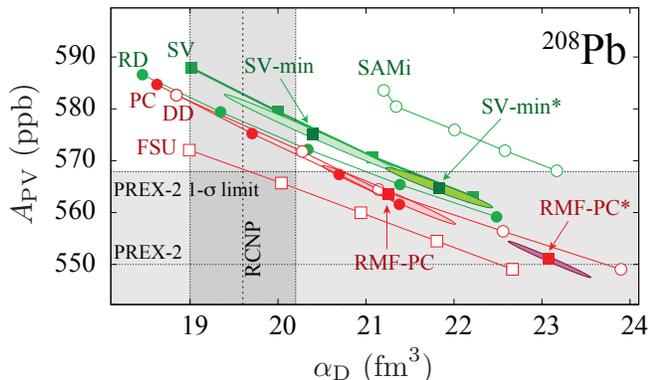


FIG. 2.  $A_{\text{PV}}$  versus  $\alpha_{\text{D}}$  in  $^{208}\text{Pb}$  for a set of covariant (red) and non-relativistic (green) EDFs. Sets with systematically varied symmetry energy  $J$  are connected by lines. (Note that  $\alpha_{\text{D}}$  increases as a function of  $J$ .) The SV-min, SV-min\*, RMF-PC, and RMF-PC\* results are shown together with their 1-sigma error ellipses. The experimental values of  $\alpha_{\text{D}}$  [8, 13] and  $A_{\text{PV}}$  [1] are indicated together with their 1-sigma error bars.

*Tension between the PREX-2 result and electric dipole polarizability.*—The dipole polarizability  $\alpha_{\text{D}}$  in nuclei, directly related to the photo-absorption cross-section, provides an excellent constraint on  $r_{\text{skin}}$  [7, 20, 40]. The measurements of  $\alpha_{\text{D}}$  have been carried out for a number of nuclei, in particular for  $^{208}\text{Pb}$  [13] and  $^{48}\text{Ca}$  [41]. These experiments provide a reliable information on the photo-absorption cross section up to about 20 MeV. Small high-energy contributions to  $\alpha_{\text{D}}$  require careful modeling of the quasi-deuteron effect [42, 43], which motivated the correction from the original value  $20.1 \pm 0.6 \text{ fm}^3$  [13] to the value  $19.6 \pm 0.6 \text{ fm}^3$  used here (cf. Ref. [8]).

Figure 2 shows the predicted values of  $A_{\text{PV}}$  versus  $\alpha_{\text{D}}$  obtained with the set of covariant and non-relativistic EDFs. The figure illustrates a nearly linear trend of  $A_{\text{PV}}$  versus  $\alpha_{\text{D}}$  with the same slope for all models, but slightly different offset mostly depending on different values of the symmetry-energy coefficient  $J$  predicted by the EDFs [7]. The parametrizations SV-min and RMF-PC stem from unconstrained fits to ground state data and their results are shown with the predicted 1-sigma error ellipses, which align along the average trend. This indicates that the statistical uncertainties of SV-min and RMF-PC are consistent with the systematic inter-model trends. It is apparent that there is only one model which

is able to reproduce simultaneously  $A_{\text{PV}}$  and  $\alpha_{\text{D}}$  within the experimental 1- $\sigma$  error bands. The figure demonstrates therefore some tension: the models that are consistent with  $\alpha_{\text{D}}$  yield large values of  $A_{\text{PV}}$  that are outside the 1-sigma limit of PREX-2 while the models that reproduce  $A_{\text{PV}}$  yield the values of  $\alpha_{\text{D}}$  that are well outside the experimental bounds. The single model that seems to be consistent with the current limits on  $A_{\text{PV}}$  and  $\alpha_{\text{D}}$  is the FSU EDF with  $J \sim 32 \text{ MeV}$  and  $L \sim 60 \text{ MeV}$ . Its value of  $L$  is consistent with the other models in this survey but stays off the value  $L = 106 \pm 37 \text{ MeV}$  advocated in Ref. [2]. Unfortunately, when it comes to other observables for  $^{208}\text{Pb}$ , such as binding energy and charge radius, the performance of FSU models is inferior to the other EDFs discussed here, see [19] for details.

*New EDFs constrained on  $A_{\text{PV}}$  and  $\alpha_{\text{D}}$ .*—Figure 2 shows that the unconstrained fits, SV-min for the Skyrme functionals and RMF-PC for the RMF family, form a compromise between  $A_{\text{PV}}$  and  $\alpha_{\text{D}}$  with the Skyrme functional tending toward the mean value of  $\alpha_{\text{D}}$  and the RMF – toward the mean value of  $A_{\text{PV}}$ . To explore the compromise more systematically, we have fitted two new parametrizations taking the same set of ground state data from [37] as were used for SV-min and PC-min and adding the experimental values for  $A_{\text{PV}}$  and  $\alpha_{\text{D}}$  to the dataset of constraining observables. The relative weight of these two new data points is regulated by taking for the adopted errors the uncertainty of the model predictions from the unconstrained fits (this amounts to  $7 \text{ ppb}/5.7 \text{ ppb}$  for  $A_{\text{PV}}$  and  $1.0 \text{ fm}^3/0.7 \text{ fm}^3$  for  $\alpha_{\text{D}}$  for SV-min/PC-min). We note that our adopted errors for  $A_{\text{PV}}$  are close to the systematic error of PREX-2 measurement, which is 8 ppb, and well below the statistical error of 16 ppb. The resulting parametrizations, called SV-min\* and RMF-PC\*, stay on the general trend and move toward the mean value of  $A_{\text{PV}}$ . We also carried out optimizations assuming the total experimental uncertainty of PREX-2 of 17.9 ppb, dominated by statistics, for the adopted error of  $A_{\text{PV}}$ . The models calibrated under such assumption provide practically the same results as SV-min and RMF-PC because the prior uncertainty on  $A_{\text{PV}}$  is so large that the information content of this variable in this calibration scenario is low. Based on Fig. 2 we conclude that SV-min\* and RMF-PC\* yield results that are consistent with the current data on  $A_{\text{PV}}$ . On the other hand, the model RMF-PC\*, while closest to the mean value of  $A_{\text{PV}}$ , has  $\alpha_{\text{D}} = 23.1 \text{ fm}^3$  which is clearly inconsistent with the measured value  $\alpha_{\text{D}} = 19.6 \pm 0.6 \text{ fm}^3$ .

*Symmetry energy and neutron skin.*—Over the years, strong correlations have been established between  $r_{\text{skin}}$  in heavy nuclei and various nuclear matter properties. Of particular importance, is the correlation of  $r_{\text{skin}}$  with the symmetry energy at the saturation point  $J$  [20, 44–46] and with the slope of the bulk symmetry energy  $L$  [45, 47, 48], see also Refs. [11, 49–51]. In addition to numerous inter-model comparisons published, strong corre-

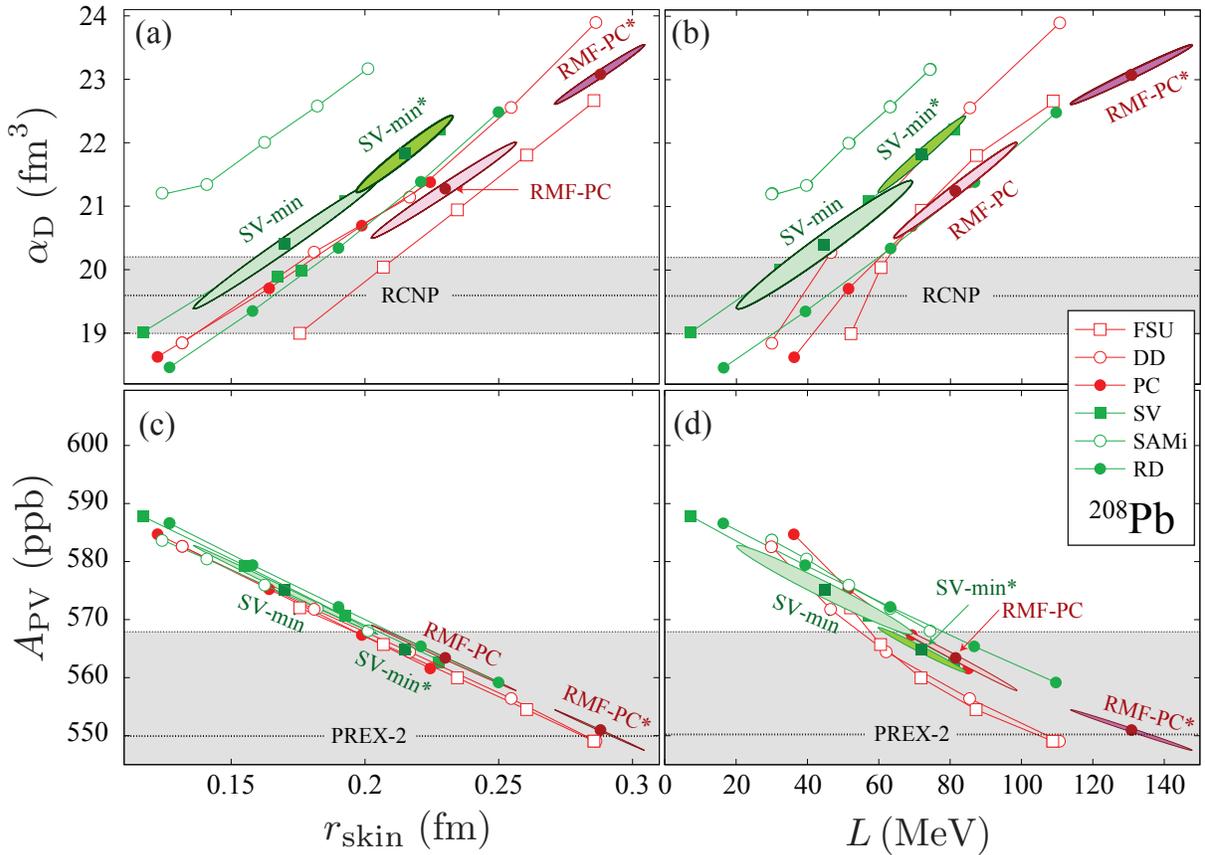


FIG. 3.  $A_{PV}$  (panels c,d) and  $\alpha_D$  in  $^{208}\text{Pb}$  (panels a,b) versus neutron skin (left panels) and slope of symmetry energy  $L$  (right panels), for the same set of EDFs as in Fig. 2. The experimental ranges of  $\alpha_D$  [8, 13] and  $A_{PV}$  [1] are marked. The values of  $r_{\text{skin}}$  (in fm) obtained in our models are:  $0.17 \pm 0.03$  for SV-min;  $0.22 \pm 0.02$  for SV-min\*;  $0.23 \pm 0.03$  for RMF-PC; and  $0.29 \pm 0.02$  for RMF-PC\*. The values of  $L$  (in MeV) are:  $45 \pm 25$  for SV-min;  $72 \pm 12$  for SV-min\*;  $82 \pm 17$  for RMF-PC; and  $128 \pm 17$  for RMF-PC\*.

lation between  $L$ ,  $J$ , and  $r_{\text{skin}}$  in medium-mass and heavy spherical closed-shell nuclei has been demonstrated by means of the statistical correlation analysis [20, 52, 53]. One can conclude from the previous body of work that the models with large symmetry energy parameters  $J$  and  $L$  predict smaller  $A_{PV}$  and large  $\alpha_D$ , as indicated by the trend shown in Fig. 2. Also, the relativistic models tend to yield stiffer (larger value of  $L$ ) neutron equation of state compared to the non-relativistic models [6, 50].

Figure 3 shows the model predictions as functions of  $r_{\text{skin}}$  and  $L$  for the models employed. Our result for  $J$  can be found in SM [19]. There is one more important aspect in Fig. 3(c): the trend of  $A_{PV}$  versus  $r_{\text{skin}}$  has the by far smallest spread within the families of the models employed. This intimate connection is also confirmed by statistical analysis for SV and RMF-PC EDFs: the correlation coefficient between  $A_{PV}$  and  $r_{\text{skin}}$  is 99.9%.

It is interesting to compare the values of symmetry energy predicted in this work with the most current estimates based on astrophysical constraints [5, 54, 55] and chiral effective field theory [56, 57]. To this end, we go

back to Fig. 2 and search for those parametrization in each series (SV, RD, PC, DD) which comes closest to the intercept of the RCNP and PREX-2 band. Specifically, the “best compromise” parametrization is determined by drawing a line from the intercept of the mean RCNP and PREX-2 lines through the intercept of the upper limits of their error bands and checking where this line crosses the trend-trajectories of the various model families. The resulting inter-model average is our prediction and the corresponding variance becomes our estimate for the systematic model error. For the symmetry energy, this procedure yields  $J = 32 \pm 1$  MeV. This value is consistent with the estimates based on astrophysical constraints  $J = 31.6 \pm 2.7$  MeV [5] (see also Refs. [3, 4, 54, 55]) and chiral effective field theory  $31.7 \pm 1.1$  MeV [56] and  $34 \pm 3$  MeV [57], while the estimate  $J = 38.1 \pm 4.7$  MeV of Ref. [2] differs much more.

The symmetry-energy slope is determined with larger uncertainty:  $L = 54 \pm 8$  MeV. This value is comparable with  $L = 57.7 \pm 19$  MeV [54],  $L = 59.8 \pm 4.1$  MeV [56], and  $58 \pm 19$  MeV [57]. The analysis of [2] using specific

relativistic EDFs yields a fairly large value of  $L = 106 \pm 37$  MeV.

The models compatible with the experimental  $\alpha_D$  for  $^{208}\text{Pb}$  predict  $r_{\text{skin}}$  in the range  $0.13 - 0.19$  fm [6–8], i.e., in the range of SV-min values. Our expectation for  $r_{\text{skin}}$  from the present analysis is  $0.19 \pm 0.02$  fm, i.e., a mean value that is lower than the estimate  $0.283 \pm 0.071$  fm of Ref. [1].

*CREX measurement of  $A_{\text{PV}}$  in  $^{48}\text{Ca}$ .*—The CREX measurement will soon provide the highly anticipated data on  $A_{\text{PV}}$  in  $^{48}\text{Ca}$  [14]. In SM [19] we discuss our predictions at the kinematic point of CREX  $Q^2 = 0.03 \text{ GeV}^2$ . Considering our results for  $^{208}\text{Pb}$ , we chose the value for  $A_{\text{PV}}(^{48}\text{Ca})$  close to the prediction of SV-min with a slight bias toward SV-min\*, which amounts to  $2400 \pm 60$  ppb. We note that our predictions of  $\alpha_D(^{48}\text{Ca})$  are in a slight conflict with the current experimental estimate [41].

*Summary and perspectives.*—For the quantified EDFs, there exists a tension between  $A_{\text{PV}}$  and  $\alpha_D$ . The functionals SV-min, SV-min\*, and RMF-PC offer a reasonable compromise between the data on  $A_{\text{PV}}$  and  $\alpha_D$ ; they also perform well for other properties of  $^{208}\text{Pb}$ . According to our analysis, the significant 1-sigma uncertainty of PREX-2 value of  $A_{\text{PV}}$  makes it difficult to use this observable as a meaningful constraint on the isovector sector of current EDFs. On the other hand, our estimated model uncertainty on  $A_{\text{PV}}$ , 6-7 ppb is close to the estimated systematic error of PREX-2 of 8 ppb. We recommend this value for the future calibration studies. In this respect, the anticipated precision measurements of  $A_{\text{PV}}$  and  $\alpha_D$  will be extremely useful for the calibration of nuclear models.

As stated in [2], their values of  $J$ ,  $L$ , and  $r_{\text{skin}}$  in  $^{208}\text{Pb}$  “systematically overestimate current limits based on both theoretical approaches and experimental measurements.” On the other hand, the values predicted in this work are significantly lower: they are consistent with much of the previous work and the recent astrophysical estimates.

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