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Parity-violating asymmetry and dipole polarizabilities in atomic nuclei: how do they reconcile with each other?

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Abstract. In the recent years, considerable attention has been paid to the measurement of the dipole polarizability and parity violating asymmetry in medium and heavy mass nuclei such as ^{48}Ca and ^{208}Pb [1–4]. These two observables, as it already happened for the neutron skin thickness, are thought to be particularly sensitive to the properties of the nuclear equation of state at densities around nuclear saturation [5]. Hence, the interest in the low energy nuclear physics community to foster the needed experimental and theoretical developments to accurately study these two observables. In this proceeding I will briefly overview our recent theoretical analysis of the parity violating asymmetry and electric dipole polarizability [6–10].

1 Introduction

The recent measurement of the parity-violating asymmetry $A_{\rm PV}$ in ^{48}Ca [4] by the CREX collaboration and ^{208}Pb by the PREX collaboration [3] is analyzed taking special care of the employed models and the associated theoretical uncertainties. The reported value for the neutron skin thickness ($r_{\rm skin} \equiv \langle r_n\rangle^{1/2} - \langle r_p\rangle^{1/2}$) in ^{48}Ca somehow underestimates previous expectations while in ^{208}Pb systematically overestimate the currently accepted limits [5, 11, 12].

It is important to emphasize that the new experimental information provided by CREX and PREX collaborations is the $A_{\rm PV}$ measured at a specific kinematic condition. Other nuclear quantities of interest reported in [3, 4], 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.

Hence it is very timely to address whether the CREX and PREX values of $A_{\rm PV}$ create a principle tension with other data and models [7, 8]. With this aim, we first study $A_{\rm PV}$ directly rather than non-observable quantities and second, we employ a broad set of structurally different EDFs together with a statistical sound analysis [13] to estimate the uncertainty on $A_{\rm PV}$ intrinsic to each EDF as well as the correlation with other observables. Specifically, we concentrate on the electric dipole polarizability $\alpha_{\rm D}$ in both ^{48}Ca and ^{208}Pb which is known to be strongly correlated with $r_{\rm skin}$ [10, 14–16] and for which independent experimental data exist [1, 2].

2 Methods

2.1 Parity Violating Asymmetry

$A_{\rm PV}$ has been calculated from longitudinally polarized elastic electron scattering taking into account the important contributions from Coulomb distortions [17]. Its definition is as follows,

$$A_{\rm PV}(Q^2) = \frac{d\sigma_R/d\Omega - d\sigma_L/d\Omega}{d\sigma_R/d\Omega + d\sigma_L/d\Omega}, \qquad (1)$$

where $d\sigma_L/d\Omega$ ($d\sigma_R/d\Omega$) is the differential cross section for the scattering of left (right) handed electrons, Ω is the solid angle, and Q^2 is the transferred four-momentum square. The main input from nuclear structure models in order to calculate $A_{\rm PV}$ are the neutron and proton densities. For details on the nucleon electromagnetic form factors and other relevant quantities such as the weak charge of ^{48}Ca and ^{208}Pb, we refer the reader to Ref. [7, 8] where all details are given.

2.2 Dipole polarizability

The dipole polarizability $\alpha_{\rm D}$, related to the nuclear dipole response, has been shown to be sensitive on the isovector channel of the EDF. Specifically, a relation with the symmetry energy at saturation J and the slope parameter L has been discussed in Refs. [9, 10]. Experimentally, $\alpha_{\rm D}$ can be deduced from the total photo-absorption cross section [1, 2] while theoretically, it can be computed from static response or from dynamical response via the dipole strength distribution [9, 10, 18–22]. Within this framework, the $\alpha_{\rm D}J$ product has been shown to be linearly correlated with the neutron skin thickness in neutron rich heavy nuclei [9, 10].

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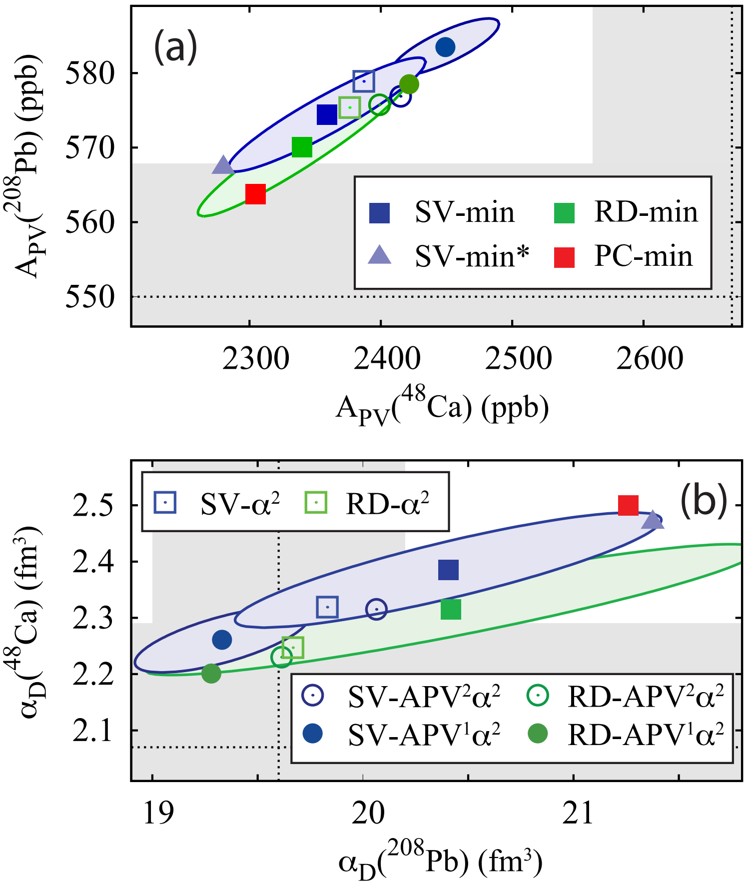

Figure 1. Trends of measured observables: (a) $A_{\rm PV}$ ^{208}Pb versus $A_{\rm PV}$ ^{48}Ca and (b) $\alpha_{\rm D}$ ^{48}Ca versus $\alpha_{\rm D}$ ^{208}Pb. Different functionals are distinguished by symbols and colors. For three parametrizations (SV-min, SV-APV^1-α^2, RD-min), the error ellipsoids are indicated. The experimental means are marked by dotted lines and their errors are marked by gray bands. Figure taken from Ref. [8]

2.3 Energy density functionals

There exists a variety of nuclear Energy Density Functionals (EDFs) in the literature (see, e.g., [23]). In the present contribution, we use different families of EDFs having different functional form. Each family is based on controlled variations on the isovector channel of the functional while keeping the overal performance of the optimal parametrization in the isoscalar part. The families of EDFs considered are: the covariant RMF-PC [24] as well as the non-relativistic SV [25] and RD [26] Skyrme EDFs. These families are calibrated to exactly the same set of ground state observables [25]. Hence, the differences among them are exclusively due to the impact of the EDF form since the fitting protocol is identical. After the χ^2 calibration, information on uncertainties and statistical correlations between observables within a single EDF parametrization is obtained by means of a covariance analysis [13, 16].

3 Results

In Fig. 1 we compare predictions of theoretical models for $A_{\rm PV}$ and $\alpha_{\rm D}$ in ^{48}Ca and ^{208}Pb. The lower panel shows the results for $\alpha_{\rm D}$. 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 $\alpha_{\rm D}$. The upper panel shows similar comparison for $A_{\rm PV}$. 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 $A_{\rm PV}$ values cannot produce a consistent explanation of PREX-2 and CREX measurements. In order to check this, in Fig. 1, we also show results for the Skyrme SV and RD type models in which we have added to the above mentioned fitting protocol the information on the two dipole polarizabilities (SV-α^2 and RD-α^2 depicted by empty squares) and one (SV-APV$^1\alpha^2$ and RD-APV$^1\alpha^2$ depicted by full circles) or two (SV-APV$^2\alpha^2$ and RD-APV$^2\alpha^2$ depicted by empty circles) $A_{\rm PV}$. The results of these new parametrizations do not change the previous picutre. All of them are compatible with the exprimental data on $\alpha_{\rm D}$ and fall into the same trend for the $A_{\rm PV}$ as the other parametrizations of the same models, remaining away form the crossing of the experimetal bands. Therefore, a simultaneous description of both $A_{\rm PV}$ do not seem to be possible given the current fitting protocols and the limitations of the employed models.

4 Conclusions

Our results raise questions on the suitability of the current theory to describe the measured A_{PV} values. However, 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. We note that the current ab-initio results on r_{skin} in ^{48}Ca and ^{208}Pb are consistent with our presented analysis.

The results presented in Fig. 1 suggest a tension between the A_{PV} data and global nuclear EDFs *or* that the A_{PV} values of CREX and PREX-2 are not mutually compatible within the given experimental errors (1-σ) with the current theory. This calls for a critical search of limitations of current nuclear EDFs and/or possible other sources of uncertainty in experiment. We also confirm the conclusion reached in Ref. [7]: the significant uncertainties, specially of PREX-2 value of A_{PV}, make it difficult to use this observable as a constraint on the isovector sector of current EDFs.

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