Neutron density distribution and neutron skin thickness of $^{208}$Pb

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We present and discuss numerical predictions for the neutron density distribution of $^{208}$Pb using various non-relativistic and relativistic mean-field models for the nuclear structure. Our results are compared with the very recent pion photoproduction data from Mainz. The parity-violating asymmetry parameter for elastic electron scattering at the kinematics of the PREX experiment at JLab and the neutron skin thickness are compared with the available data. We consider also the dependence between the neutron skin and the parameters of the expansion of the symmetry energy.

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I. INTRODUCTION

An accurate description of matter distribution in nuclei is a longstanding problem in modern nuclear physics that has a wide impact on our understanding of nuclear structure. Whereas the charge distribution has been measured with high accuracy using electron-nucleus elastic scattering, so that the charge radii are usually known with uncertainties lower than 1% [1, 2], our knowledge of neutron distribution is considerably less precise. Several experiments of neutron radius have been carried out in recent years [3–5], but the use of hadronic probes produces uncertainties in the experimental results due to the assumptions of the models required to deal with the complexity of the strong interaction. An accurate and model independent probe of neutron distributions is provided by parity-violating electron scattering (PVES): the parity-violating asymmetry $A_{pv}$, i.e., the difference between the cross sections for the scattering of electrons longitudinally polarized parallel and antiparallel to their momentum, represents an almost direct measurement of the Fourier transform of the neutron density [6, 7] that is free from most strong interaction uncertainties.

The PREX Collaboration [8] at JLab used parity-violating electron scattering (PVES) to study the neutron distribution of $^{208}$Pb and provided us with the first determination of the neutron radius through an electroweak probe that gives $R_{\text{skin}} = 0.33^{+0.16}_{-0.18}$ fm for the neutron skin thickness. Although the total error is large, the PREX method is very interesting and future higher statistics data are expected to reduce the uncertainty [9]. The CREX Collaboration at JLab has made a successful proposal to measure the neutron radius of $^{48}$Ca using PVES with a goal of $\pm0.02$ fm in accuracy [10]. Recently, in a measurement of the coherent $\pi^0$ photoproduction from $^{208}$Pb at Mainz [11], the shape of the neutron distribution has been found to be 20% more diffuse than the charge distribution and the neutron skin thickness is $R_{\text{skin}} = 0.19 \pm 0.03$ (stat) $^{+0.03}_{-0.01}$ (syst) fm. This value is compatible with previous independent measurements, i.e., proton elastic scattering [5, 12], x-ray cascade of antiprotonic atoms [3, 4], anti-analog giant dipole resonances [13–15], giant quadrupole resonances [16], pionic dipole resonance [17–20], electric dipole polarizability [21] or pionic probes [22].

The neutron skin of $^{208}$Pb has important implications for astrophysics [23–25], owing to its strong correlation with the pressure of neutron matter at densities near 0.1 fm$^{-3}$. The larger the pressure of neutron matter, the thicker is the skin as neutrons are pushed out against surface tension. The same pressure supports neutron stars against gravity, therefore correlations between neutron skins of neutron-rich nuclei and various neutron star properties are naturally expected [26, 27]. In addition, the magnitude of $R_{\text{skin}}$ in heavy nuclei provides very interesting information on the nature of 3-body forces in nuclei, nuclear drip lines and collective nuclear excitations, as well as heavy-ion collisions. A recent review of experimental measurements of $R_{\text{skin}}$ and their theoretical implications can be found in [28].

In this work we present and discuss numerical predictions for the neutron density distribution of $^{208}$Pb. In [29, 30] we have already considered the evolution of the charge density distribution and of the proton wave functions along different isotopic chains. In [31] we have extended our study to isotonic chains. In [30] we have already compared our calculations for the asymmetry parameter $A_{pv}$ using the relativistic DM2E interaction with the results of the first run of PREX on $^{208}$Pb and we have provided numerical predictions for the future experiment CREX on $^{48}$Ca. In addition, we have studied the behavior of $A_{pv}$ along oxygen and calcium isotopic chains [30]. In this paper we extend the work undertaken in [30] comparing results obtained with different non-relativistic and relativistic model interactions. Our results are compared with the recent ($\gamma, \pi^0$) data from Mainz and with the data of the PREX experiment. In addition, we consider also the correlations between the neutron skin and the slope and curvature coefficients of the nuclear symmetry energy.

II. NEUTRON DISTRIBUTION OF $^{208}$Pb

The best description of heavy nuclei, at the moment, relies on energy density functionals in terms of effective interactions calibrated on the bulk properties of a limited set of nuclei. The isoscalar part of the interaction is usually constrained by reproducing binding energies and charge radii ($^{208}$Pb is usually included in fit protocol) where the isospin-dependent part of the interaction is mainly constrained reproducing some ab-initio equation of state (EOS) for neutron matter, like the Akmal-Friedmann-Pandharipande EOS [45], or the empirical value of the asymmetry energy at the saturation point. So far, theoretical calculations based on realistic potentials are limited to medium-light nuclei, even if new approaches based on renormalization group potentials look very promising [46]. In this work we consider different non-relativistic and relativistic mean-field (RMF) models and compare their predictions for the neutron distribution of $^{208}$Pb. The details of the mean-field approaches we have adopted in our investigation are presented in various publications, for instance in [33–44, 47–50]. We do not repeat here the derivation of the various expressions used in our calculations but we refer the readers to the original papers. Our strategy is to explore all variants of density functional approaches in terms of covariant (Walecka type) vs. non-covariant (Skyrme and Gogny) descriptions, finite range vs. contact interactions and non-linear vs. density dependent couplings.
Interaction & $R$ & $a$
\hline
L2 [32] & 6.832 (9) & 0.522 (8) \\
NL3 [33] & 6.902 (7) & 0.556 (6) \\
NL3-II [33] & 6.888 (7) & 0.557 (6) \\
NL-SH [34] & 6.895 (9) & 0.527 (8) \\
DDME1 [35] & 6.770 (9) & 0.574 (7) \\
DDME2 [36] & 6.758 (9) & 0.570 (8) \\
PKDD [37] & 6.832 (9) & 0.562 (7) \\
DDPC1 [38] & 6.783 (7) & 0.573 (6) \\
PC-F1 [39] & 6.903 (7) & 0.566 (6) \\
PC-F2 [39] & 6.900 (7) & 0.566 (6) \\
PC-F4 [39] & 6.899 (6) & 0.567 (5) \\
D1S [40] & 6.697 (21) & 0.575 (18) \\
SIII [41] & 6.854 (4) & 0.528 (3) \\
SKM* [42] & 6.746 (4) & 0.583 (3) \\
SLY4 [43] & 6.752 (4) & 0.582 (6) \\
SLY5 [43] & 6.744 (7) & 0.582 (6) \\
SIII (mod) [44] & 6.860 (4) & 0.537 (3) \\
SLY5 (mod) [44] & 6.754 (7) & 0.595 (6) \\
\hline
\end{tabular}

Table I. Predictions for the half-height radius $R$ and diffuseness $a$ of $^{208}$Pb from various nuclear structure calculations. In parentheses the error on the last significant digit. The experimental data of [11] are $R = 6.77 \pm 0.03$ fm and $a = 0.55 \pm 0.01$ (stat) $\pm 0.025$ (syst) fm.

Figure 1. (Color online) The half-height radius plotted versus the diffuseness for $^{208}$Pb. The red square shows the experimental data of [11] with statistical and systematic errors.

We have checked that the different forces adopted for our calculations give some differences in the neutron single-particle levels around the Fermi surface in $^{208}$Pb, but do not produce significant inversions in the energy levels. The levels above the $N = 126$ shell closure are unoccupied.

Generally, the nucleon distributions are parameterized as a single symmetrised two-parameter Fermi distribution (2pF) [51] with half-height radius $R$ and diffuseness $a$. The analysis of the ($\gamma$, $\pi^0$) cross sections data from Mainz gives $R = 6.77 \pm 0.03$ fm and $a = 0.55 \pm 0.01$ (stat) $+0.00_{-0.025}$ (syst) fm [11] and suggests that the neutron distribution of $^{208}$Pb is $\approx 20\%$ more diffuse than the charge distribution and that the neutron skin of lead is of partial halo type.

In Table I we report our results for the half-heigth radius and diffuseness parameter of the 2pF neutron density distributions extracted from the different models. In Fig. 1 these results are directly compared with the experimental
Figure 2. (Color online) Theoretical weak charge density in comparison with the experimental error band as determined in Ref. [53] for $^{208}$Pb with the kinematics of the PREX experiment.

Neither the nonrelativistic Gogny and Skyrme nor the RMF models are able to simultaneously reproduce the experimental data for both $R$ and $a$. The finite-range Gogny DIS interaction underestimates $R$ and overestimates $a$. The Skyrme interaction parametrizations (those starting with S) generally give similar results for $R$ and $a$ that reproduce the experimental value of $R$ and overestimate $a$, but the SIII interactions that reproduce the experimental value of $a$ and overestimate $R$. The RMF models that include nonlinear self-interaction meson couplings (those starting with NL) reproduce the diffuseness but overestimate the radius over three standard deviations. These results are consistent with the observation that the mixed isoscalar-isovector coupling terms in the Lagrangian densities should be taken into account to significantly change the neutron radii [25, 52]. The RMF models with point-coupling interaction (those with PC), i.e., where the zero-range point-coupling interaction is used instead of the meson exchange, give almost coincident results that overestimate both $R$ and $a$. The relativistic functionals with density-dependent vertex functions (those starting with DD) give the best agreement with the experimental radius but slightly overestimate the diffuseness. The density-dependent PKDD model overestimates $R$ and slightly underpredicts $a$.

To obtain a simple model of the neutron density distributions, we have evaluated the weighted average parameters of the 2pF profiles extracted from the results of the different models and have obtained $R_{\text{mean}} = 6.822 \pm 0.001$ fm and $a_{\text{mean}} = 0.558 \pm 0.001$ fm: the surface diffuseness is in fair agreement with the Mainz data and the radius is a bit larger, but in agreement with the experimental value within two standard deviations. This “weighted” result is plotted with the green square (MEAN) in Fig. 1. To be more confident, we have checked that the 2pF profile of the charge distribution obtained with this weighted average procedure is able to satisfactorily reproduce the experimental data of elastic electron scattering cross sections off $^{208}$Pb.

A. Comparison with PREX

The parity-violating asymmetry parameter $A_{pv}$ is defined as the difference between the cross sections for the elastic scattering of electrons longitudinally polarized parallel and antiparallel to their momentum. $A_{pv}$ is proportional to the weak form factor and, in Born approximation, it is very close to the Fourier transform of the neutron density.

In Fig. 2 we show our theoretical predictions for the weak charge density ($-\rho_W$) that has been deduced from the weak charge form factor [53, 54]. The error band (shaded area) represents the incoherent sum of experimental and model errors. Owing to the fact that the $Z^0$ boson couples mainly with the neutron, $\rho_W$ depends essentially on the neutron distribution. Our predictions for different interactions are in rather good agreement with the empirical data. In addition, the weak distribution evaluated using the 2pF functions for the proton and neutron density distributions with weighted average parameters is also in good agreement with the data.

The PREX Collaboration measured the parity-violating asymmetry parameter $A_{pv}$ averaged over the experimental
Figure 3. (Color online) Parity-violating asymmetry at the kinematics of the PREX experiments versus the neutron rms radius for $^{208}$Pb. The dashed orange line is a linear fit of the correlation between the neutron rms radius and $A_{pv}$. The red square shows the experimental data from PREX [8] with statistical and systematic errors.

Figure 4. (Color online) Parity-violating asymmetry at the kinematics of the PREX experiments versus the neutron skin for $^{208}$Pb. The red square shows the experimental data from PREX [8] with statistical and systematic errors. The dashed orange line is a linear fit of the correlation between the neutron skin and $A_{pv}$. The vertical solid green lines show the constraints on $R_{\text{skin}}$ from Mainz ($\gamma, \pi^0$) measurements [11]. The vertical purple dashed lines show the constraints on $R_{\text{skin}}$ from Osaka polarized proton elastic scattering measurements [5].

The acceptance function $\epsilon(\theta)$ [55]

$$\langle A_{pv} \rangle = \frac{\int d\theta \sin \theta A_{pv}(\theta) \frac{d\sigma}{d\Omega} \epsilon(\theta)}{\int d\theta \sin \theta \frac{d\sigma}{d\Omega} \epsilon(\theta)}, \quad (1)$$

where $A_{pv}(\theta)$ and $d\sigma/d\Omega$ are the asymmetry and the differential cross section at the scattering angle $\theta$. The charge radius of $^{208}$Pb is very well known [1, 2]; therefore, the empirical estimate $A_{pv} = 0.656 \pm 0.060(\text{stat}) \pm 0.014(\text{syst})$ ppm can be related to the neutron radius and the neutron rms radius results $R_n = 5.78_{-0.18}^{+0.16}$ fm that implies that the neutron skin thickness is $R_{\text{skin}} = 0.33_{-0.18}^{+0.16}$ fm.

The results for the parity-violating asymmetry $A_{pv}$ versus the neutron rms radius for different models are displayed in Fig. 3. The result with the 2pF functions for the density distributions with averaged parameters is also in good agreement with the data. It is interesting to observe that there is a linear correlation between $A_{pv}$ and the neutron
radius as well as the neutron skin [56]. Our results in Fig. 3 are in accordance with this observation. Owing to the large experimental uncertainties, our theoretical predictions are in agreement with the data but they all predict a smaller radius than the central value of 5.78 fm. To obtain a significantly larger $R_n$ and a smaller $A_{pn}$ the Lagrangian density should contain also the mixed isoscalar-isovector coupling term as described in [57]. We observe, however, that a large neutron radius is not in agreement with other experimental measurements [28].

In Fig. 4 we present the results for the parity-violating asymmetry versus the neutron skin predicted by the different models. Owing to the fact that the neutron skin is highly correlated with the neutron radius, these results are similar to those in Fig. 3. The constraints on the neutron skin from Mainz ($\gamma, \pi^0$) [11], as well as those from Osaka polarized proton elastic scattering measurements at proton energy $\varepsilon = 295$ MeV [5], are displayed for a comparison. Although all the predictions in Fig. 3 and 4 are compatible with the PREX results, the large error bars prevent us from discriminating among some of them. Other $R_{\text{skin}}$ measurements are more precise and seem to rule out models with either very small or very large neutron skins. However, a careful analysis of all available data in [58] demonstrates that it is still premature to rule out the existence of a thick neutron skin in $^{208}\text{Pb}$.

### B. Neutron skin and the symmetry energy at saturation density

Around the nuclear matter saturation density $\rho_0$ the nuclear symmetry energy can be expanded to second order in density as

$$\varepsilon_{\text{sym}}(\rho) \simeq \varepsilon_{\text{sym}}(\rho_0) + \frac{L}{3} \left( \frac{\rho - \rho_0}{\rho} \right) + \frac{K_{\text{sym}}}{18} \left( \frac{\rho - \rho_0}{\rho} \right)^2. \quad (2)$$

The coefficient of the linear term of the expansion is directly related to the energy of pure neutron matter at $\rho_0$ and it is defined as

$$L = 3\rho_0 \left. \frac{\partial \varepsilon_{\text{sym}}(\rho)}{\partial \rho} \right|_{\rho = \rho_0}, \quad (3)$$

and the curvature parameter is

$$K_{\text{sym}} = 9\rho_0^2 \left. \frac{\partial^2 \varepsilon_{\text{sym}}(\rho)}{\partial \rho^2} \right|_{\rho = \rho_0}. \quad (4)$$

Owing to the fact that the thickness of the neutron skin results from an interplay between the surface tension and the gradient of the symmetry energy between the surface and the center of the nucleus, there is a well-established linear dependence between the neutron skin and $L$ that is usually adopted to constrain the density derivative of the symmetry energy [59–67].

In Fig. 5 we present the correlation of the neutron skin thickness of $^{208}\text{Pb}$ versus $L$. The nonrelativistic Gogny and Skyrme interactions have soft symmetry energies ($L \leq 50$ MeV), while most relativistic nuclear interactions lead to stiff symmetry energies ($L \geq 100$ MeV). The inclusion of the mixed isoscalar-isovector coupling terms in the Lagrangian densities produces a softer symmetry energy [25, 52]. The point-coupling interactions give stiff symmetry energy ($L \approx 120$ MeV) but the density-dependent interaction DDPC1 produces $L \approx 70$ MeV. On the contrary, the relativistic functionals with density-dependent vertex functions generally give softer symmetry energies ($50 \leq L \leq 60$ MeV) but PKDD which gives $L \approx 90$ MeV. The PREX result yields a very large central value for $L$, i.e., $L \approx 150$ MeV, but, owing to the very large error bars, it constrains very mildly $L$, and all theoretical models are compatible with PREX. Other neutron skin measurements suggest a smaller range of uncertainties for $L$, but they still have non-negligible uncertainties. For instance, the Mainz ($\gamma, \pi^0$) experiment suggests $30 \leq L \leq 80$ MeV. It would be very important to reduce the experimental uncertainties to obtain more stringent constraints on $L$. The updated run PREX-II [9] aims at a new determination of $R_{\text{skin}}$ with an accuracy of $\pm 0.06$ fm and thus it will constrain the range of uncertainties of the slope $L$ to $\approx \pm 40$ MeV.

In Fig. 6 we present the correlation of the neutron skin thickness of $^{208}\text{Pb}$ versus $K_{\text{sym}}$. In this case the correlation is less strong but it is still significant [60]. The Gogny and Skyrme interactions have large negative curvatures ($K_{\text{sym}} \leq -100$ MeV), while most relativistic nuclear interactions lead to positive curvatures ($K_{\text{sym}} \approx 100$ MeV), but the relativistic functionals with density-dependent vertices give also negative $K_{\text{sym}}$. Very mild constraints on $K_{\text{sym}}$ are provided by the PREX result and only the future PREX-II [9] experiment will constrain the range of uncertainties of $K_{\text{sym}}$ to $\approx \pm 150$ MeV, i.e., a constraint similar to that of the Osaka experiment on proton elastic scattering.
We have presented and discussed numerical predictions for the neutron density distribution of $^{208}\text{Pb}$. The determination of the neutron distribution in nuclei has proven to be a serious challenge to our understanding of nuclear structure and it is one of the major topics of interest in nuclear physics. Great experimental and theoretical efforts have been devoted over the last years to achieve this goal. In the next years several experiments are planned, in different laboratories worldwide, to measure the neutron skin thickness, i.e., the difference between the neutron and proton distributions, as accurately as possible.

Parity-violating electron scattering is an accurate and almost model-independent tool for probing neutron properties as it is directly related to the Fourier transform of the neutron density. Starting from various different theoretical models for nuclear structure, we have extracted the 2pF parameters for the neutron distribution and we have compared them with the very recent $(\gamma, \pi^0)$ data from Mainz. We have then analyzed the linear correlation between the neutron radius and the parity-violating asymmetry. The PREX data at average momentum transfer $q = 0.475$ fm$^{-1}$ have
unfortunately a too much large experimental uncertainty to discriminate among the models and only the future run PREX-II will help to rule out some of them. Taking advantage of the linear relations between the neutron skin and the slope and the curvature of the symmetry energy around saturation density we can estimate the range of variation of $L$ and $K_{sym}$ using the available experimental values.

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