Dipole polarizability, neutron skin and symmetry energy

X. Viñas[a]

[a]Departament d'Estructura i Constituents de la Matèria and Institut de Ciències del Cosmos, Universitat de Barcelona, Barcelona, Spain

In collaboration with
X. Roca-Maza, M. Brenna and G. Colò (Milano)
M. Centelles (Barcelona)
B.K. Agrawal (Kolkata)
N. Paar and D. Vretenar (Zagreb)
J. Piekarewicz (Florida)

For a review of the contributions of the Barcelona Group to the Symmetry Energy and related topic see the review articles
X. Viñas, M. Centelles, X. Roca-Maza andd M. Warda,
AIP Proceeding **1606** 256 (2014)
Eur.Phys.J **50** 27 (2014)

Present status

- The electric dipole polarizability α_D is an isospin sensitive observable that provides some information about the **Symmetry energy and its density content.**
- The electric dipole polarizability has been recenly measured in ^{208}**Pb** A.Tamii et al. Phys.Rev.Lett. **107**, 065502 (2011). A value $\alpha_{\mathbf{D}} = \mathbf{20.1} \pm \mathbf{0.6}$ fm^3 has been reported.
- In ^{68}**Ni** D. Rossi et al. Phys.Rev.Lett. **111**, 242503 (2013). A value $\alpha_{\mathbf{D}} = \mathbf{3.40} \pm \mathbf{0.23}$ fm^3 has been reported.
- In ^{120}**Sn** T. Hashimoto et al. arXiv 1503.08321 (2015). A value $\alpha_{\mathbf{D}} = \mathbf{8.93} \pm \mathbf{0.36}$ fm^3 has been reported.
- Theoretical studies about the electric dipole polarizability and its impact on symmetry energy and related quantities can be found in eg
  P.-G. Reinhard and W. Nazarewicz, Phys. Rev. **C81** 051303 (2010).
  J. Piekarewicz et al. Phys. Rev. **C85** 041302 (2012).
  X. Roca-Maza et al. Phys. Rev. **C88** 024316 (2013).

Theoretical framework (I)

- RPA calculations with the dipole operator

$$\mathcal{D} = \frac{Z}{A}\sum_{n=1}^{N} r_n Y_{1M}(\hat{r}_n) - \frac{N}{A}\sum_{p=1}^{Z} r_p Y_{1M}(\hat{r}_p)$$

allows to compute the electric dipole strength $R(\omega; E1)$, which in turn determine the dipole polarizability

$$\alpha_D = \frac{8\pi e^2}{9}\int_0^\infty \omega^{-1} R(\omega; E1)\, d\omega = \frac{8\pi e^2}{9} m_{-1}(E1)$$

- The dielectric theorem implies that

$$m_{-1}(E1) = \frac{1}{2}\left.\frac{\partial^2 \langle\lambda|\mathcal{H}|\lambda\rangle}{\partial\lambda^2}\right|_{\lambda=0}$$

where $|\lambda\rangle$ are the constrained wavefunctions of $\mathcal{H} + \lambda\mathcal{D}$

Theoretical framework (II)

- Solving the constrained calculation within the Droplet Model (DM) (J. Meyer, P. Quentin and B. Jenning NPA385, 269 (1985)) it is found

$$\alpha_D^{\rm DM} = \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}\left(1+\frac{5}{3}\frac{9J}{4Q}A^{-1/3}\right)$$

- In the same model the neutron skin reads

$$\Delta r_{np}^{\rm DM} = \sqrt{3/5}\left[t - e^2 Z/(70J) + \frac{5}{2R}(b_n^2 - b_p^2)\right]$$

where

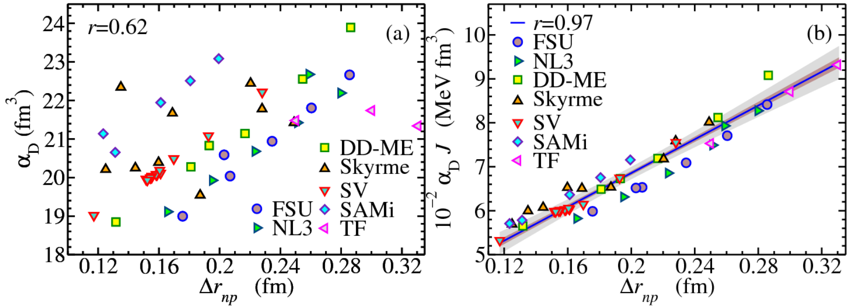
$$t = \frac{3r_0}{2}\frac{J/Q}{1+\frac{9J}{4Q}A^{-1/3}}(I - I_{\rm C}) \quad I_{\rm C} = \frac{e^2 Z}{20Jr_0A^{1/3}}$$

- From these two expressions one can relate the electric dipole polarizability and the neutron skin thickness in a nearly analytical way

$$\alpha_D^{\rm DM} \approx \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}\left[1+\frac{5}{2}\frac{\Delta r_{np}^{\rm DM}}{(I-I_C)\langle r^2\rangle^{1/2}}\right]$$

- This result suggests possible correlations between α_D and Δr_{np} or between $\alpha_D J$ and Δr_{np}

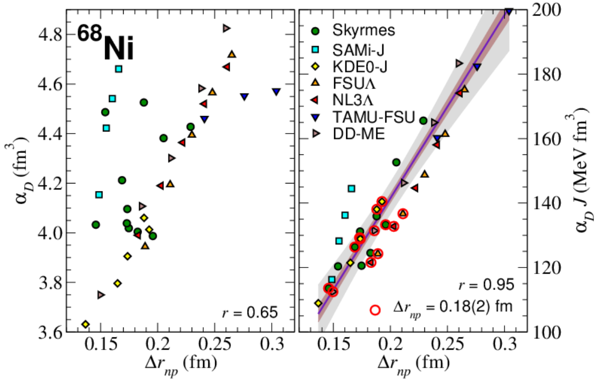
^{208}Pb



$$10^{-2} \times \alpha_D J = 3.01 \pm 0.32 + (19.22 \pm 0.73)\Delta r_{np}$$

$\alpha_D(measured) = \mathbf{20.1 \pm 0.6} fm^3$ $\quad$ $\alpha_D(corrected) = \mathbf{19.6 \pm 0.6} fm^3$

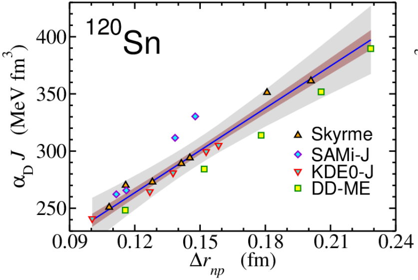
^{68}Ni

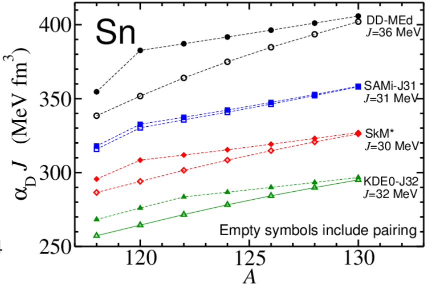


$$\alpha_D J = 28 \pm 14 + (567 \pm 32)\Delta r_{np}$$

$$\alpha_D(measured) = \mathbf{3.40 \pm 0.23} fm^3 \quad \alpha_D(corrected) = \mathbf{3.88 \pm 0.31} fm^3$$

^{120}Sn





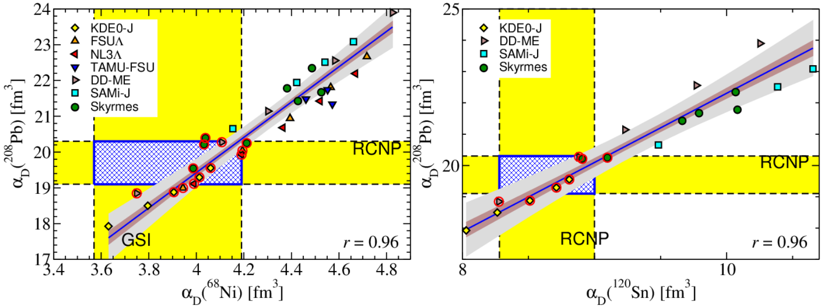
$$\alpha_D J = 116 \pm 34 + (1231 \pm 88)\Delta r_{np}$$

$$\alpha_D(measured) = \mathbf{8.93 \pm 0.36} fm^3 \quad \alpha_D(corrected) = \mathbf{8.59 \pm 0.37} fm^3$$

Theory versus experiment

- 1p-1h RPA has been proven to be succesful in describing E_x in many giant resonances.
- Experimental data of α_D analyzed via RPA need to include the full dipole response with low and high-energy contributions.
- If experimental data are only known in a given energy range, one may extrapolate them to high and low energies regions in order to compare with theoretical RPA calcultions. The low energy part is more important than the high energy region
- Data in the high energy range shall be taken carefully due to the quasi-deuteron contributions not accounted in RPA, which produce small but sizeable corrections to α_D
- The experimental resonance width is not reproduced by the 1p-1h RPA calculations. The correction to that on the theoretical electric dipole polarizability can be estimated as $\Delta\alpha_D \lesssim -\alpha_D \frac{\Gamma^2}{4E_x^2}$

^{68}Ni and ^{120}Sn



$$\alpha_D(^{68}Ni) = 0.063 \pm 0.048 + (0.20 \pm 0.01)\alpha_D(^{208}Pb)$$

$$\alpha_D(^{120}Sn) = 0.22 \pm 0.45 + (2.21 \pm 0.14)\alpha_D(^{208}Pb)$$

Results

- Neutron skin thickness

^{208}Pb **0.187 - 0.125**[a] **0.159 ± 0.028**[b] fm
^{120}Sn **0.158 - 0.108**[a] **0.122 ± 0.033**[b] fm
^{68}Ni **0.193 - 0.146**[a] **0.163 ± 0.034**[b] fm

- Symmetry energy J and slope L at saturation

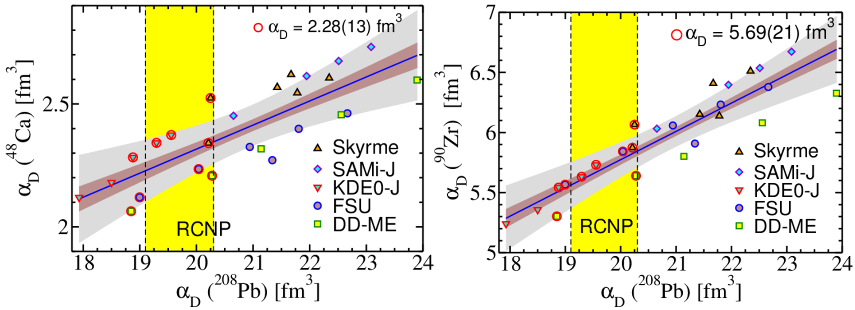
$J = \mathbf{35} - \mathbf{28}$[a] $L = \mathbf{66} - \mathbf{10}$[a] MeV

- Comments

a) From models that reproduce simultaneously the experimental polarizability in ^{208}Pb, ^{120}Sn and ^{68}Ni.

b) From the $\alpha_D J - \Delta r_{np}$ correlation with $J = 31 \pm 2$ MeV

^{48}Ca and ^{90}Zr



$$\alpha_D(^{48}Ca) = 0.36 \pm 0.06 + (0.098 \pm 0.013)\alpha_D(^{208}Pb)$$

$$\alpha_D(^{90}Zr) = 1.07 \pm 0.10 + (0.23 \pm 0.02)\alpha_D(^{208}Pb)$$

With the selected models

$$\alpha_D(^{48}Ca) = 2.28 \pm 0.13 fm^3 \quad \alpha_D(^{90}Zr) = 5.69 \pm 0.21 fm^3$$

Parity-violating electron scattering (I)

- See C.J. Horowitz et al, Phys. Rev. **C63**, 025501 (2001); Shufang Ban et al, J.of Phys. **G39**,015104 (2012).

- A_{LR} is the parity-violating asymmetry

- $A_{LR} \equiv \dfrac{\dfrac{d\sigma_+}{d\Omega} - \dfrac{d\sigma_-}{d\Omega}}{\dfrac{d\sigma_+}{d\Omega} + \dfrac{d\sigma_-}{d\Omega}}$

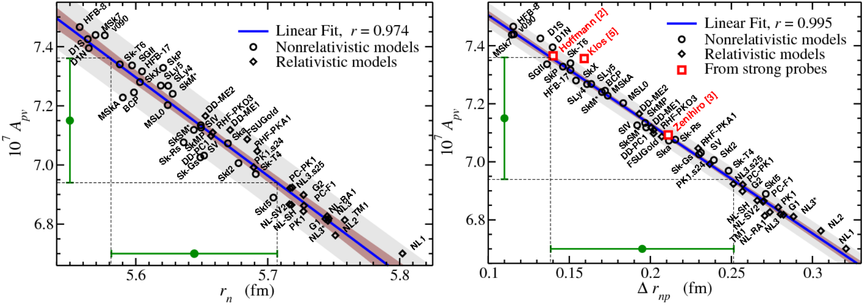
- $V_\pm(r) = V_{\mathrm{Coulomb}}(r) \pm V_{\mathrm{weak}}(r)$

- $V_{\mathrm{weak}}(r) = \frac{G_F}{2^{3/2}}\left[(1 - 4\sin^2\theta_W) Z\rho_p(r) - N\rho_n(r)\right]$

- $A_{LR}^{\mathrm{PWBA}} = \frac{G_F q^2}{4\pi\alpha\sqrt{2}}\left[4\sin^2\theta_W + \frac{F_n(q) - F_p(q)}{F_p(q)}\right]$

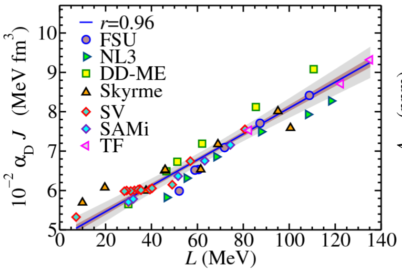
- PREX experiment $E \sim 1.05$ GeV and $\theta \sim 5^\circ$

Parity-violating electron scattering (II)



with E=1.06 GeV and $\theta = 5^\circ$

Dipole polarizability + parity-violating electron scattering



$$L = -146 \pm (1)_{theor} + [6.11 \pm (0.18)_{expt} \pm (0.26)_{theor}] \times J$$

with $J = 31 \pm 2$ MeV $\quad L = 43 \pm 16$ MeV

Conclusions

- We use insights from the Droplet Model to understand correlations between the electric polarizability, the neutron skin thickness and the properties of symmetry energy at saturation.
- The product $\alpha_D J$ is as far a better correlated with the neutron skin thickness than α_D alone.
- It is found that the electric polarizabilities in two neutron-rich nuclei are also correlated between them.
- Using the mean-field models that simultaneously reproduce the experimental electric polarizability in ^{208}Pb, ^{120}Sn and ^{68}Ni, one can estimate the neutron skin thickness in these nuclei as well as the symmetry energy and its slope at saturation.
- The estimates of the symmetry energy extracted from electric polarizability measurements are in agreement with the commonly accepted range of this quantity. The estimated slope points towards a rather soft symmetry energy.
- A_{pv} is strongly correlated not only with Δr_{np} but also with $\alpha_D J$.