Constraining the density slope of the symmetry energy at subsaturation densities using electric dipole polarizability in ^{208}Pb

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Outline

EoS and Symmetry energy

- EoS of asymmetric nuclear matter:

$$E(\rho,\delta) = E_0(\rho) + E_{\rm sym}(\rho)\delta^2 + \mathcal{O}(\delta^4).$$

- EoS of symmetric nuclear matter

$$E_0(\rho) = E_0(\rho) + \frac{1}{2}K_0\chi^2 + \frac{1}{6}J_0\chi^3 + \mathcal{O}(\chi^4)$$

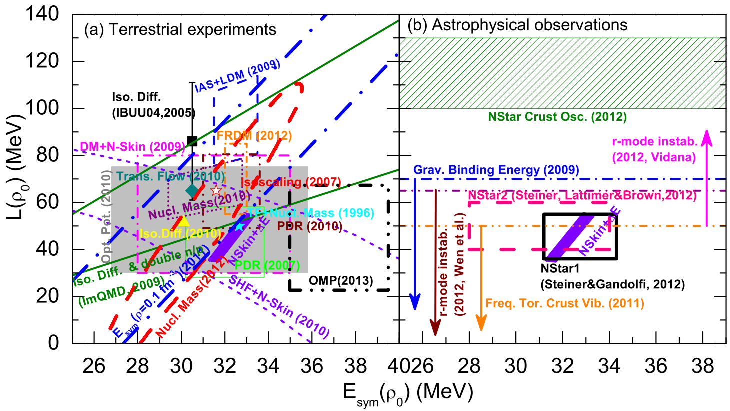
- Symmetry Energy

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + L(\rho_0)\chi + \frac{1}{2}K_{\rm sym}\chi^2 + \mathcal{O}(\chi^3)$$

where, $\delta = \frac{\rho_n - \rho_p}{\rho}$, $\chi = \frac{\rho-\rho_0}{3\rho_0}$ and $L(\rho) = 3\rho\frac{dE_{\rm sym}}{d\rho}$

$E_{\rm sym}(\rho)$ and $L(\rho)$ essentially determine the density dependence of the symmetry energy around ρ.

Constraints on $E_{\rm sym}(\rho_0)$ and $L(\rho_0)$

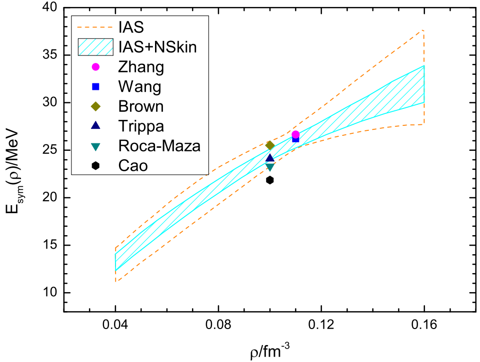


L.W. Chen, arXiv:1212.0284

B.A. Li *et al.*, arXiv:1212.1178

The properties of finite nuclei usually provide more precise constraints on $E_{\rm sym}(\rho)$ and $L(\rho)$ at subsaturation densities instead of saturation density.

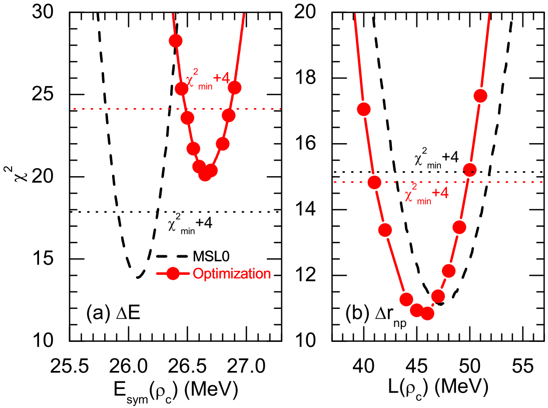
Symmetry energy at subsaturation densities



- IAS and IAS+NSkin
  P. Danielewicz and J. Lee, Nucl. Phys. **A922**, 1 (2014)
- Zhang: Isotope binding energy difference
  Z. Zhang and L.W. Chen, Phys. Lett. **B726**, 234 (2013)
- Wang: Fermi energy difference
  N. Wang *et al.*, Phys. Rev. C **87**, 034327 (2013)
- Brown: Doubly magic nuclei
  B.A. Brown, Phys. Rev. Lett. **11**, 232502 (2013)
- Trippa: Giant dipole resonance
  L. Trippa *et al.*, Phys. Rev. C **77**, 061304(R) (2008)
- Roca-Maza: Giant quadrupole resonance
  X. Roca-Maza *et al.*, Phys. Rev. C **87**, 034301 (2013)
- Cao: Pygmy dipole resonance
  L.G. Cao and Z.Y. Ma, Chin. Phys. Lett. **25**, 1625 (2008)

The density slope L at subsaturation densities need further study.

Constraints on $E_{\rm sym}(\rho_c)$ and $L(\rho_c)$ at $\rho_c = 0.11 \text{fm}^{-3}$



- $E_{\rm sym}(\rho_c) = 26.65 \pm 0.2\text{MeV}$ is extracted from the isotope binding energy difference.
- $L(\rho_c) = 46 \pm 4.5\text{MeV}$ is extracted from the neutron skin thickness of Sn isotopes.

Z. Zhang and L.W. Chen, Phys. Lett. **B726**, 234 (2013).

The electric dipole polarizability α_{D}

- α_{D} is related to the inverse energy weighted m_{-1} sum rule of isovector giant dipole resonance(IVGDR) by:

$$\alpha_{\mathrm{D}} = \frac{8\pi}{9}e^2 \int dE E^{-1} S(E) = \frac{8\pi}{9}e^2 m_{-1}.$$

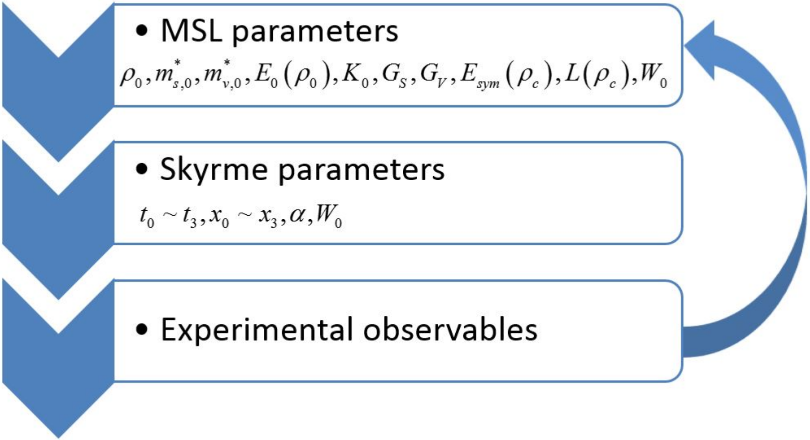
- α_{D} is sensitive to the density dependence of the symmetry energy.
  P.G. Reinhard, W. Nazarewicz, Phys. Rev. C 81, 051303 (2010).
  J. Piekarewicz *et al.*, Phys. Rev. C 85, 041302(R) (2012).
  X. Roca-Maza *et al.*, Phys. Rev. C 88, 024316 (2013).

- α_{D} in ^{208}Pb was measured at the Research Center for Nuclear Physics (RCNP) using polarized proton inelastic scattering at forward angle: A.
  Tamii *et al.*, Phys. Rev. Lett. **107**, 062502 (2011).

$$\alpha_{\mathrm{D}} = 20.1 \pm 0.6 \mathrm{fm}^3$$

Since at forward angles *Coulomb excitation dominates*, the extracted α_{D} is expected to be a relatively clean isovector indicator.

MSL model



We vary one quantity at one time to reveal the dependence of experimental observables on each macroscopic quantity.

L.W. Chen et al., PRC80, 014322 (2009)
L.W. Chen, C.M. Ko, B.A. Li, and J. Xu, PRC82, 024321 (2010)

Random phase approximation

We employ the Skyrme-RPA program by G. Colò *et al.*. This program allows us to compute IVGDR excitation in the framework of HF-RPA with Skyrme-type interaction.

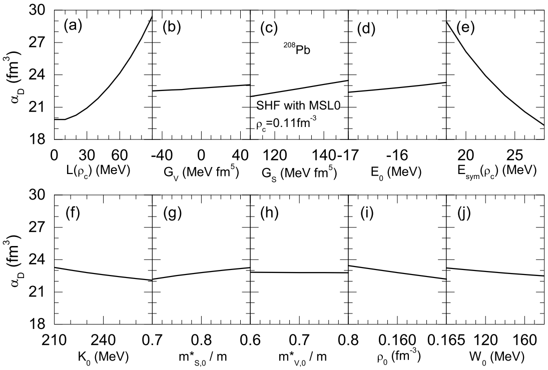
G. Colò, *et al.*, Comput. Phys. Commun. **184**, 142 (2013)

- The radius of the spherical box is 24 fm;
- The radial mesh is 0.1 fm;
- The cutoff energy is 150 MeV;
- When calculating α_{D}, we set the upper integration limit as 130 MeV.

$$\alpha_D = \frac{8\pi}{9} e^2 \int dE E^{-1} S(E)$$

where, $S(E)$ is IVGDR strength function.

α_D in ^{208}Pb varying with MSL parameters

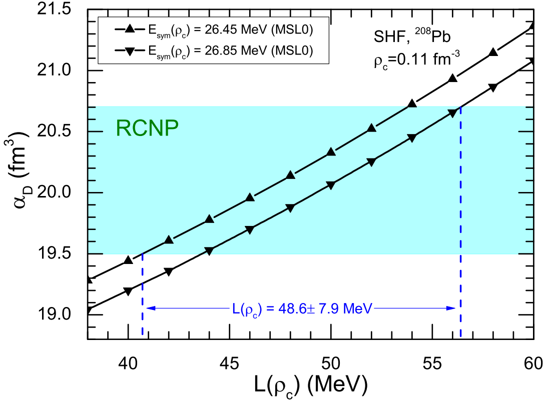


- α_D in ^{208}Pb exhibits strong correlations with both $E_{sym}(\rho_c)$ and $L(\rho_c)$
- A fixed value of α_D will lead to a strong positive correlation between $E_{sym}(\rho_c)$ and $L(\rho_c)$
- Combined with $E_{sym}(\rho_c) = 26.45 \pm 0.20$MeV, α_D can be used to constrain $L(\rho_c)$.

MSL0

ρ_0(fm^{-3})	E_0(MeV)	K_0(MeV)	$m^*_{s,0}/m$	$m^*_{v,0}/m$	G_S(MeV· fm^5)	G_V(MeV· fm^5)	W_0(MeV· fm^5)	$E_{sym}(\rho_c)$(MeV)	$L(\rho_c)$(MeV)
0.16	-16.0	230	0.80	0.70	132.0	5.0	133.3	23.2	49.4

α_D in ^{208}Pb as a function of $L(\rho_c)$



- Fix other 8 parameters at their default values in MSL0.
- Up(down)-triangles represent the result with $E_{\text{sym}}(\rho_c) = 26.45(26.85)$MeV.
- $L(\rho_c) = 48.6 \pm 7.9$MeV.

Optimization

Experimental data

- Binding energy of 12 spherical even-even nuclei;

  M. Wang *et al.*, Chin. Phys. C **36** (2012) 1287

- Charge rms radii of 10 spherical even-even nuclei;

  I. Angeli, At. Data Nucl. Data. Tab. **87** (2004) 185

  F. Le Blanc *et al.*, Phys. Rev. C **72**, (2005) 034305

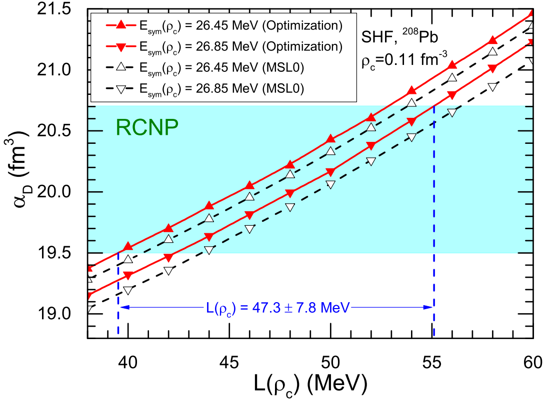
- Breathing mode energy of ^{90}Zr,^{116}Sn,^{144}Sm and ^{208}Pb.

  D.H. Youngblood *et al.*, Phys. Rev. Lett. **82**, 691 (1999)

Constraints

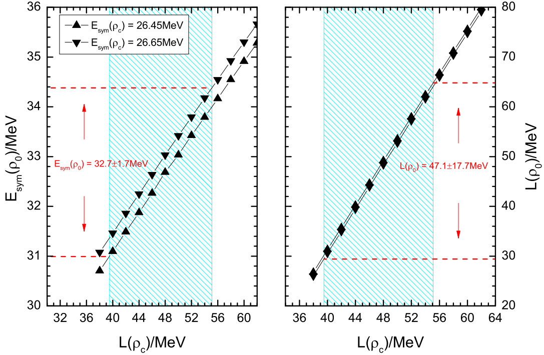
- The neutron $3p_{1/2} - 3p_{3/2}$ splitting in ^{208}Pb lies in the range of 0.8-1.0 MeV;
- $m^*_{s,0}$ should be greater than $m^*_{v,0}$ and here we set $m^*_{s,0} - m^*_{v,0} = 0.1m$.

$\alpha_{\rm D}$ in ^{208}Pb as a function of $L(\rho_c)$



- Optimize other 8 parameters to fit experimental data.
- Up(down)-triangles represent the result with $E_{\rm sym}(\rho_c) = 26.45(26.85)$MeV.
- $L(\rho_c) = 47.3 \pm 7.8$MeV.
- This result is in very good agreement with $L(\rho_c) = 46.0 \pm 4.5$MeV.

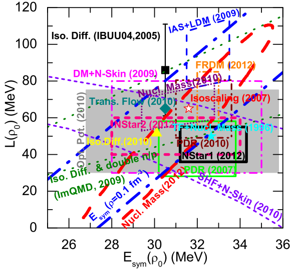
$E_{\rm sym}(\rho_0)$ and $L(\rho_0)$



$$E_{\rm sym}(\rho_0) = 32.7 \pm 1.7\text{MeV}$$

$$L(\rho_0) = 47.1 \pm 17.7\text{MeV}$$

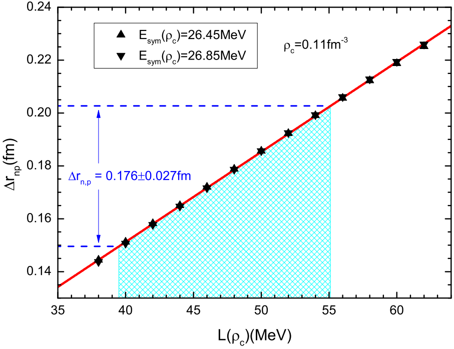
Using the optimized parameters, we can evaluate $E_{\rm sym}(\rho_0)$ and $L(\rho_0)$.



L.W. Chen, arXiv:1212.0284

B.A. Li *et al.*, arXiv:1212.1178

Neutron skin thickness of ^{208}Pb



- $\alpha_D + E_{sym}(\rho_0) = 31 \pm 2$(est):
  $\Delta r_{np} = 0.165 \pm (0.009)_{expt} \pm (0.013)_{theor} \pm (0.021)_{est}$
  X. Roca-Maza *et al.*, Phys. Rev. C **88**, 024316 (2013)
- PREX:
  $\Delta r_{np} = 0.33^{+0.16}_{-0.18}$
  S. Abrahamyan *et al.*, Phys. Rev. Lett **108**, 112502 (2012)
- Coherent Pion Photoproduction:
  $\Delta r_{np} = 0.15 \pm 0.03(\mathrm{stat.})^{+0.01}_{-0.03}(\mathrm{sys.})$
  C.M. Tarbert *et al.*, Phys. Rev. Lett. **112**, 242502 (2014)
- α_D:
  $\Delta r_{np} = 0.156^{+0.025}_{-0.021}$
  A. Tamii *et al.*, Phys. Rev. Lett. **107**, 062502 (2011).

This work: $\Delta r_{np} = 0.176 \pm 0.027$fm.

Summary

- We have demonstrated that the electric dipole polarizability in ^{208}Pb is sensitive to both $E_{\rm sym}(\rho_c)$ and $L(\rho_c)$ at a subsaturation cross density $\rho_c = 0.11\text{fm}^{-3}$.
- Combining $\alpha_{\rm D} = (20.1 \pm 0.6)\text{fm}^3$ in ^{208}Pb and $E_{\rm sym}(\rho_{\rm c}) = (26.65 \pm 0.20)$MeV, we have obtained a strong constraint on the slope parameter $L(\rho_{\rm c}) = 47.3 \pm 7.8$ MeV.
- This constraint is in very good agreement with $L(\rho_{\rm c}) = 46.0 \pm 4.5$ MeV extracted from neutron skin thickness of Sn isotopes.
- We have obtained the corresponding constraints at ρ_0 as $E_{\rm sym}(\rho_0) = 32.7 \pm 1.7$MeV and $L(\rho_0) = 47.1 \pm 17.7$MeV.

Thank you