HINP2014: New Aspects and Perspectives in Nuclear Physics

Thessaloniki, Greece, April 12 2014

Symmetry energy effects on isovector properties of neutron rich nuclei with a density functional approach

M. C. Papazoglou, Ch. C. Moustakidis
Department of Nuclear and Elementary Particle Physics,
School of Physics, Aristotle University of Thessaloniki, Greece

Abstract

- Model: Variational approach to study the effect of the symmetry energy on isovector properties of various medium and heavy nuclei.
- Case study: ^{208}Pb, ^{124}Sn, ^{90}Zr, ^{48}Ca.
- Calculations: R_{skin}, a_A, etc.
- Crucial Point: The Coulomb interaction managed in a self-consistent way.
- Conclusion: Strong dependence of the SE on the various isovector properties for medium and heavy nuclei.

Introduction

- Nuclei Properties
  - Asymmetry Coefficient

$$E_B = \alpha_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - \boldsymbol{a_A} \frac{(N-Z)^2}{A} - \delta(A,Z)$$

$$\boldsymbol{a_A} \sim S(\rho)$$

  - Neutron Skin Thickness

$$\boldsymbol{R_{skin}} = R_n - R_p$$

$$\boldsymbol{R_{skin}} \sim a(\rho)$$

Model & Approach

✧ Total Energy Functional

$$F_0\left(\frac{d\rho(r)}{dr}\right)^2 \qquad \frac{e^2}{2}\int\frac{\rho(r')\big(1-a(r)\big)\rho(r)}{|r-r'|}d^3r'$$

$$E[\rho,\alpha]=\int_v\left[\epsilon_{ANM}(\rho,a)+F_0|\nabla\rho(r)|^2+\frac{1}{4}\rho(r)\big(1-\alpha(r)\big)V_c(r)\right]d^3r$$

$$\rho(r)T_0\left(a\left(\frac{\rho(r)}{\rho_0}\right)^{2/3}-b\left(\frac{\rho(r)}{\rho_0}\right)+\boldsymbol{c}\left(\frac{\rho(r)}{\rho_0}\right)^{5/3}\right)+\alpha^2(r)\rho(r)S(\rho(r))$$

$$J \longleftarrow S(\rho_0)\left(\frac{\rho(r)}{\rho_0}\right)^{\gamma} \longrightarrow \frac{L}{3J}$$

Model & Approach

✧ Basic Idea: Minimization of Total Energy

$$E[\rho, \alpha] = \int_v \left[\epsilon_{ANM}(\rho, a) + F_0|\nabla\rho(r)|^2 + \frac{1}{4}\rho(r)\big(1 - \alpha(r)\big)V_c(r)\right] d^3r$$

→ Total density $\rho(r)$

→ Isospin asymmetry function $a(r)$

$$\int \rho(r) d^3r = A \qquad \int r^2 a(r)\rho(r) dr = N - Z$$

Model & Approach

✧ Variational Method – Lagrangian Function

$$\mathcal{L} = 4\pi r^2 \left(\epsilon_{ANM}\big(\rho(r), a(r)\big) + F_0 \left(\frac{dp}{dr}\right)^2 + \frac{1}{4}\rho(1-\alpha)V_c(r) \right) - \lambda_1 4\pi r^2 \rho - \lambda_2 4\pi r^2 \alpha\rho$$

→ Total density $\rho(r)$

→ Isospin asymmetry function $a(r)$

$$\rho(r) = \frac{n_0}{1 + e^{\frac{r-d}{w}}}$$

$$\frac{\partial \mathcal{L}}{\partial a} - \frac{d}{dr}\left(\frac{\partial \mathcal{L}}{\partial \alpha'}\right) = 0 \qquad \frac{\partial \mathcal{L}}{\partial \rho} - \frac{d}{dr}\left(\frac{\partial \mathcal{L}}{\partial \rho'}\right) = 0$$

Model & Approach

✧ LDE – Solutions

$$\frac{\partial \mathcal{L}}{\partial a} - \frac{d}{dr}\left(\frac{\partial \mathcal{L}}{\partial \alpha'}\right) = 0$$

$$\rho'' + \frac{2\rho'}{r} - \frac{1}{2F_0}\left[\frac{\partial \epsilon_{SNM}(\rho)}{\partial \rho} + a^2\left(S(\rho) + \rho\frac{\partial S(\rho)}{\partial \rho}\right) + \frac{1}{4}(1-\alpha)V_c(r) - \lambda_1 - \lambda_2\alpha\right] = 0$$

$$\frac{\partial \mathcal{L}}{\partial \rho} - \frac{d}{dr}\left(\frac{\partial \mathcal{L}}{\partial \rho'}\right) = 0$$

$$a(r) = \frac{1}{8S(\rho)}\left(V_c(r) + 4\lambda_2\right) \qquad 0 \le a(r) \le 1$$

Model & Approach

- Coulomb Interactions
  - Coulomb Potential

$$V_c(r) = \frac{e^2}{2}\int \frac{\rho(r')\big(1-a(r)\big)\rho(r)}{|r-r'|}d^3r'$$

  - Discontinuity Behavior on Integral

$a(r) = 1$

$r \leq r_C$

$$V_c(r) = 2\pi e^2\left[\int_0^r \frac{1}{r}\big(1-a(r')\big)\rho(r')r'^2 d^2r' + \int_r^{r_C}\big(1-a(r')\big)\rho(r')r'dr'\right]$$

$r \geq r_C$

$$V_c(r) = 2\pi e^2\left[\int_0^{r_C} \frac{1}{r}\big(1-a(r')\big)\rho(r')r'^2 d^2r'\right]$$

Model & Approach

✧ Self-Consistency

$$a(r) = \frac{\lambda_2}{4S(\rho)}$$

$$\int r^2 a(r)\rho(r)dr = N - Z$$

$$a(r) = 1$$

$$\lambda_2$$

$$r_C$$

$$V_c(r)$$

$$V_c(r) = 0$$

1st Iteration

$$a(r) = \frac{1}{8S(\rho)}(V_c(r) + 4\lambda_2) \qquad 0 \leq a(r) \leq 1$$

M. C. Papazoglou, Department of N&EPP, School of Physics, Aristotle University of Thessaloniki, Greece

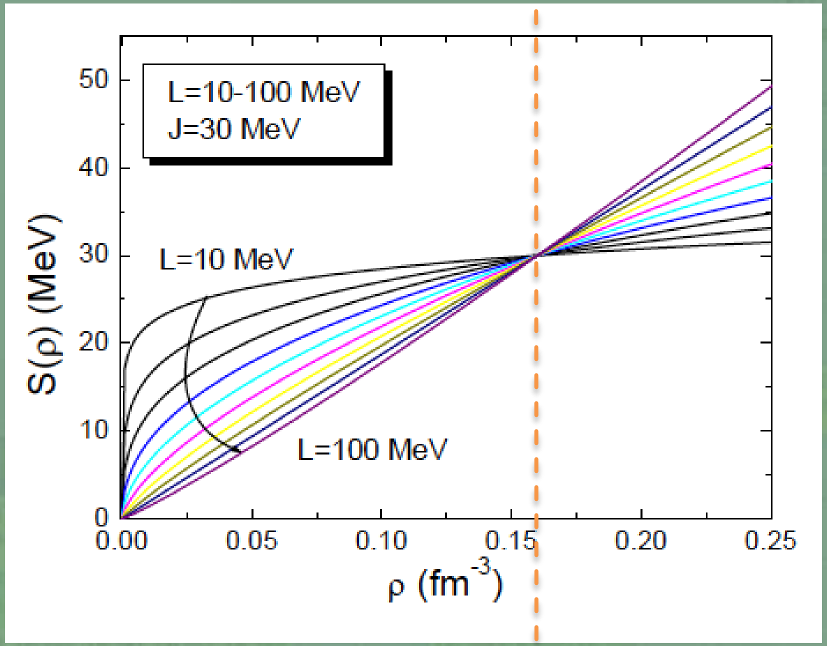
Model & Approach

✧ Calculations

Inputs (Constants)	Inputs (Variables)	Outputs
^{48}Ca	L	E_{total}
^{90}Zr	J	ΔR
^{208}Pb		a_A
^{124}Sn		

- All the calculated properties are studied as a function of the slope of the SE (L) and the value of the SE at the nuclear saturation density (J).

Results and Discussion



finite nuclei | neutron stars

$$S(\rho_0)\left(\frac{\rho(r)}{\rho_0}\right)^{\gamma}$$

- Lower values of L ➔ higher values of the S(ρ). (nucleons less bound, N>>Z)
- Higher values of L ➔ lower contribution of the S(ρ). (nucleons more bound), N≈Z)

L	E	R_n	R_p	R_{skin}	a_A
10	-1581.36	5.629	5.623	0.006	28.52
20	-1593.44	5.659	5.604	0.055	26.77
30	-1606.35	5.695	5.586	0.109	24.85
40	-1620.28	5.723	5.560	0.163	22.90
50	-1633.62	5.756	5.537	0.219	20.87
60	-1646.40	5.780	5.517	0.263	19.03
70	-1658.36	5.803	5.500	0.303	17.32
80	-1669.35	5.816	5.478	0.338	15.80
90	-1679.37	5.828	5.458	0.370	14.41
100	-1688.46	5.846	5.448	0.398	13.11

- The isovector properties of nuclei are related with the trend of the symmetry energy in the region $10MeV < L < 100MeV$

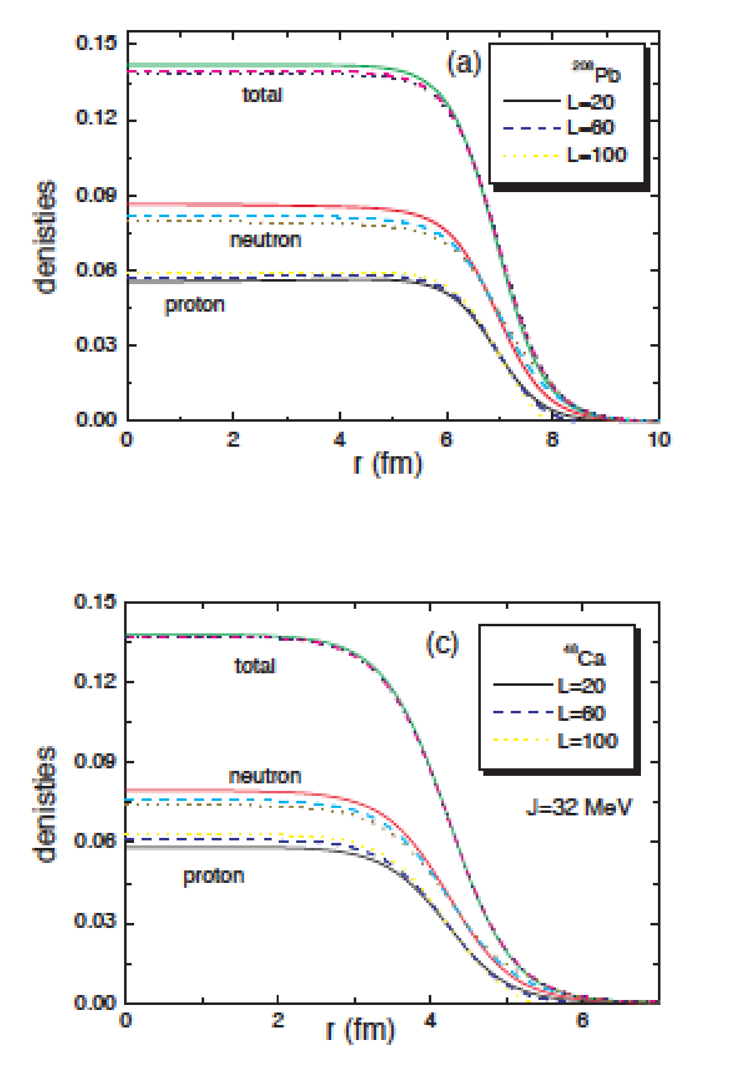
Results and Discussion

Higher values of L:

➔ Shift the neutron distribution to the outer part of the nucleus.

➔ Concentrates deeper the protons.

➔ Shift of r_c, increasing dramatically the neutron skin, forming a kind of neutron halo inside the nucleus.



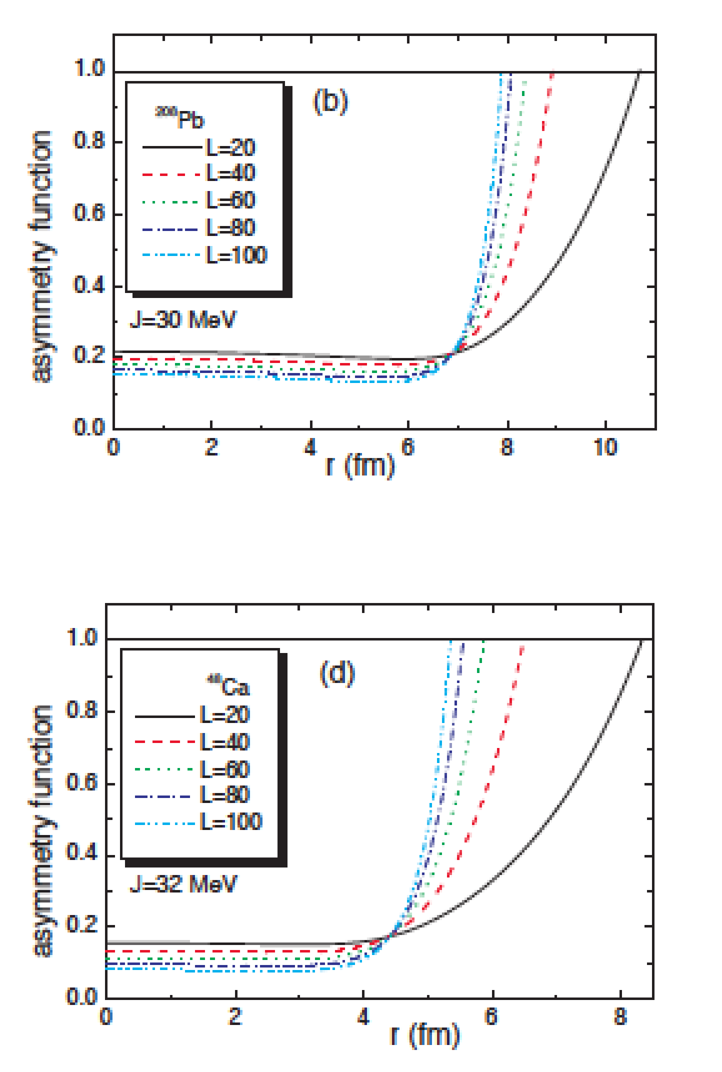
Results and Discussion

The asymmetry function α(r):

➔ Acts as a regulator on the proton and neutron distributions in order to minimize the total energy of the nucleus.

➔ Coulomb potential $V_c(r)$ acts inversely.

➔ Long range Coulomb forces – Isovector part of nuclear forces ⟶ creation of the neutron skin thickness.



Results and Discussion

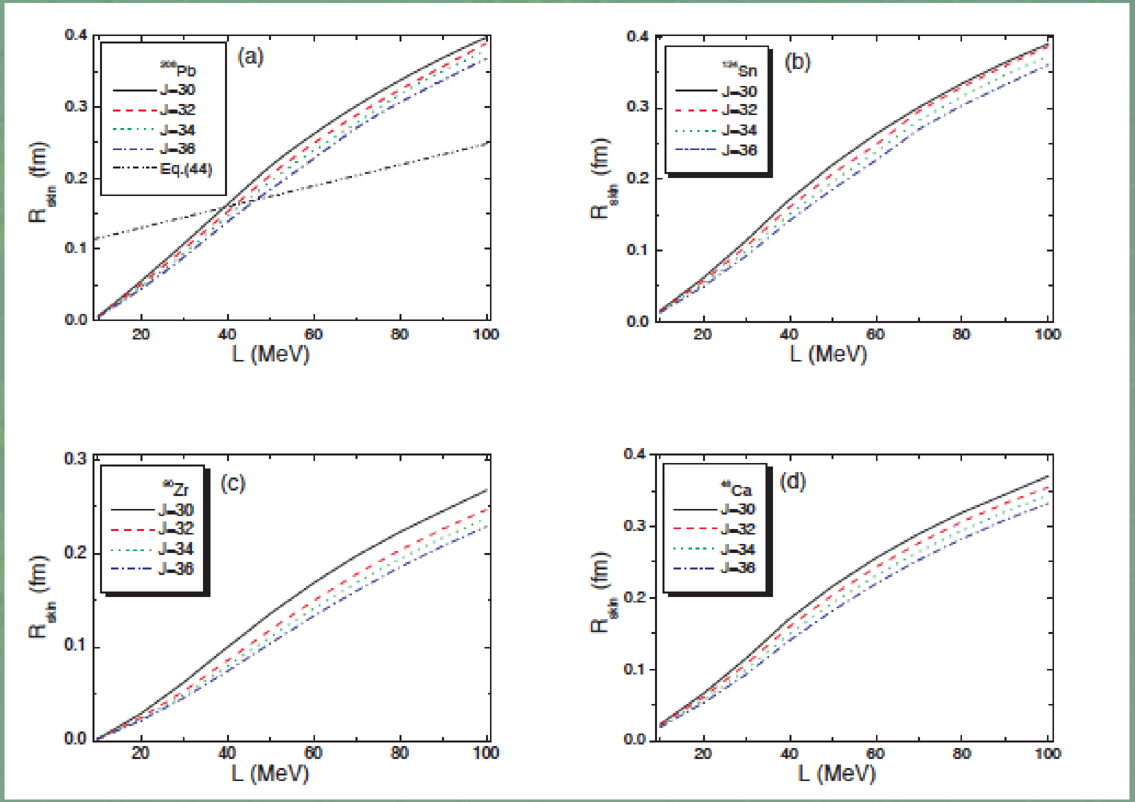
Strong dependence of R_{skin} on L:

$R_{skin}(fm) = 0.101 + 0.00147L\ (MeV)$

Centelles et. al.

◆That relation supports a softer dependence of R_{skin} on L compared to the present study.

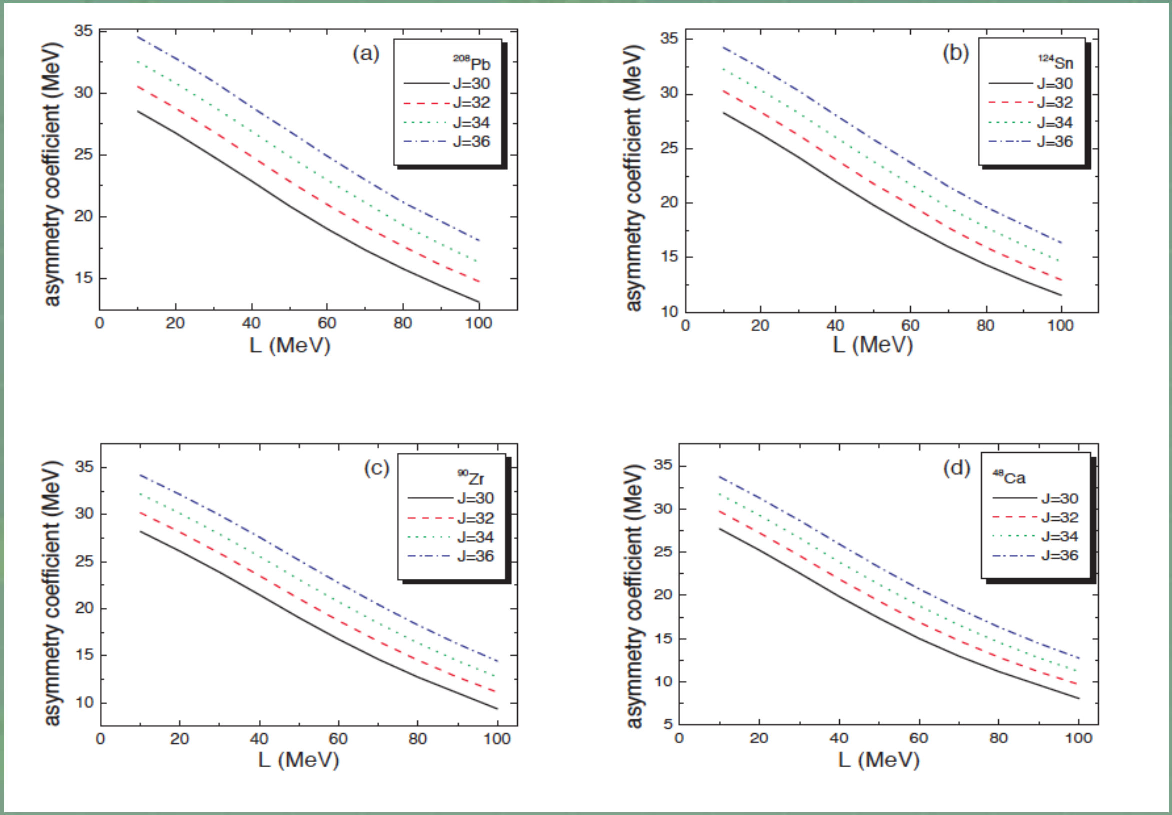
◆The intersection between our results and the results compatible with Centelles approximation corresponds to values of binding energy are very close to the experimental data for the specific nuclei.



M. C. Papazoglou, Department of N&EPP, School of Physics, Aristotle University of Thessaloniki, Greece

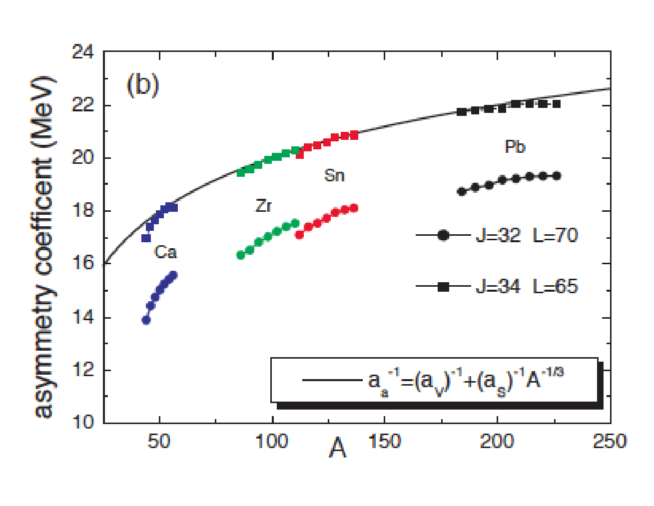
Results and Discussion

- a_A is a decreasing function of L.
- Higher values of L → Low values of $\alpha(\rho)$.
- a_A exhibits a mass depended A behavior.

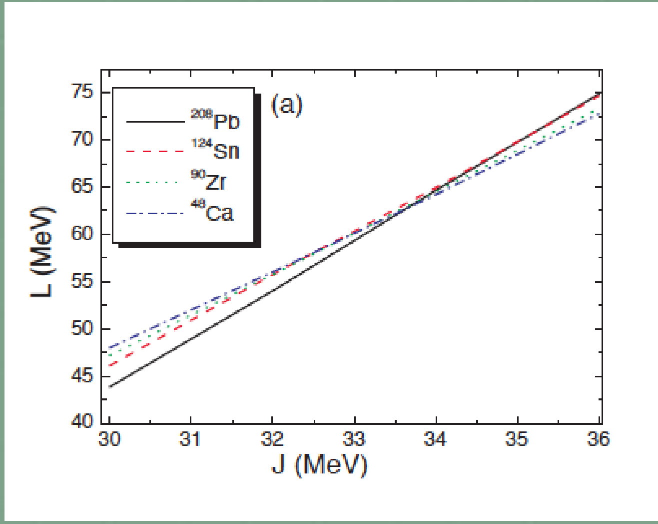


Results and Discussion

- The set J=34 MeV and L=65MeV reproduces very well the empirical values of aA for almost all of the medium and heavy isotopes.



- Possible universal dependence holds between L and J for nuclei at least in the mass region A = 40-200.
- The same set of L and J reproduce in a very good accuracy the a_A for medium as well as heavy nuclei.

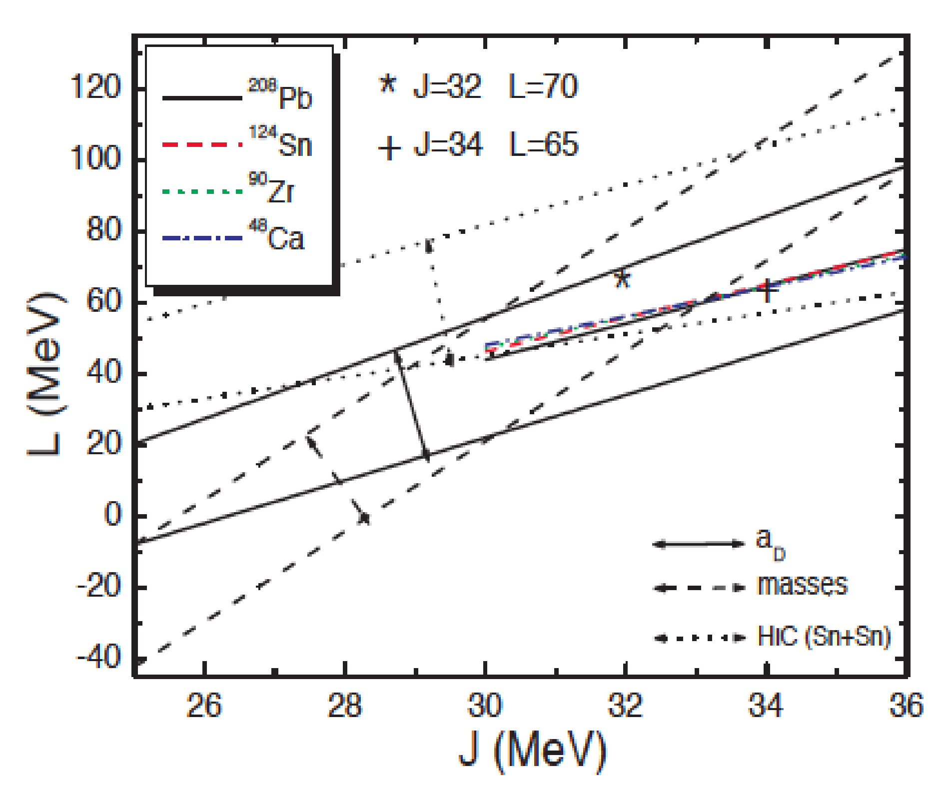


M. C. Papazoglou, Department of N&EPP, School of Physics, Aristotle University of Thessaloniki, Greece

Results and Discussion

- Heavy ion collision
- Nuclear structure observables.

➔ The present results lies inside the relevant area.



Results and Discussion

- Dependence of the coefficient a_A on the asymmetry parameter I for all the relevant isotopes.

- In almost all cases there is a soft dependence of a_A on I but a strong dependence on the value of J.

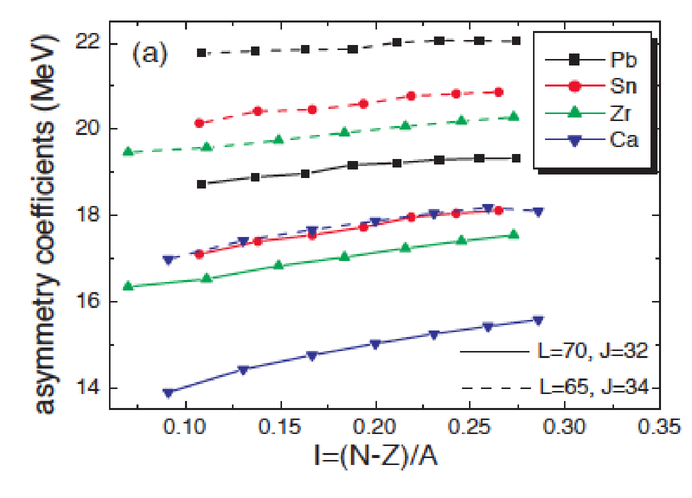
- Linear dependence of R_{skin} on I.

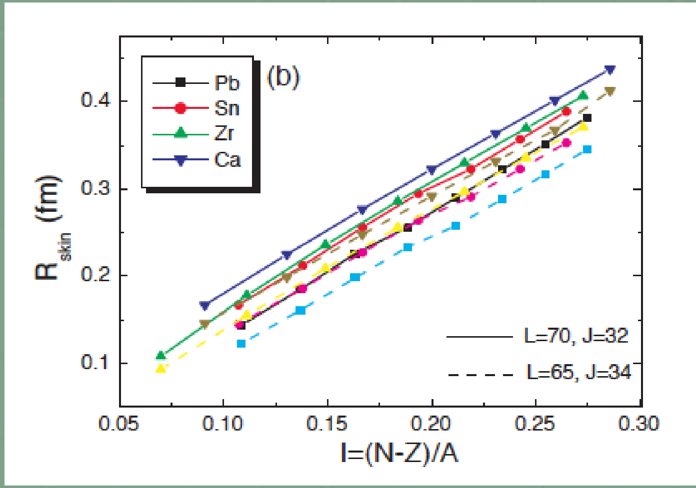
$$R_{skin} = a + bI$$

$$-0.02 \leq a \leq 0.045$$

$$1.31 \leq b \leq 1.45$$

- Intervals are dependent on the specific set of values of L and J.





Conclusion

✧ About the present work

➔ Neutron skin thickness is very sensitive on L.

➔ Case of ^{208}Pb: The present approximation supports a stronger sensitivity of the neutron skin thickness on L.

➔ Comparison to the empirical formula.

➔ J imposes strong constraints on L.

Conclusion

✧ About the present work

- ➔ The method can be applied in the totality of medium and heavy neutron rich nuclei.
- ➔ Coulomb interaction can easily be separated from the nucleon-nucleon interaction.
- ➔ The approach can be easily extended to include more complicated expressions:
    - SE
    - SNM

Conclusion

✧ About future works (open problems)

- Experimental and theoretical work is necessary.
    - ➔ Finite nuclei.
    - ➔ Neutron star structure.
- SE contribution for low densities.
- Correlation between the nuclear EOS of nuclear matter and the DFT of infinite nuclei.

The End

Thank you for your attention!