Parity-Violating Asymmetry for ^{208}Pb

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Outline

- Introduction
- Parity-violating asymmetry
- Nuclear structure models
- Symmetry energy at saturation density
- Results for ^{208}Pb
- Predictions for ^{48}Ca

- Collaborators

  C. Giusti (Pavia), A. Meucci (Pavia)
  P. Finelli (Bologna)

Purpose

Our goal is present and discuss numerical predictions for the neutron density distribution of ^{208}Pb and compare the results with the experimental data obtained from different reactions

Theoretical background

- Relativistic and non-relativistic mean-field models for the nuclear structure
- Parity-violating asymmetry parameter for elastic electron scattering is computed at the kinematics of the PREX experiment and is obtained averaging the theoretical results over the experimental acceptance function
- Theoretical predictions of the neutron skin thickness are obtained from mean field models

Osaka measurement - Phys. Rev. C, **82**, 044611 (2010)

- Cross sections and analyzing power for polarized proton elastic scattering
- Measurement of neutron density distribution and neutron skin thickness

PREX measurement - Phys. Rev. Lett. **108**, 112502 (2012)

- Parity-violating asymmetry A_{pv} from ^{208}Pb
- Information about the difference between the radii of the neutron and proton distributions $R_n - R_p$
- First electroweak observation of the neutron skin

Mainz measurement - Phys. Rev. Lett. **112**, 242502 (2014)

- Coherent pion photoproduction from ^{208}Pb
- Information on the size and shape of the neutron skin

Dirac equation

$$[\boldsymbol{\alpha} \cdot \mathbf{p} + U_\pm(r)]\Psi_\pm = E\Psi_\pm$$

Total potential: $U(r)_\pm = V(r) \pm \gamma_5 A(r)$

Axial potential: $A(r) = \frac{G_F}{2\sqrt{2}} \rho_W(r)$

Weak charge density

$$\rho_W(r) = \int \mathrm{d}\mathbf{r}' \, G_E\left(|\mathbf{r} - \mathbf{r}'|\right) \times \left[-\rho_n(r') + (1 - 4\sin^2\Theta_W)\rho_p(r')\right]$$

Electric form factor: $G_E(r) \approx \frac{\Lambda^3}{8\pi} \, e^{-\Lambda r}$ $\qquad \Lambda = 4.27 \ \mathrm{fm}^{-1}$

Parity-violating asymmetry in Born approximation

$$A_{pv} = \frac{G_F \, Q^2}{4\sqrt{2} \, \pi\alpha} \left[4 \sin^2 \Theta_W - 1 + \frac{F_n(q)}{F_p(q)}\right]$$

Relativistic models

- Nonlinear RMF model (NL)
- Density-dependent RMF model (DD)
- Nonlinear point-coupling RMF model (PC)
- Density-dependent point-coupling RMF model (DDPC)

Non-relativistic models

- Skyrme interaction (SIII, SKM*, SLY4, SLY5)
- Gogny interaction (D1S)

Approximations

- Mean field description
- Spherical symmetry
- No-sea approximation (relativistic models)

Nuclei are described as a system of Dirac nucleons interacting by the exchange of mesons and the electromagnetic field

Nonlinear RMF model

- Lagrangian: $\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int}$
- $\mathcal{L}_m$ includes terms like: $\omega_\mu \omega^\mu , \quad (\omega_\mu \omega^\mu)^2 , \ldots$
- $\mathcal{L}_{int}$ contains the interaction terms between nucleons and mesons

Density-dependent RMF model

- Lagrangian: $\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int}$
- $\mathcal{L}_{int}$ contains the interaction terms between nucleons and mesons with density-dependent coupling constants
- $g_i(\rho) = g_i(\rho_{sat}) f_i(x)$ for $i = \sigma \, , \omega \, , \rho \, ,$ $\quad x = \rho/\rho_{sat}$
- $\rho_{sat} = 0.152 \, \mathrm{fm}^{-3}$ denotes the nucleon density at saturation in symmetric nuclear matter

The point-coupling models are defined by a Lagrangian density that only consists of nucleon fields

Nonlinear point-coupling RMF model

- Lagrangian: $\mathcal{L} = \mathcal{L}_{free} + \mathcal{L}_{4f} + \mathcal{L}_{hot} + \mathcal{L}_{der}$
- $\mathcal{L}_{4f}$ includes 4-fermion terms: $(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)$
- $\mathcal{L}_{hot}$ includes higher order terms: $[(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)]^2$
- $\mathcal{L}_{der}$ includes derivative terms: $(\partial_\nu\bar{\psi}\gamma_\mu\psi)(\partial^\nu\bar{\psi}\gamma^\mu\psi)$

Density-dependent point-coupling RMF model

- Lagrangian: $\mathcal{L} = \mathcal{L}_{free} + \mathcal{L}_{4f} + \mathcal{L}_{der}$
- $\mathcal{L}_{4f}$ includes 4-fermion terms: $(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)$
- $\mathcal{L}_{der}$ represents derivatives in the nucleon scalar density
- Coupling constants are density-dependent

Skyrme interaction

- Interaction: $V = \sum_{i<j} V(ij) + \sum_{i<j<k} V(ijk)$
- Short-range expansion for the two-body interaction:

$$V(1,2) = V_0\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2) + V_1\left[\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)\hat{\boldsymbol{k}}^2 + \hat{\boldsymbol{k}}^2\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)\right] + V_2\hat{\boldsymbol{k}}\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)\hat{\boldsymbol{k}} + iW_0(\boldsymbol{\sigma}^{(1)} + \boldsymbol{\sigma}^{(2)})\hat{\boldsymbol{k}} \times \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)\hat{\boldsymbol{k}}$$

- Zero-range force for three-body interaction:

$$V(1,2,3) = V_3\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)\,\delta(\boldsymbol{r}_2 - \boldsymbol{r}_3)$$

Gogny interaction

- Zero-range forces of Skyrme interaction might not be able to simulate the long range parts of the realistic effective interaction
- V_0, V_1 and V_2 of Skyrme force are replaced by a sum of two Gaussians with spin-isospin exchange mixtures

EOS of isospin asymmetric nuclear matter

$$E(\rho,\alpha) = E(\rho,\alpha=0) + E_{\rm sym}(\rho)\,\alpha^2 + O(\alpha^4)$$

Nuclear symmetry energy and isospin asymmetry:

$$E_{\rm sym}(\rho) = \frac{1}{2}\,\frac{\partial^2 E(\rho,\alpha)}{\partial\alpha^2}\bigg|_{\alpha=0} \qquad \alpha = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

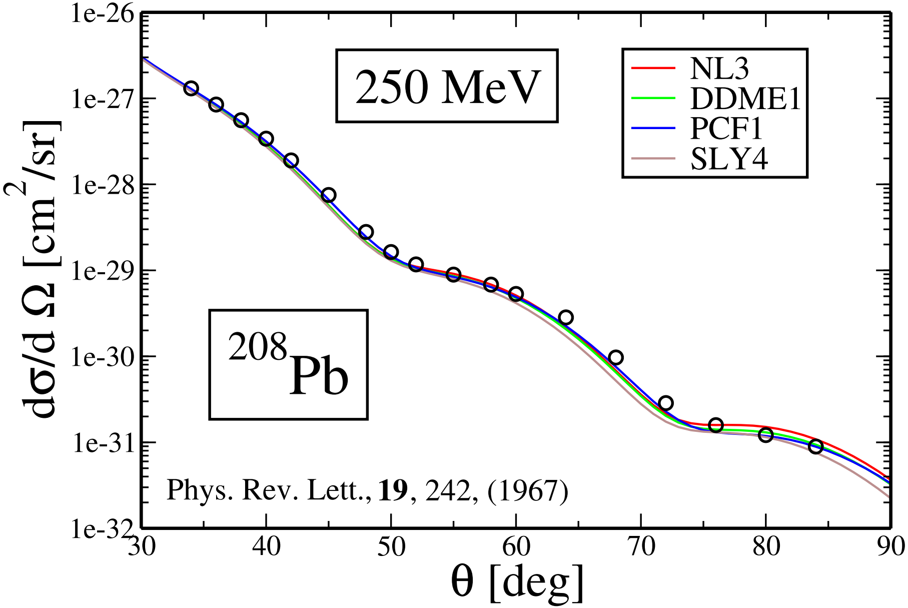
Nuclear symmetry energy at saturation density

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

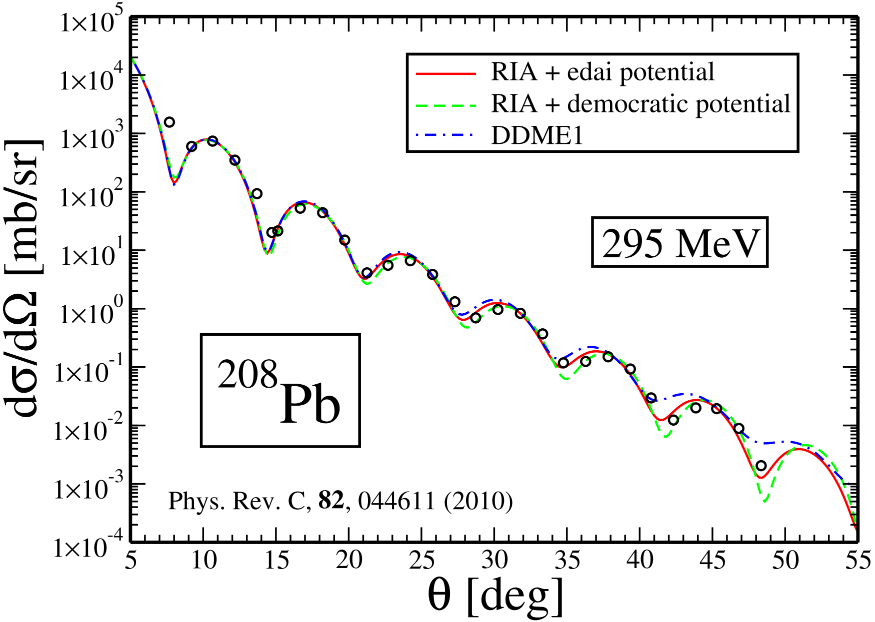
Parameters of expansion:

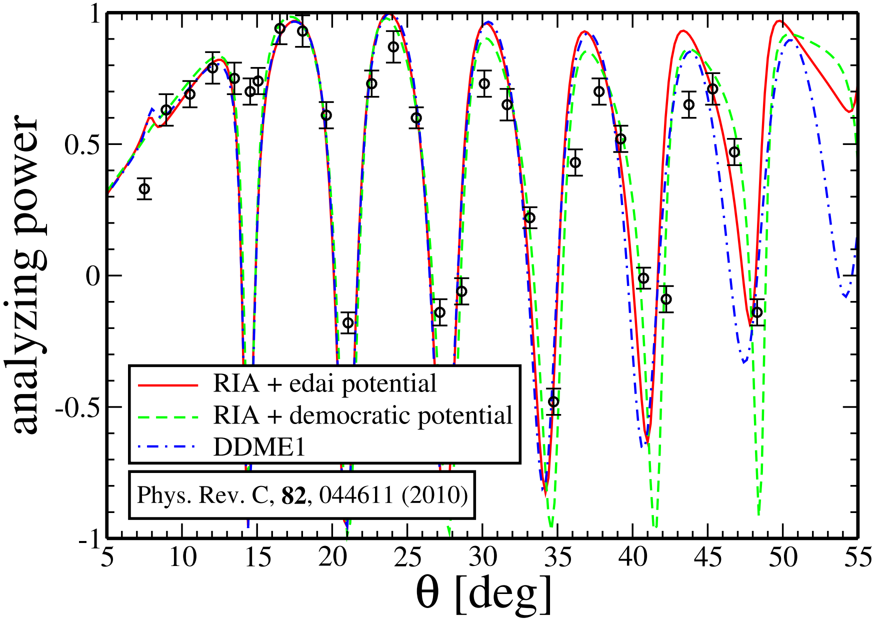
$$L = 3\rho_0\,\frac{\partial E_{sym}(\rho)}{\partial\rho}\bigg|_{\rho=\rho_0} \qquad K_{sym} = 9{\rho_0}^2\,\frac{\partial^2 E_{sym}(\rho)}{\partial\rho^2}\bigg|_{\rho=\rho_0}$$

Elastic Scattering off ^{208}Pb

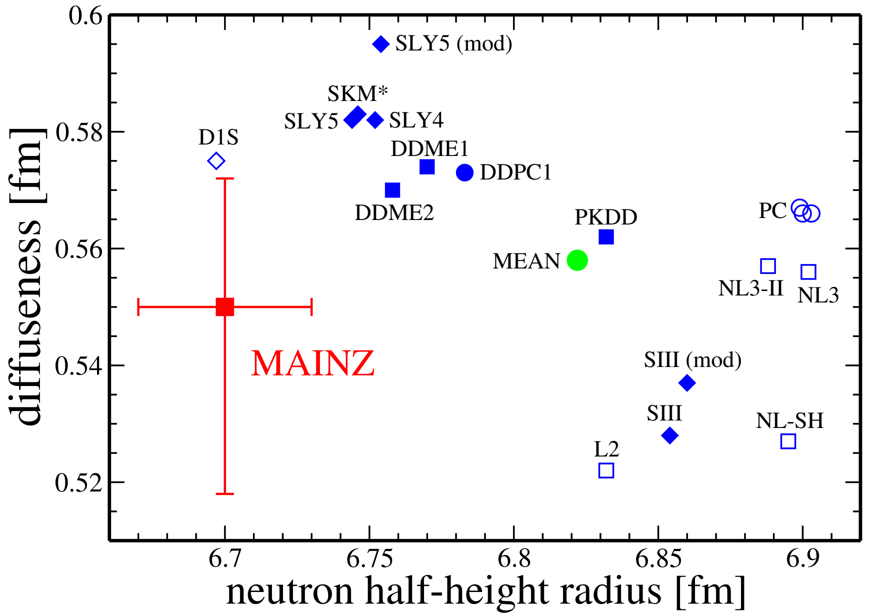


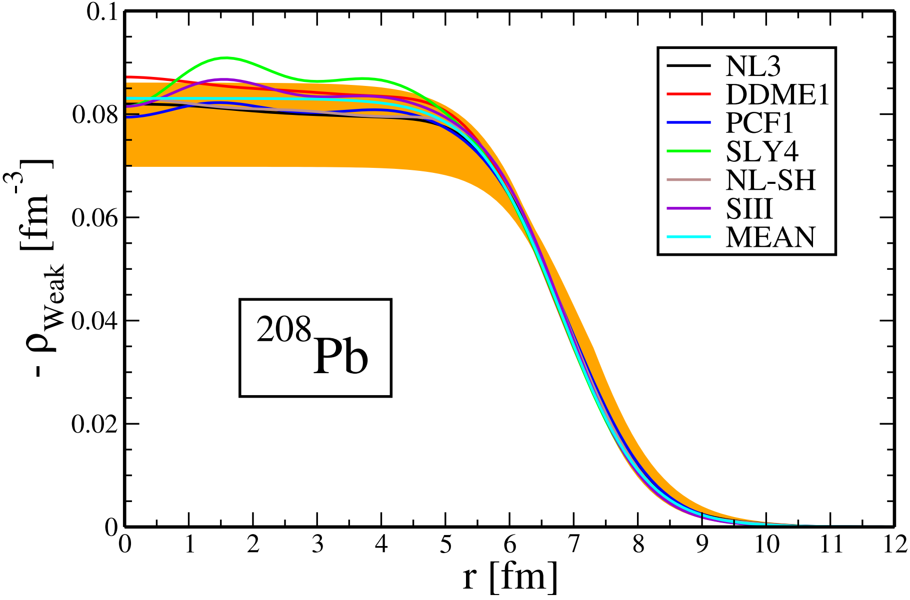
250 MeV
NL3
DDME1
PCF1
SLY4
208Pb
Phys. Rev. Lett., 19, 242, (1967)
dσ/d Ω [cm2/sr]
θ [deg]
1e-26
1e-27
1e-28
1e-29
1e-30
1e-31
1e-32
30
40
50
60
70
80
90

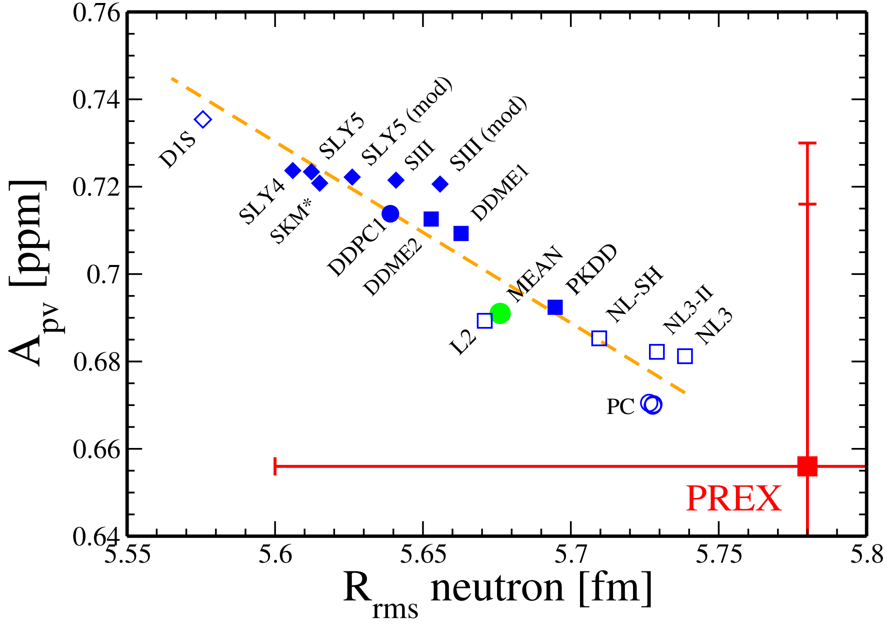

RIA + edai potential
RIA + democratic potential
DDME1
295 MeV
208Pb
Phys. Rev. C, 82, 044611 (2010)
dσ/dΩ [mb/sr]
θ [deg]


analyzing power
θ [deg]
RIA + edai potential
RIA + democratic potential
DDME1
Phys. Rev. C, **82**, 044611 (2010)
1
0.5
0
-0.5
-1
5
10
15
20
25
30
35
40
45
50
55

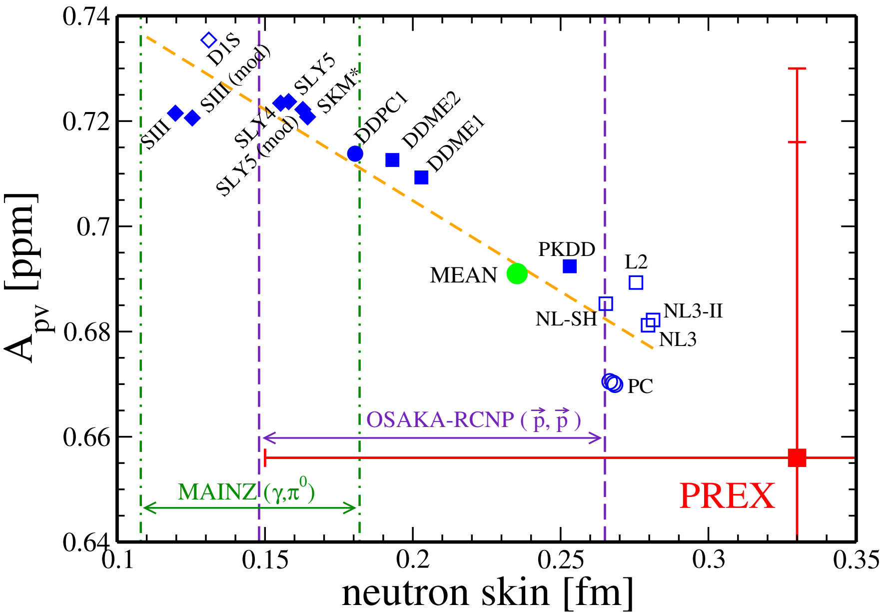
Results for ^{208}Pb


0.6
0.58
0.56
0.54
0.52
diffuseness [fm]
6.7
6.75
6.8
6.85
6.9
neutron half-height radius [fm]
SLY5 (mod)
SKM*
SLY5
SLY4
D1S
DDME1
DDPC1
DDME2
PKDD
PC
MEAN
NL3-II
NL3
MAINZ
SIII (mod)
SIII
NL-SH
L2

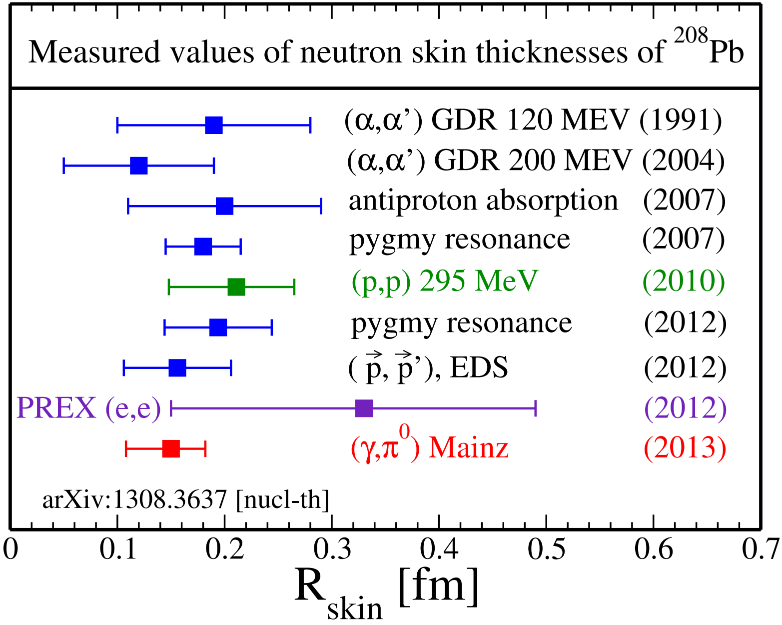

0.1
0.08
0.06
0.04
0.02
0
- ρWeak [fm-3]
0
1
2
3
4
5
6
7
8
9
10
11
12
r [fm]
NL3
DDME1
PCF1
SLY4
NL-SH
SIII
MEAN
208Pb

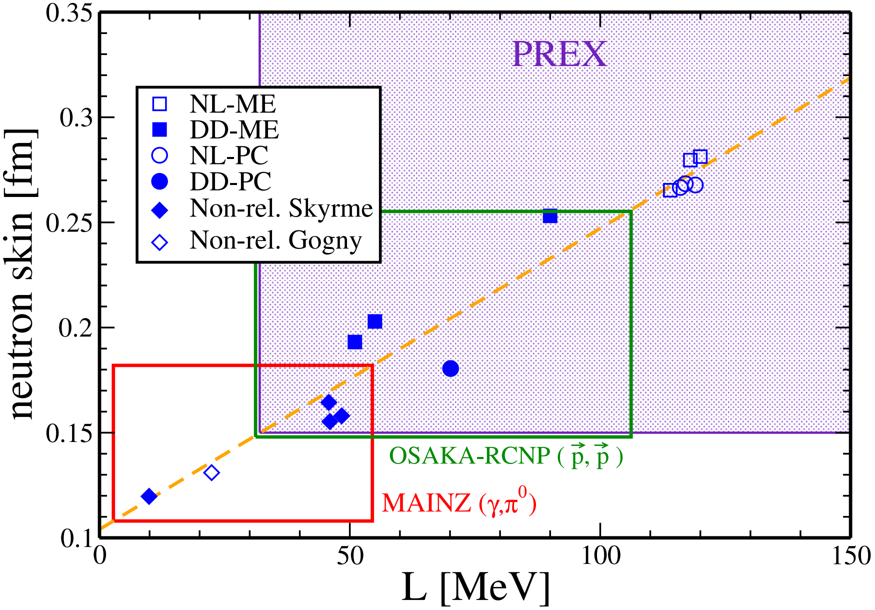


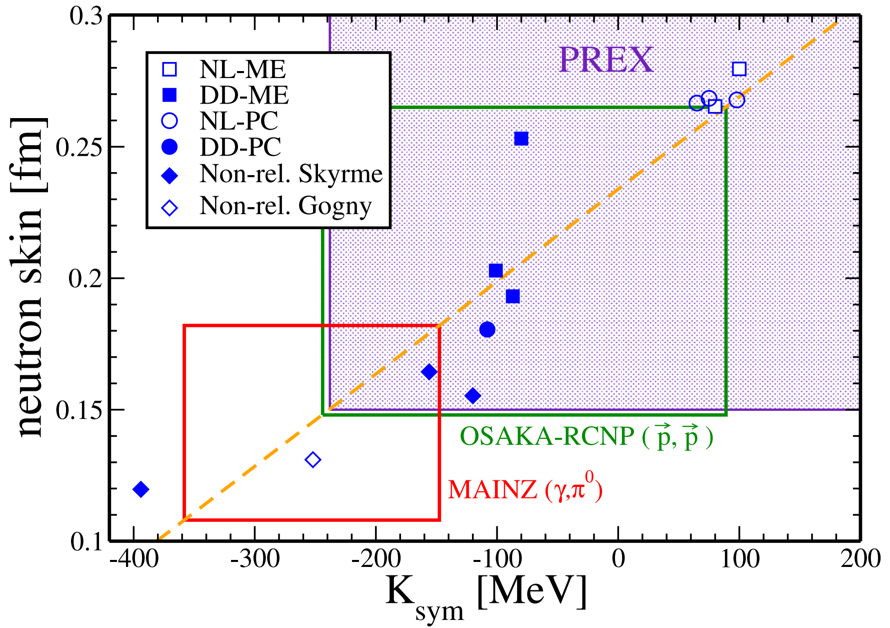
A_pv [ppm]
0.76
0.74
0.72
0.7
0.68
0.66
0.64
5.55
5.6
5.65
5.7
5.75
5.8
R_rms neutron [fm]
D1S
SLY4
SKM*
SLY5
SLY5 (mod)
SIII
SIII (mod)
DDME1
DDPC1
DDME2
MEAN
L2
PKDD
NL-SH
NL3-II
NL3
PC
PREX



0.74
0.72
0.7
0.68
0.66
0.64
0.1
0.15
0.2
0.25
0.3
0.35
A_{pv} [ppm]
neutron skin [fm]
D1S
SIII (mod)
SLY5
SKM*
SIII
SLY4
SLY5 (mod)
DDPC1
DDME2
DDME1
PKDD
L2
MEAN
NL-SH
NL3-II
NL3
PC
OSAKA-RCNP ($\vec{p}$, $\vec{p}$)
MAINZ (γ,π^0)
PREX

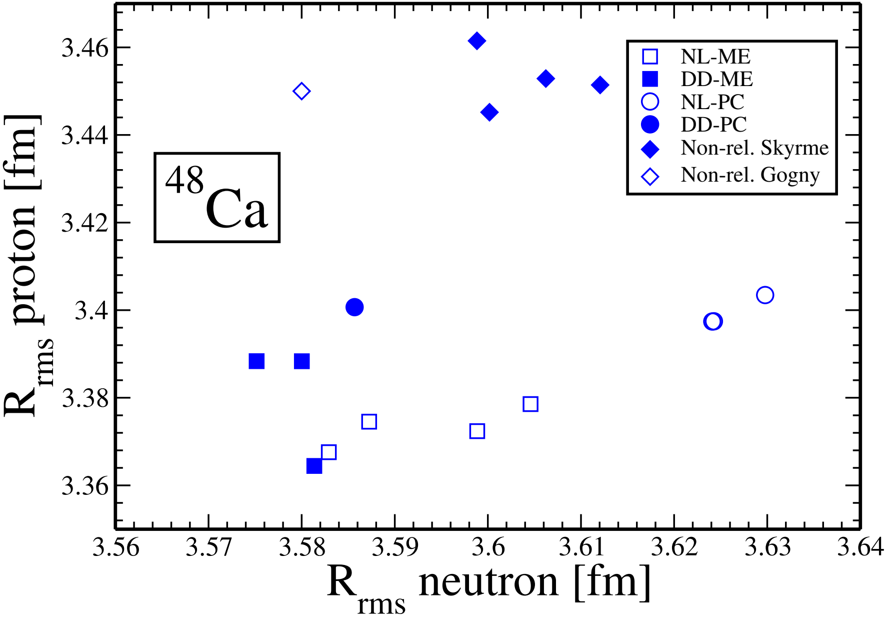

Measured values of neutron skin thicknesses of 208Pb
(α,α') GDR 120 MEV (1991)
(α,α') GDR 200 MEV (2004)
antiproton absorption (2007)
pygmy resonance (2007)
(p,p) 295 MeV (2010)
pygmy resonance (2012)
(p⃗, p⃗'), EDS (2012)
PREX (e,e) (2012)
(γ,π0) Mainz (2013)
arXiv:1308.3637 [nucl-th]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
R skin [fm]


PREX
NL-ME
DD-ME
NL-PC
DD-PC
Non-rel. Skyrme
Non-rel. Gogny
neutron skin [fm]
0.35
0.3
0.25
0.2
0.15
0.1
0
50
100
150
L [MeV]
OSAKA-RCNP (p, p)
MAINZ (γ,π0)

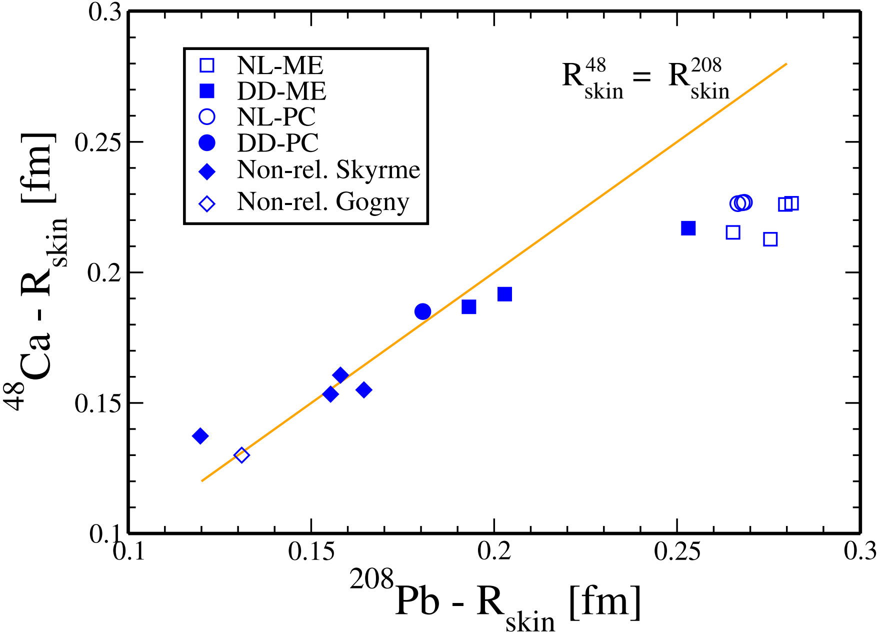


0.3
0.25
0.2
0.15
0.1
-400
-300
-200
-100
0
100
200
neutron skin [fm]
K_{sym} [MeV]
NL-ME
DD-ME
NL-PC
DD-PC
Non-rel. Skyrme
Non-rel. Gogny
PREX
OSAKA-RCNP ($\vec{p}$, $\vec{p}$)
MAINZ (γ,π^0)

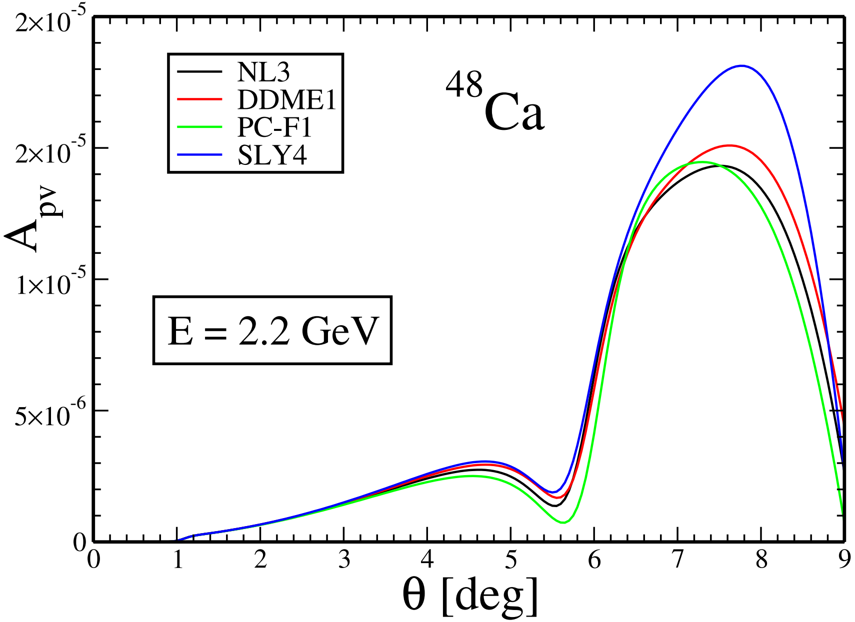
Predictions for ^{48}Ca



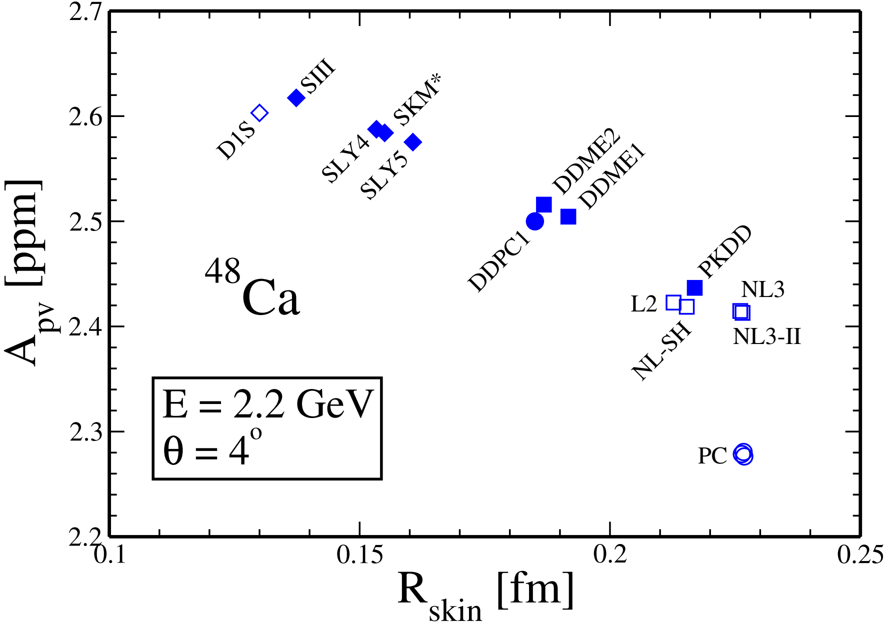
^{48}Ca
NL-ME
DD-ME
NL-PC
DD-PC
Non-rel. Skyrme
Non-rel. Gogny
R_{rms} proton [fm]
R_{rms} neutron [fm]
3.46
3.44
3.42
3.4
3.38
3.36
3.56
3.57
3.58
3.59
3.6
3.61
3.62
3.63
3.64



NL-ME
DD-ME
NL-PC
DD-PC
Non-rel. Skyrme
Non-rel. Gogny
$R^{48}_{skin} = R^{208}_{skin}$
0.1
0.15
0.2
0.25
0.3
^{208}Pb - R_{skin} [fm]
^{48}Ca - R_{skin} [fm]



NL3
DDME1
PC-F1
SLY4
48Ca
E = 2.2 GeV
Apv
θ [deg]
2×10-5
2×10-5
1×10-5
5×10-6
0
0
1
2
3
4
5
6
7
8
9



2.7
2.6
2.5
2.4
2.3
2.2
0.1
0.15
0.2
0.25
A_pv [ppm]
R_skin [fm]
48Ca
E = 2.2 GeV
θ = 4°
D1S
SIII
SKM*
SLY4
SLY5
DDME2
DDME1
DDPC1
PKDD
L2
NL3
NL-SH
NL3-II
PC

Conclusions

- Determination of neutron distribution in nuclei
- Great experimental and theoretical efforts have been devoted to achieve this goal
- Parity-violating electron scattering is an accurate and model-independent tool for probing neutron properties
- More information on nuclear structure
- More stringent constraints of the range of variation of nuclear matter expansion parameters

Backup Slides

Symmetrized Fermi Density

- Two-parameter distribution

$$\rho(r) = \rho_0 \, \frac{\sinh(R/a)}{\cosh(R/a) + \cosh(r/a)}$$

$$\rho_0 = \frac{3}{4\pi R^3} \left[1 + \left(\frac{\pi a}{R} \right)^2 \right]^{-1}$$

- Properties

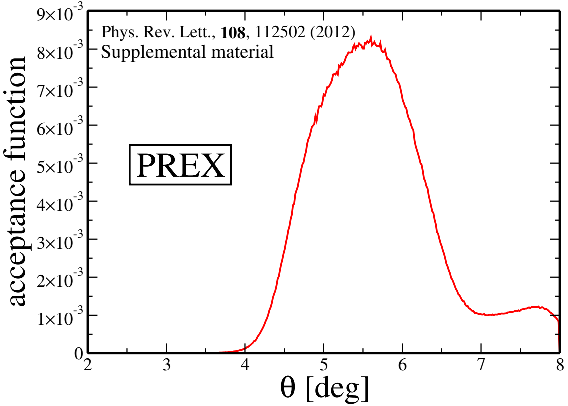
$$\int d^3 r \, \rho(r) = 1$$

Asymmetry parameter and acceptance function

- Asymmetry parameter

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

- Acceptance function



Best fit lines

	Slope	Intercept	Chi-Square
$R_{rms} - A_{pv}$	-4.133×10^{-1}	3.045	1.07×10^{-3}
$R_{skin} - A_{pv}$	-3.426×10^{-1}	7.738×10^{-1}	1.39×10^{-3}
$L - R_{skin}$	$+1.455 \times 10^{-3}$	1.019×10^{-1}	1.15×10^{-2}
$K_{sym} - R_{skin}$	$+3.494 \times 10^{-4}$	2.363×10^{-1}	2.67×10^{-2}