Neutron-skin thickness of heavy-ions studied with α-particle scattering

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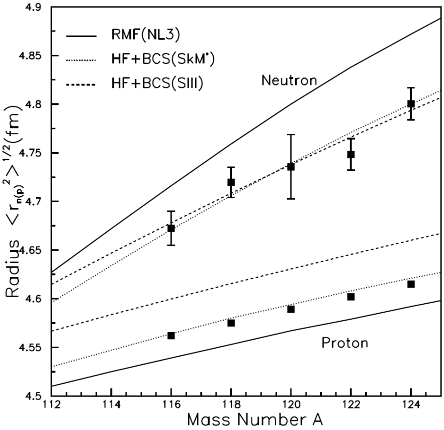
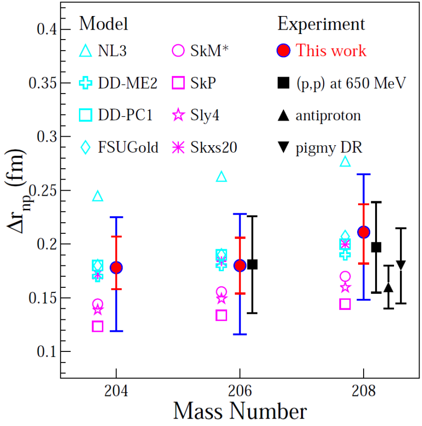
August 14, 2014

Introduction

S. Terashima, Kyoto U. 2008



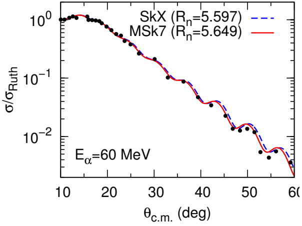
J. Zenihiro, Kyoto U. 2011



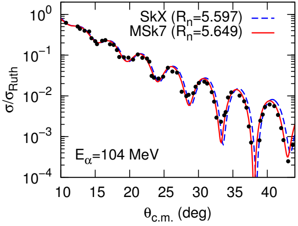
Precision required: $\Delta R_n / R_n < 1\%$

Introduction

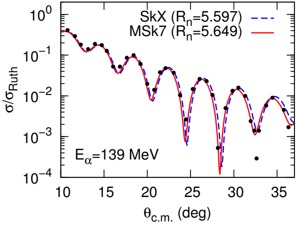
$\alpha+^{208}$Pb at 60 MeV



$\alpha+^{208}$Pb at 104 MeV



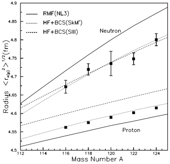
$\alpha+^{208}$Pb at 139 MeV

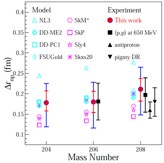


Effect of $\Delta R_n/R_n \sim 1\%$ is visible in angular distributions

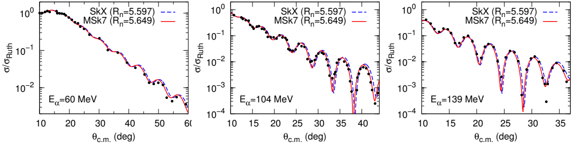
Introduction

Terashima's and Zenihiro's PhD thesis





Precision required: $\Delta R_n / R_n < 1\%$

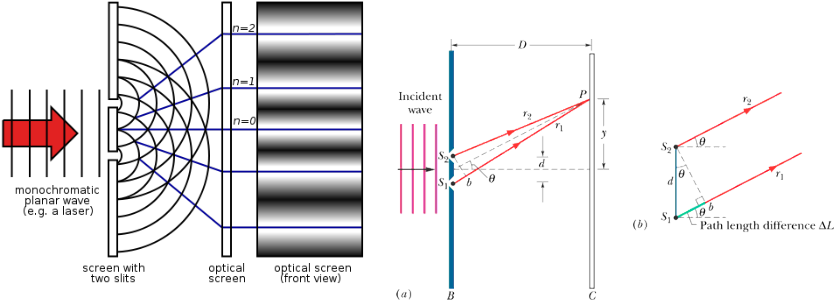


Effect of $\Delta R_n / R_n \sim 1\%$ visible

Question: how to get R_n from α-elastic scattering?

Diffraction of light

Double-slit with light

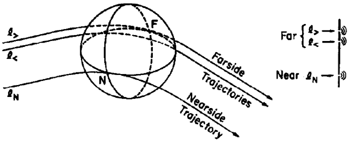


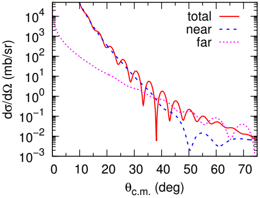
(http://ipodphysics.com/prop-of-light-youngs-double-slit.php)

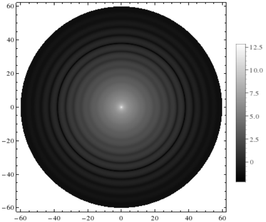
$$\Delta y = \frac{D}{d}\lambda \Rightarrow \Delta\theta = \frac{\Delta y}{D} = \frac{\lambda}{d} = \frac{2\pi}{kd} = \frac{\pi}{k(d/2)}$$

Diffraction of α-particle

Double-slit with α-particle





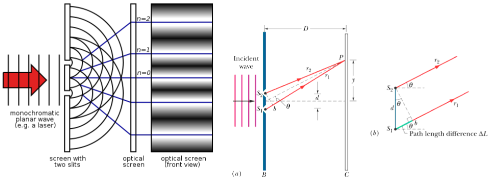


$$\Delta\theta \approx \frac{\pi}{kR}$$

G.R. Satchler, *Direct Nuclear Reactions*, Chapter 11

Diffraction of light

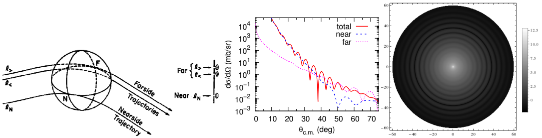
Double-slit with light



$$\Delta x = \frac{\lambda}{Dd} \Rightarrow$$

$$\Delta\theta = \frac{2\pi}{kd} = \frac{\pi}{k(d/2)}$$

Double-slit with α-particle

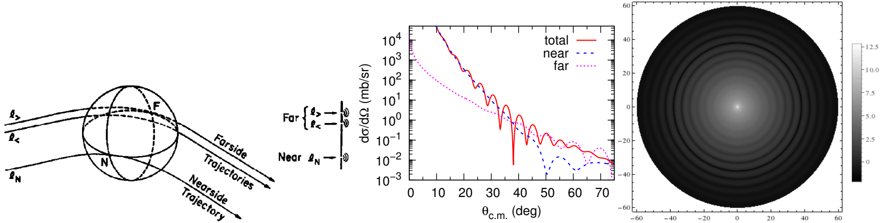


$$\Delta\theta \approx \frac{\pi}{kR}$$

Question: how does this R relate to the radius of the nucleus?

Logic chain in this work

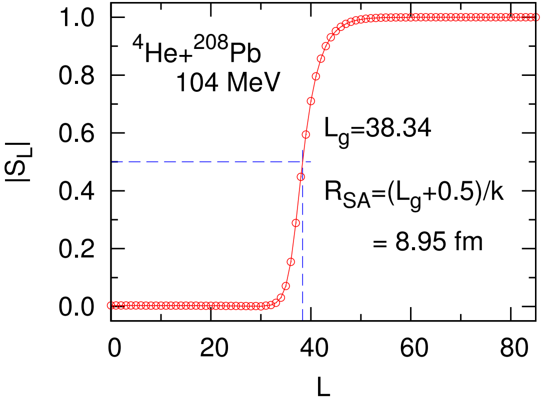
Double-slit with α-particle



$$\Delta\theta \approx \frac{\pi}{kR} = \frac{\pi}{kR_{SA}}$$

1. Angular distribution $\Leftrightarrow$ Strong absorption radius R_{SA}
2. R_{SA} $\Leftrightarrow$ radius of the optical potential R_U
3. R_U $\Leftrightarrow$ neutron density distribution ρ_n
4. ρ_n $\Leftrightarrow$ neutron radius R_n

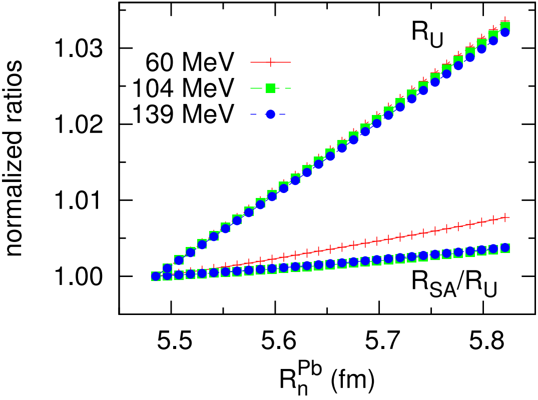
Strong absorption radius R_{SA}



G.R. Satchler, *Direct Nuclear Reactions*, Chapter 11

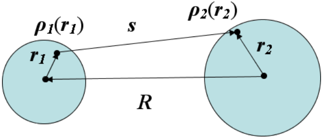
Strong absorption radius and rms radius of OMP

R_{SA} change closely with the changes of R_U



Double-folding model of OMP

The double-folding model



$$U_{DF}(R) = \iint \rho_1(r_1)\rho_2(r_2)V_{NN}(|\boldsymbol{s}|)\mathrm{d}r_1\mathrm{d}r_2.$$

relation of RMS radii in double-folding model

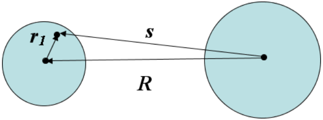
$$\begin{aligned}\langle R^2_{U_{DF}}\rangle &= \langle R_1^2\rangle + \langle R_2^2\rangle + \langle V_{NN}^2\rangle \\ \Rightarrow \langle R_2^2\rangle &= \langle R^2_{U_{DF}}\rangle - (\langle R_1^2\rangle + \langle R_{NN}^2\rangle)\end{aligned}$$

$\langle R^2_{U_{DF}}\rangle$ depends on incident energy $\Rightarrow$ Need calibration of U_{DF} for $\langle R_2^2\rangle$

M.E. Brandan and G.R. Satchler, Phys. Rep. 285, 143 (1997)

The systematic single-folding α-nucleus potential

The single-folding model



$$U_{SF}(R) = \iint \rho_1(r_1) U_{NA}(|\mathbf{s}|) \mathrm{d}r_1,$$ U_{NA} being JLMB (JLM+Bruyères) systematics

E. Bauge, J.P. Delaroche, and M. Girod, PRC 63, 024607 (2001)

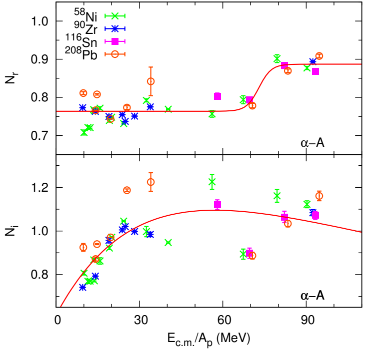
renormalization factors N_r and N_i

$$U(E,R) = N_r(E)\mathrm{Re}[U_{SF}(E,R)] + N_i(E)\mathrm{Im}[U_{SF}(E,R)] + V_C(R)$$

DYP, Y.L. Ye, F.R. Xu, Phys. Rev. C 83, 064619 (2011)

The systematic single-folding α-potential

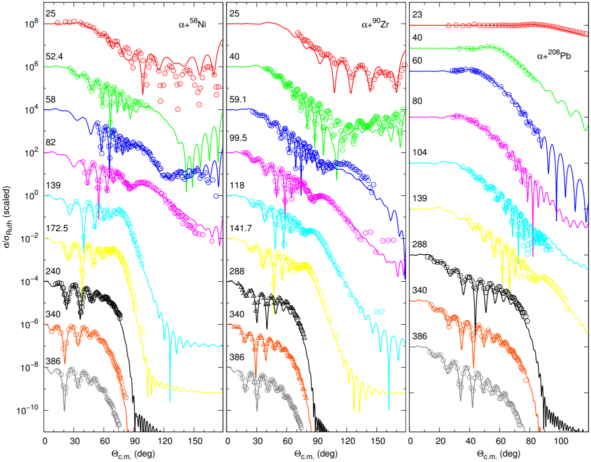
Energy dependence of N_r and N_i



DYP, Y.L. Ye, F.R. Xu, Phys. Rev. C 83, 064619 (2011)

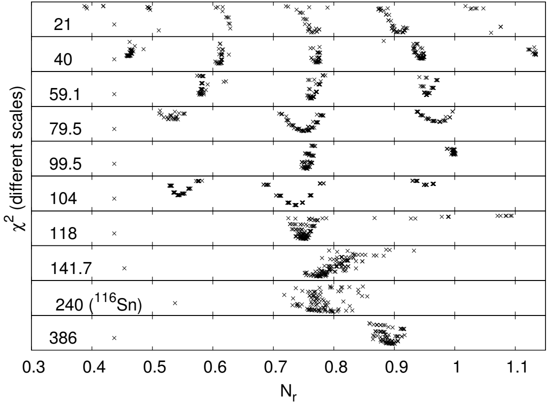
The systematic single-folding α-potential

Comparison with experimental data



Reduction of potential ambiguities

1. Discrete ambiguities



D.G. Perkin, A.M. Kobos, and J.R. Rook, NPA 245, 343 (1975), D.F. Jackson and R.C. Johnson, PLB 49, 249 (1974)

Reduction of potential ambiguities

1. Discrete ambiguities
   removed by selection of N_r families, guided by theoretical models

   D.G. Perkin, A.M. Kobos, and J.R. Rook, NPA 245, 343 (1975)

   D.F. Jackson and R.C. Johnson, PLB 49, 249 (1974)

2. continuum ambiguities
   a well-known one is VR_U^n =constant, in folding model R_U is uniquely determined by R_p, R_t and $R_{V_{NN}}$

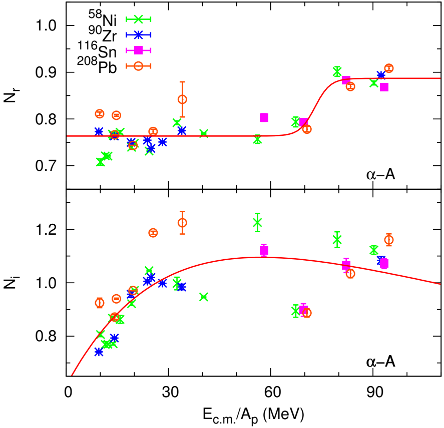
   See, e.g., G.R. Satchler, *Direct Nuclear reactions*, Chap.12

3. correlations of real and imaginary parts
   reduced in systematically fitting many sets of data

   See, e.g., L. Freindl *et al.*, Acta Phys. Pol. B11, 405 (1980)

Uncertainties in N_r and N_i

Energy dependence of N_r and N_i



$$\overline{\Delta N_r / N_r} = 0.04$$

$$\overline{\Delta N_i / N_i} = 0.08$$

The SkX interaction in HF calculations

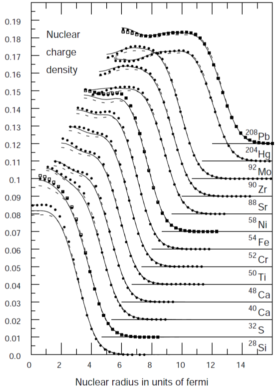
SkX was obtained by fitting:

- binding energies for ^{16,24}O, ^{34}Si, ^{40,48}Ca, ^{48,68}Ni, ^{88}Sr, ^{100,132}Sn and ^{208}Pb with "errors" ranging from 1.0 MeV for ^{16}O to 0.5 MeV for ^{208}Pb
- rms charge radii for ^{16}O, ^{40,48}Ca, ^{88}Sr and ^{208}Pb with "errors" ranging from 0.03 fm for ^{16}O to 0.01 fm for ^{208}Pb
- About 50 Single particle energies with "errors" ranging from 2.0 MeV for ^{16}O to 0.5 MeV for ^{208}Pb

B.A. Brown, PRC 58, 220 (1998), PREX Aug. 17 (2008)

The SkX interaction in HF calculations

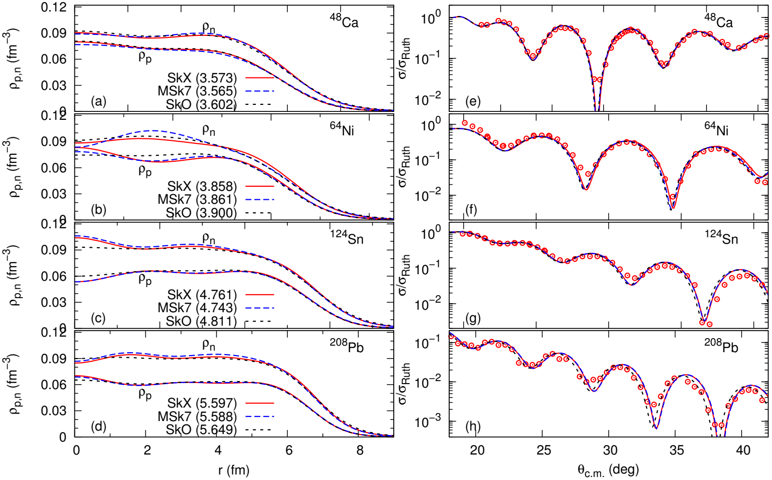
SkX in reproduction of charge density distributions



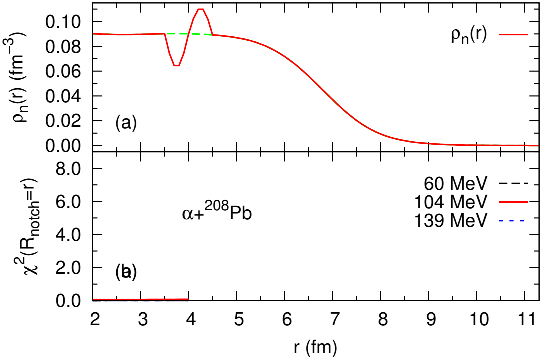
B.A. Brown, PREX Aug. 17 (2008)

Test of the systematic potential

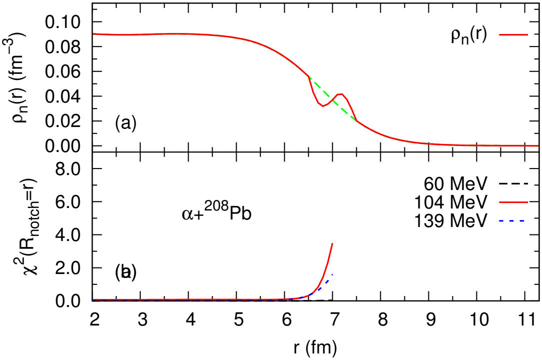
α elastic scattering at 104 MeV



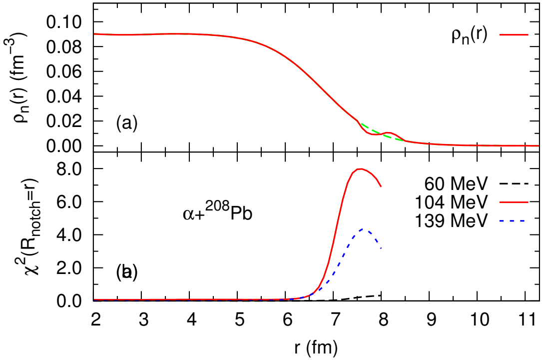
Probed region in ρ_n: a notch-test



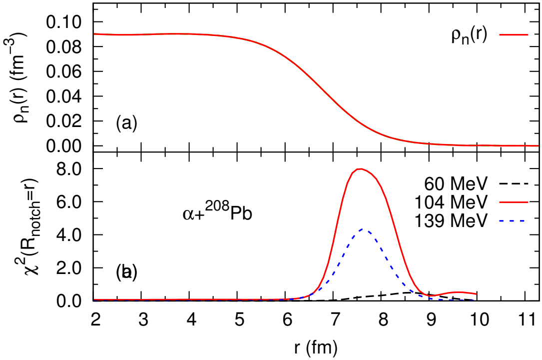
Probed region in ρ_n: a notch-test



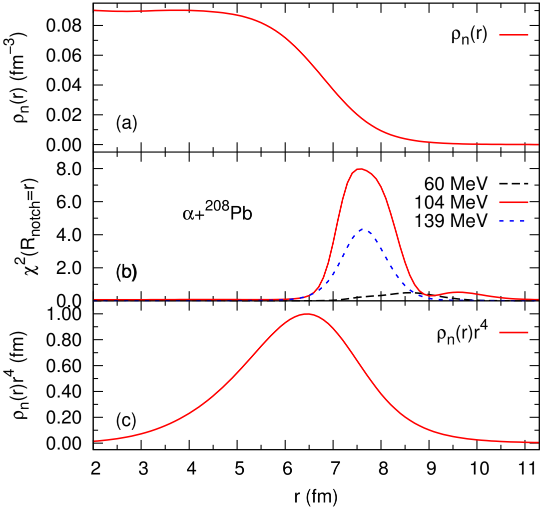
Probed region in ρ_n: a notch-test



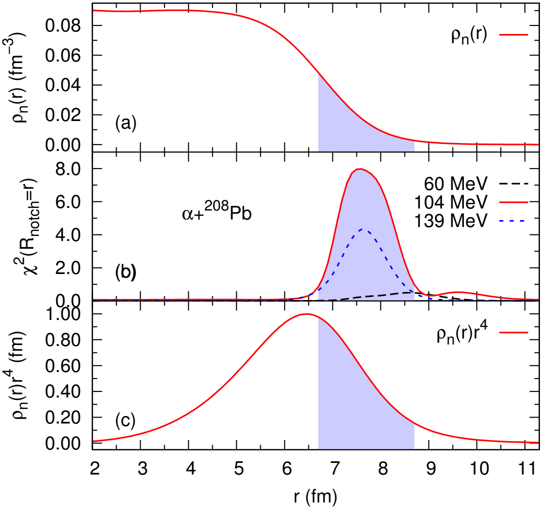
Probed region in ρ_n: a notch-test



Probed region in ρ_n: a notch-test

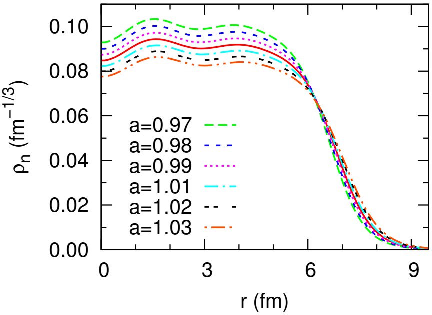


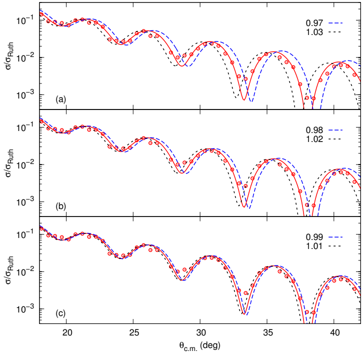
Probed region in ρ_n: a notch-test



Determination of R_n from α-scattering

Shift of scattering angls wrt $\Delta R_n/R_n$ (α+^{208}Pb 104 MeV)

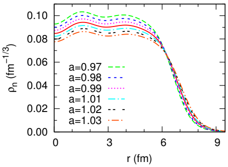


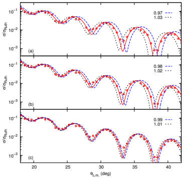


$$\rho(r) \to \rho(r) = \frac{1}{a^3}\rho_0(r/a)$$

Determination of R_n from α-scattering

Shift of scattering angls wrt $\Delta R_n/R_n$ (α+^{208}Pb 104 MeV)





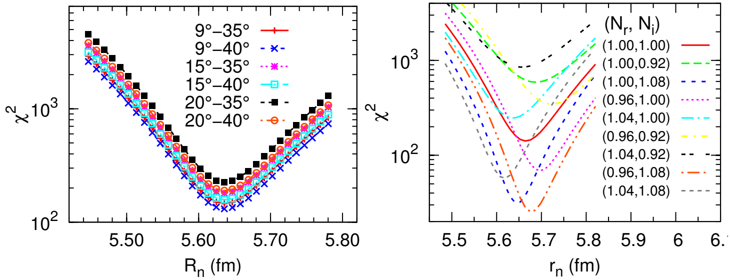
$$\rho(r) \to \rho(r) = \frac{1}{a^3}\rho_0(r/a)$$

Shift of scattering angles wrt E_{lab} (A MeV) with $\Delta R_n/R_n = 0.01$

E_{lab} (A MeV)	^{58}Ni	^{116}Sn	^{208}Pb
20	0.22	0.32	0.45
40	0.15	0.16	0.24
80	0.06	0.07	0.08

Determination of R_n from α-scattering

Determine R_n of ^{208}Pb with SkX at $E_\alpha = 139$ MeV

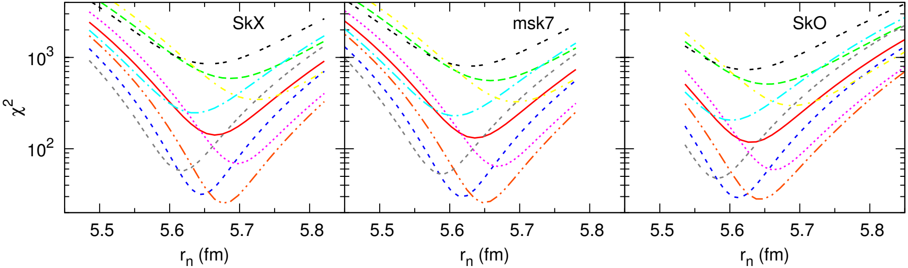


$$R_n = 5.661 \pm 0.024 \text{ fm}$$

$$\Delta r_{np} = 0.220 \pm 0.024 \text{ fm}$$

Determination of R_n from α-scattering

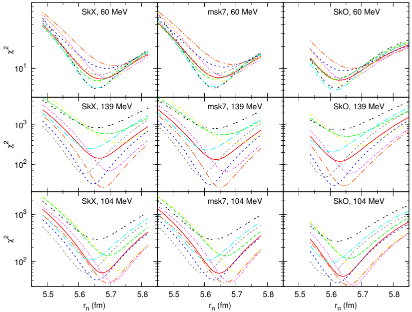
Determine R_n of ^{208}Pb with SkX, SkO and MSk7 at $E_\alpha = 139$ MeV

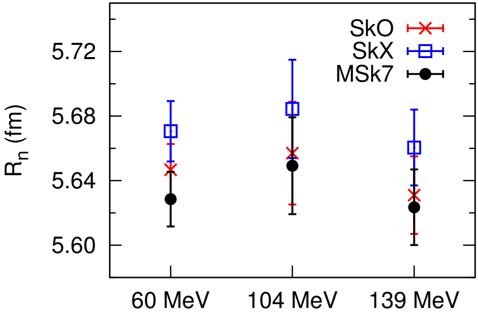


$$R_n = 5.638 \pm 0.020 \text{ fm}$$
$$\Delta r_{np} = 0.198 \pm 0.022 \text{ fm}$$

Determination of R_n from α-scattering

Determine R_n of ^{208}Pb at E_α =60, 104 and 139 MeV

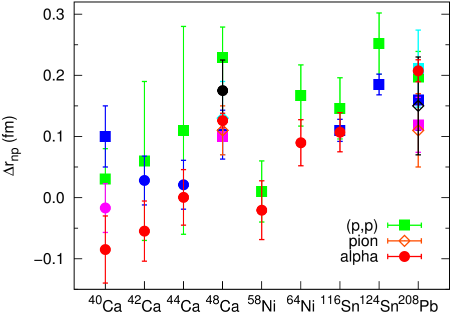




$$R_n = 5.647 \pm 0.019 \text{ fm}$$
$$\Delta r_{np} = 0.207 \pm 0.021 \text{ fm}$$

Results for ^{48}Ca, ^{64}Ni, ^{124}Sn, and ^{208}Pb

Neutron-skin thickness: a compilation



R.H. McCamis et al., PRC 33, 1624 (1984); C.J. Batty et al., Advances in Nuclear Physics, Vol. 19 (1989); E. Friedman, NPA 896, 46 (2012); H.J. Gils et al., PRC 29, 1295 (1984); L. Ray, PRC 19, 1855 (1979); B.C. Clark et al., PRC 67, 054605 (2003); S. Shlomo, Rep. Prog. Phys. 41, 957 (1978); S. Terashima and J. Zenihiro PhD thesis

The EoS parameters

The nuclear symmetry energy $E_{sym}(\rho)$ at nuclear density ρ can be expanded around the nuclear matter saturation density ρ_0 as

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 \qquad (1)$$

where L and K_{sym} are the slope and curvature of the nuclear symmetry energy at ρ_0, i.e.,

$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}|_{\rho=\rho_0} \qquad (2)$$

Lie-Wen Chen et al., Phys. Rev. C 72, 064309 (2005).

Constraints of R_n on EoS parameters

Correlation between Δr_{np} and Nuclear matter properties

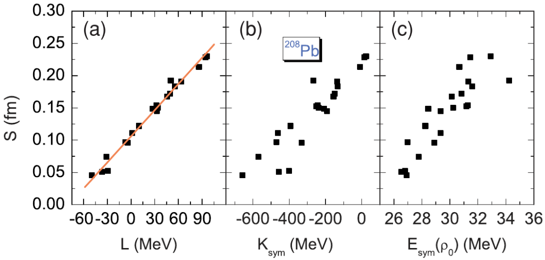
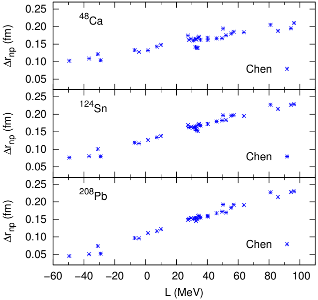


FIG. 2. (Color online) Neutron skin thickness S of ^{208}Pb as a function of (a) L, (b) $K_{\rm sym}$, and (c) $E_{\rm sym}(\rho_0)$ for 21 sets of Skyrme interaction parameters. The line in panel (a) represents a linear fit.

Lie-Wen Chen et al., PRC 72, 064309 (2005); B. Alex Brown, Phys. PRL 85, 5296 (2000); M. Centelles, et al., PRL 102, 122502 (2009).

Correlation between Δr_{np} and L

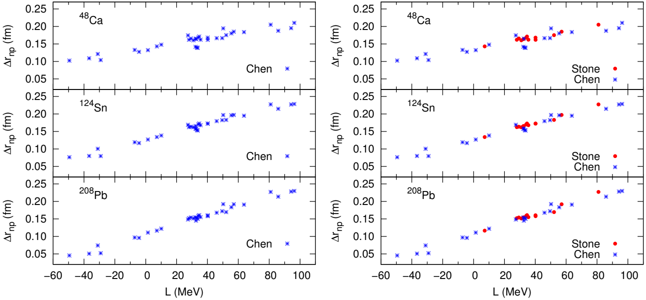
HF calculations with Skyrme parameters



Blue points: 21 sets of parameters used Lie-Wen Chen et al., PRC 72, 064309 (2005);

Correlation between Δr_{np} and L

HF calculations with Skyrme parameters



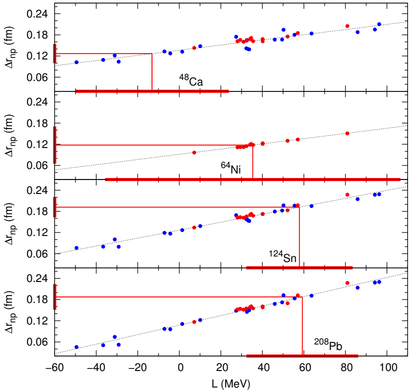
Blue points: 21 sets of parameters used Lie-Wen Chen et al., PRC 72, 064309 (2005);

Red points: 13 sets of parameters in P. Klüpfel et al., PRC 79, 034310 (2009);

The correlations seems not depend on the choice of Skyrme parameters.

Δr_{np} constraints on the L-value

Constraints on L-value from Δr_{np} of ^{48}Ca, ^{64}Ni, ^{124}Sn and ^{208}Pb



Average Δr_{np} of existing resuls weighted with their error bars

Δr_{np} constraints on the L-value

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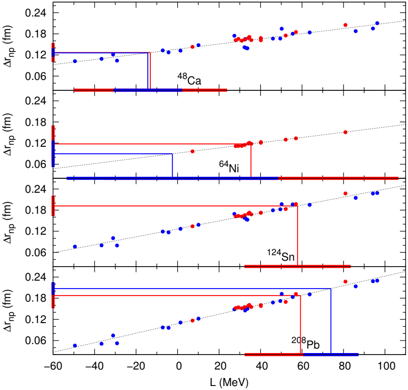
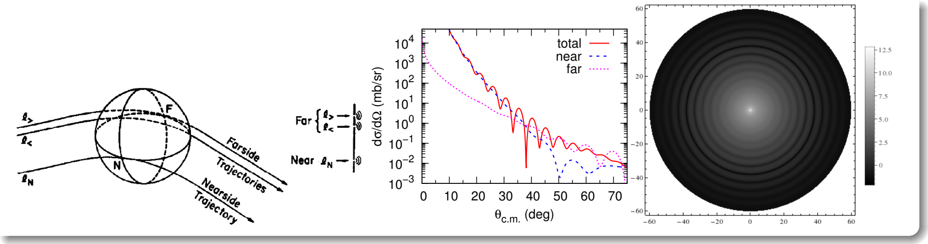


Average Δr_{np} of existing resuls weighted with their error bars

resuls of the present work

Summary



$$\Delta\theta \approx \frac{\pi}{kR_{SA}}$$

1. Angular distribution $\Leftrightarrow$ Strong absorption radius R_{SA}
2. $R_{SA} \Leftrightarrow$ radius of the optical potential R_U
3. $R_U \Leftrightarrow$ neutron density distribution ρ_n with systematic folding potential
4. $\rho_n \Leftrightarrow$ neutron radius R_n

thanks to

Collaborator: Prof. Jirina Stone

Prof. P.-G. Reinhard for providing the HF code and instructions

Prof. LieWen Chen for providing his HF results and

Prof. Peter Mohr for providing some elastic α scattering data