Neutron Skins with α-Clusters

Stefan Typel

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt
Nuclear Astrophysics Virtual Institute

Hirschegg 2015

Nuclear Structure and Reactions: Weak, Strange and Exotic

International Workshop XLIII on Gross Properties of Nuclei and Nuclear Reactions

Outline

- **Introduction**
  Neutron Skins and Neutron Matter Equation of State, Density Dependence of Symmetry Energy, Correlations in Low-Density Nuclear Matter
- **Generalized Relativistic Density Functional**
  Details of gRDF Model, Effective Interaction
- **α-Clusters on the Surface of Nuclei**
  Application of gRDF Model, Nuclei with α-Clusters
- **Experimental Test**
  Quasi-Free (p,pα) Knockout Reactions, Kinematics, Cross Sections
- **Conclusions**

Details:

S. Typel, Phys. Rev. C 89 (2014) 064321

S. Typel, H.H. Wolter, G. Röpke, D. Blaschke, Eur. Phys. J. A 50 (2014) 17

M.D. Voskresenskaya, S. Typel, Nucl. Phys. A 887 (2012) 42

S. Typel, G. Röpke, T. Klähn, D. Blaschke, H.H. Wolter, Phys. Rev. C 81 (2010) 015803

Introduction

Neutron Skins and Neutron Matter Equation of State

- neutron-rich nuclei $\Rightarrow$ development of neutron skin with thickness:

$$\Delta r_{np} = S = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

Neutron Skins and Neutron Matter Equation of State

- neutron-rich nuclei ⇒ development of neutron skin with thickness:

$$\Delta r_{np} = S = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

- charge radii of nuclei well-known from electron scattering experiments, isotope shifts, etc. (see, e.g., I. Angeli et al., ADNDT 99 (2013) 69)

Neutron Skins and Neutron Matter Equation of State

- neutron-rich nuclei ⇒ development of neutron skin with thickness:

$$\Delta r_{np} = S = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

- charge radii of nuclei well-known from electron scattering experiments, isotope shifts, etc. (see, e.g., I. Angeli et al., ADNDT 99 (2013) 69)
- neutron matter radii less precisely known, suggested experimental approach: parity violation in electron scattering ⇒ PREX@Jefferson Lab with ^{208}Pb target (C. J. Horowitz et al., Phys. Rev. C 63 (2001) 025501)

Neutron Skins and Neutron Matter Equation of State

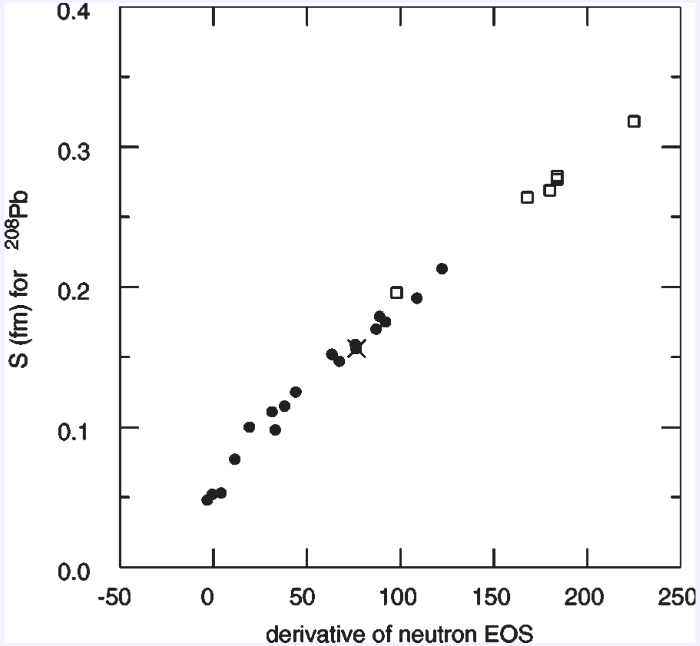
- neutron-rich nuclei ⇒ development of neutron skin with thickness:

$$\Delta r_{np} = S = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

- charge radii of nuclei well-known from electron scattering experiments, isotope shifts, etc. (see, e.g., I. Angeli et al., ADNDT 99 (2013) 69)
- neutron matter radii less precisely known, suggested experimental approach: parity violation in electron scattering ⇒ PREX@Jefferson Lab with ^{208}Pb target (C. J. Horowitz et al., Phys. Rev. C 63 (2001) 025501)
- observation of B.A. Brown: strong correlation of neutron skin thickness with derivative of neutron matter equation of state (EoS)

$$\left.\frac{d(E/A)}{dn}\right|_{n=n_0} = \frac{p_0}{n_0^2}$$ at density $n_0 = 0.1$ fm^{-3}

for 18 Skyrme Hartree-Fock parameter sets (Phys. Rev. Lett. 85 (2000) 5296)



Neutron Skins and Neutron Matter Equation of State

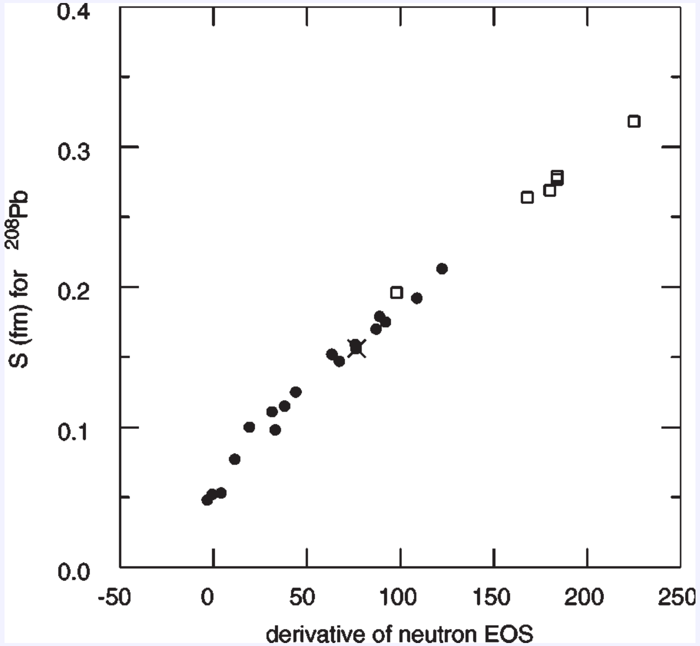
- neutron-rich nuclei ⇒ development of neutron skin with thickness:

$$\Delta r_{np} = S = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

- charge radii of nuclei well-known from electron scattering experiments, isotope shifts, etc. (see, e.g., I. Angeli et al., ADNDT 99 (2013) 69)
- neutron matter radii less precisely known, suggested experimental approach: parity violation in electron scattering ⇒ PREX@Jefferson Lab with ^{208}Pb target (C. J. Horowitz et al., Phys. Rev. C 63 (2001) 025501)
- observation of B.A. Brown: strong correlation of neutron skin thickness with derivative of neutron matter equation of state (EoS)

$$\left.\frac{d(E/A)}{dn}\right|_{n=n_0} = \frac{p_0}{n_0^2}$$ at density $n_0 = 0.1\ \mathrm{fm}^{-3}$

for 18 Skyrme Hartree-Fock parameter sets (Phys. Rev. Lett. 85 (2000) 5296)
- extension to relativistic mean-field models (S. Typel and B. A. Brown, Phys. Rev. C 64 (2001) 027302)



Neutron Skins and Symmetry Energy

- equivalent correlation of neutron skin thickness with slope of nuclear symmetry energy found in investigation guided by principles of effective field theory
  (R. J. Furnstahl, Nucl. Phys. 706 (2002) 85)

Neutron Skins and Symmetry Energy

- equivalent correlation of neutron skin thickness with slope of nuclear symmetry energy found in investigation guided by principles of effective field theory
  (R. J. Furnstahl, Nucl. Phys. 706 (2002) 85)
- expansion of energy per nucleon in nuclear matter

$$\frac{E}{A}(n,\beta) = E_0(n) + E_s(n)\beta^2 + \ldots \qquad n = n_n + n_p \qquad \beta = (n_n - n_p)/n$$

  with symmetry energy $E_s(n)$

Neutron Skins and Symmetry Energy

- equivalent correlation of neutron skin thickness with slope of nuclear symmetry energy found in investigation guided by principles of effective field theory
  (R. J. Furnstahl, Nucl. Phys. 706 (2002) 85)
- expansion of energy per nucleon in nuclear matter

  $$\frac{E}{A}(n,\beta) = E_0(n) + E_s(n)\beta^2 + \ldots \qquad n = n_n + n_p \qquad \beta = (n_n - n_p)/n$$

  with symmetry energy $E_s(n)$
- essential parameters:
  - symmetry energy at saturation

    $$J = E_s(n_{\text{sat}})$$

  - slope coefficient

    $$L = 3n\frac{d}{dn}E_s\Big|_{n=n_{\text{sat}}}$$

Neutron Skins and Symmetry Energy

- equivalent correlation of neutron skin thickness with slope of nuclear symmetry energy found in investigation guided by principles of effective field theory
  (R. J. Furnstahl, Nucl. Phys. 706 (2002) 85)
- expansion of energy per nucleon in nuclear matter

$$\frac{E}{A}(n,\beta) = E_0(n) + E_s(n)\beta^2 + \ldots \qquad n = n_n + n_p \qquad \beta = (n_n - n_p)/n$$

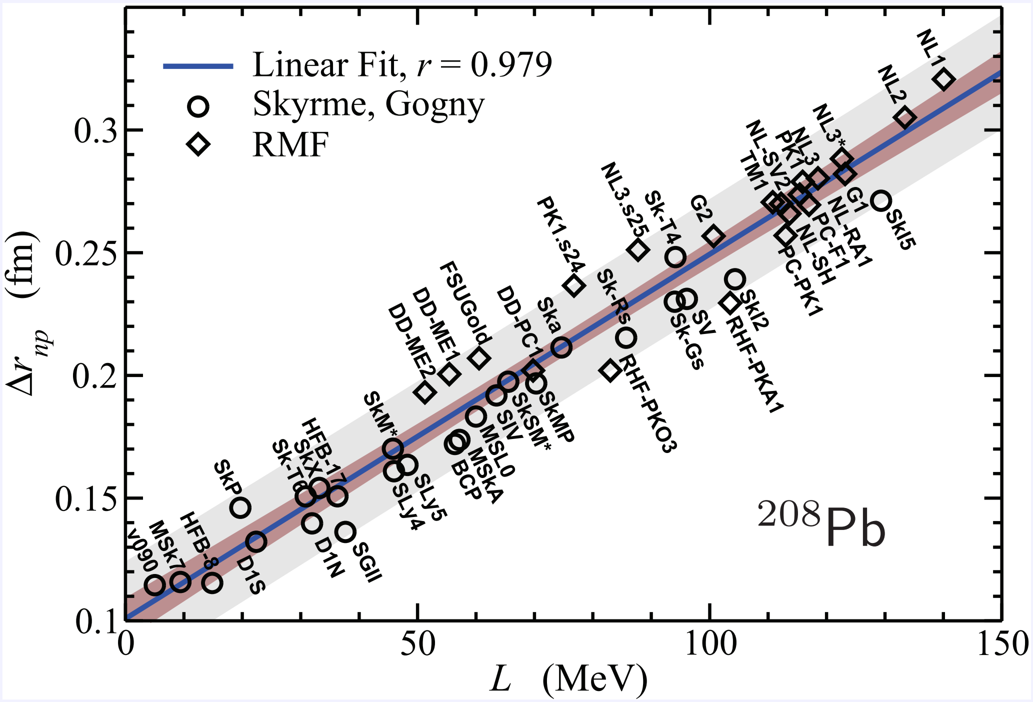
  with symmetry energy $E_s(n)$
- essential parameters:
  - symmetry energy at saturation

    $$J = E_s(n_{\rm sat})$$

  - slope coefficient

    $$L = 3n\frac{d}{dn}E_s\Big|_{n=n_{\rm sat}}$$

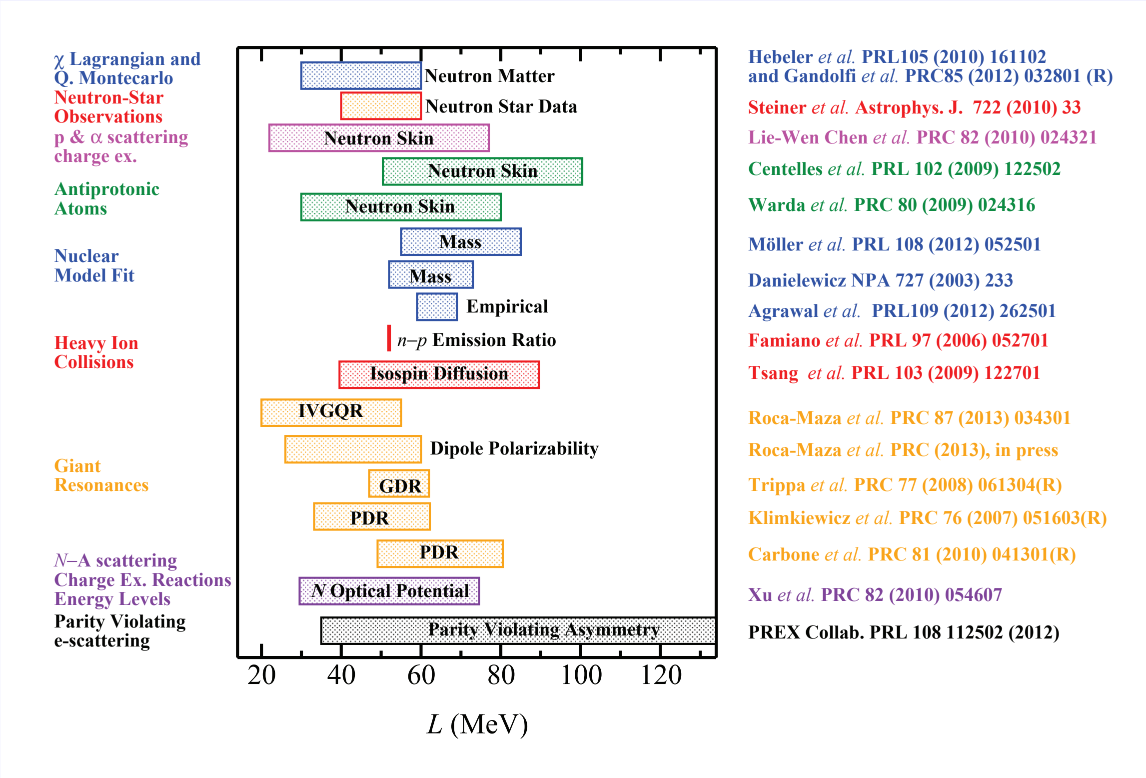
- determine L from experimental measurement of Δr_{np}
  $\Rightarrow$ constraint for neutron matter EoS



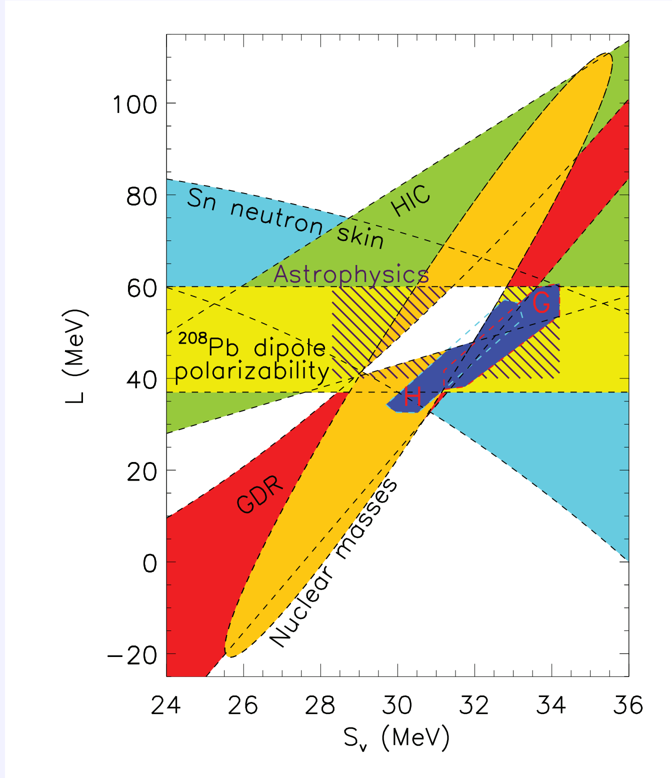
(X. Viñas et al., Eur. Phys. J. A50 (2014) 27)

Symmetry Energy Parameters

- many attempts to determine symmetry energy $J = S_0 = S_v$ and slope coefficient L experimentally



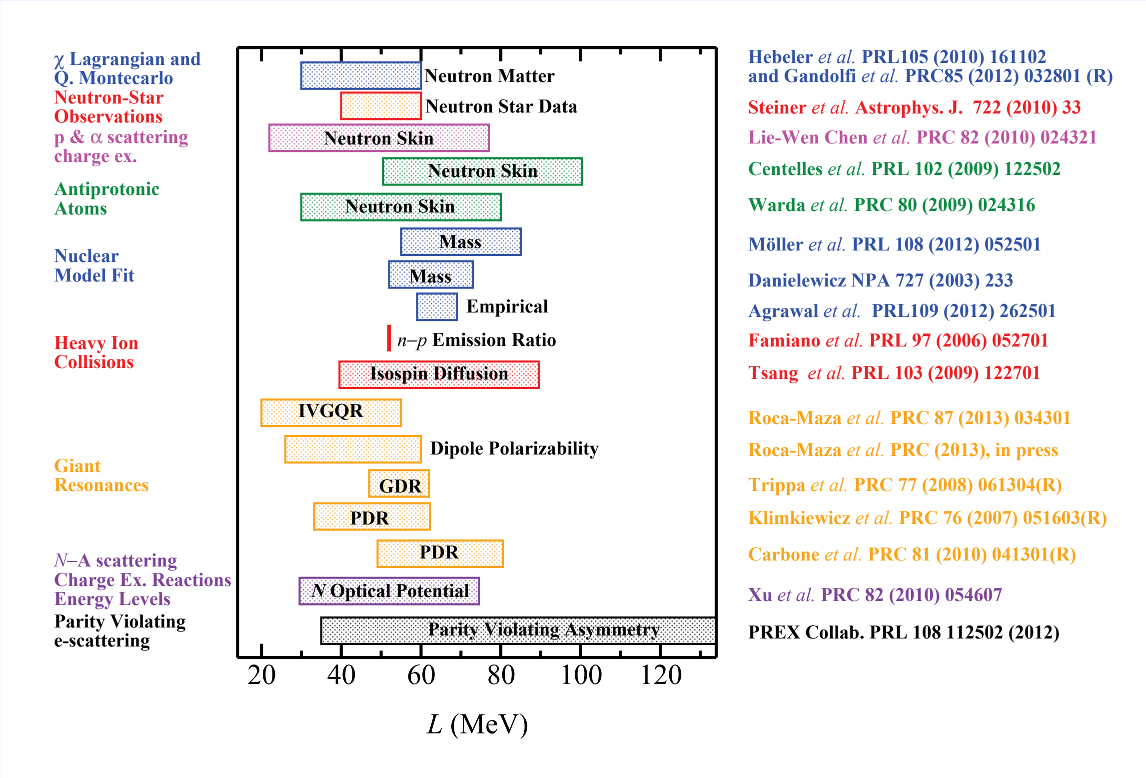
(X. Viñas et al., Eur. Phys. J. A50 (2014) 27)



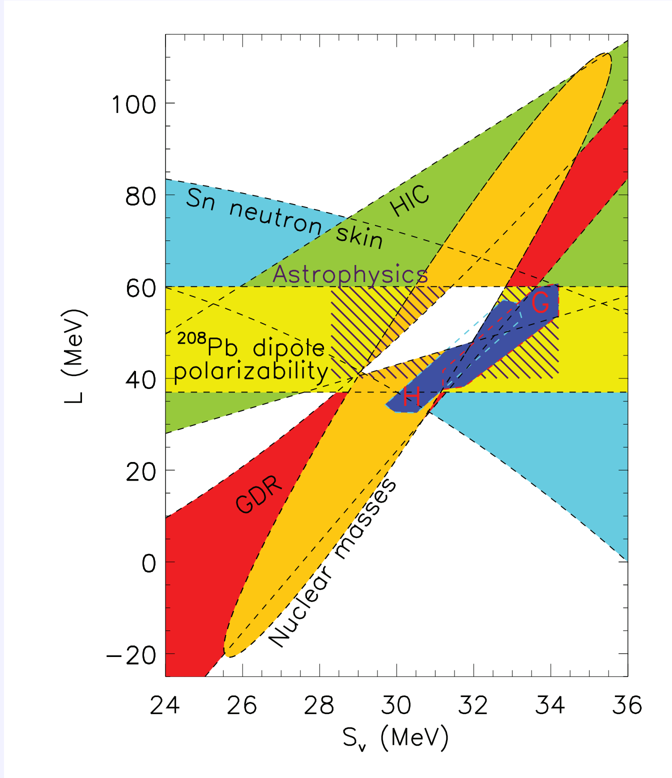
(J.M. Lattimer, Y. Lim, ApJ. 771 (2013) 51)

Symmetry Energy Parameters

- many attempts to determine symmetry energy $J = S_0 = S_v$ and slope coefficient L experimentally



(X. Viñas et al., Eur. Phys. J. A50 (2014) 27)



(J.M. Lattimer, Y. Lim, ApJ. 771 (2013) 51)

- measurement of neutron skin thickness (e.g. PREX), correlation with L from mean-field calculations: effects of clustering correlations on surface of nuclei?

Correlations in Low-Density Nuclear Matter

- surface of nuclei: densities much below saturation density
  - nucleon-nucleon pairing correlations essential,
    usually considered in nuclear structure calculations

Correlations in Low-Density Nuclear Matter

- surface of nuclei: densities much below saturation density
  - nucleon-nucleon pairing correlations essential,
    usually considered in nuclear structure calculations
- equation of state of nuclear matter at very low densities:
  - many-body correlations $\Rightarrow$ clusters/nuclei as new degrees of freedom
  - model-independent benchmark: virial equation of state
    (see, e.g., C. J. Horowitz, A. Schwenk, Nucl. Phys. A 776 (2006) 55)

Correlations in Low-Density Nuclear Matter

- surface of nuclei: densities much below saturation density
  - nucleon-nucleon pairing correlations essential, usually considered in nuclear structure calculations
- equation of state of nuclear matter at very low densities:
  - many-body correlations ⇒ clusters/nuclei as new degrees of freedom
  - model-independent benchmark: virial equation of state (see, e.g., C. J. Horowitz, A. Schwenk, Nucl. Phys. A 776 (2006) 55)
- incorporate clusters as explicit degrees of freedom in nuclear structure calculations
  - adaption of generalized relativistic density functional (gRDF) approach for EoS of nuclear and stellar matter

Correlations in Low-Density Nuclear Matter

- surface of nuclei: densities much below saturation density
  - nucleon-nucleon pairing correlations essential, usually considered in nuclear structure calculations
- equation of state of nuclear matter at very low densities:
  - many-body correlations $\Rightarrow$ clusters/nuclei as new degrees of freedom
  - model-independent benchmark: virial equation of state (see, e.g., C. J. Horowitz, A. Schwenk, Nucl. Phys. A 776 (2006) 55)
- incorporate clusters as explicit degrees of freedom in nuclear structure calculations
  - adaption of generalized relativistic density functional (gRDF) approach for EoS of nuclear and stellar matter
  - nucleons and clusters treated as quasiparticles with scalar potential S_i and vector potential V_i
  - interaction by meson exchange, well calibrated parametrisation

Correlations in Low-Density Nuclear Matter

- surface of nuclei: densities much below saturation density
  - nucleon-nucleon pairing correlations essential, usually considered in nuclear structure calculations
- equation of state of nuclear matter at very low densities:
  - many-body correlations $\Rightarrow$ clusters/nuclei as new degrees of freedom
  - model-independent benchmark: virial equation of state (see, e.g., C. J. Horowitz, A. Schwenk, Nucl. Phys. A 776 (2006) 55)
- incorporate clusters as explicit degrees of freedom in nuclear structure calculations
  - adaption of generalized relativistic density functional (gRDF) approach for EoS of nuclear and stellar matter
  - nucleons and clusters treated as quasiparticles with scalar potential S_i and vector potential V_i
  - interaction by meson exchange, well calibrated parametrisation
  - study dependence of results on neutron excess and on isovector part of interaction
  - experimental test of predictions?

Generalized Relativistic Density Functional

Generalized Relativistic Density Functional

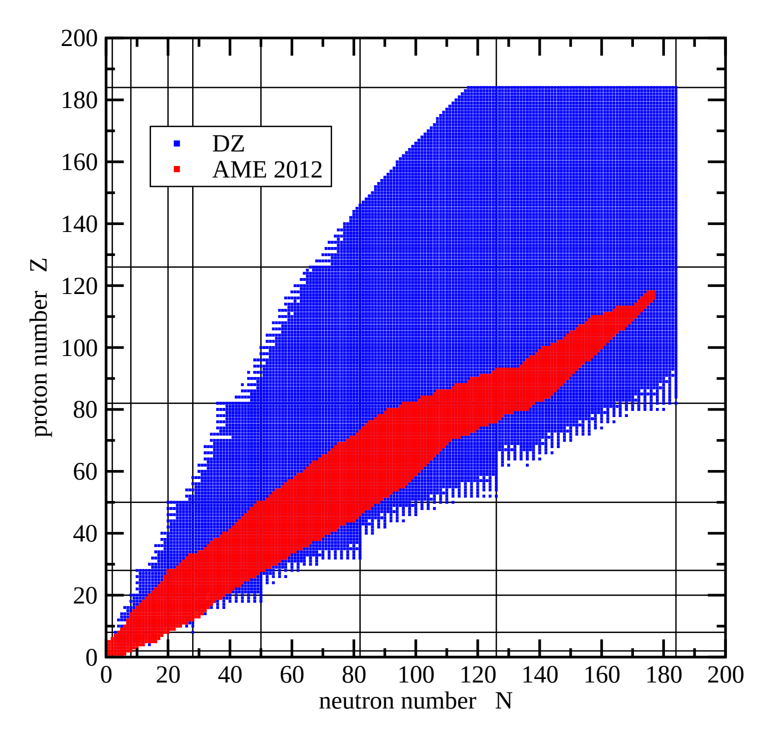
- **grand canonical approach**
  - extension of relativistic mean-field models
    with density-dependent meson-nucleon couplings
    $\Rightarrow$ grand canonical potential density $\omega(T, \{\mu_i\})$

Generalized Relativistic Density Functional

- **grand canonical approach**
  - extension of relativistic mean-field models
    with density-dependent meson-nucleon couplings
    $\Rightarrow$ grand canonical potential density $\omega(T, \{\mu_i\})$
  - chemical equilibrium $\Rightarrow$ chemical potentials μ_i
    of particles not all independent

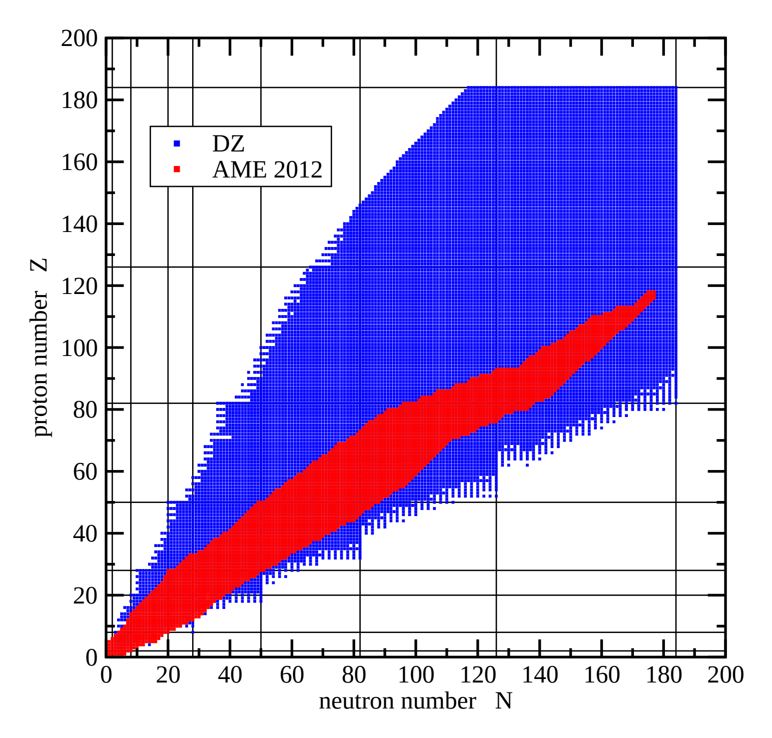
Generalized Relativistic Density Functional

- **grand canonical approach**
  - ◦ extension of relativistic mean-field models with density-dependent meson-nucleon couplings
    $\Rightarrow$ grand canonical potential density $\omega(T, \{\mu_i\})$
  - ◦ chemical equilibrium $\Rightarrow$ chemical potentials μ_i of particles not all independent
- selected **model features**
  - ◦ extended set of constituents: nucleons, light clusters (^{2}H, ^{3}H, ^{3}He, ^{4}He) and heavy nuclei
    - – experimental binding energies: AME 2012
      (M. Wang et al., Chinese Phys. 36 (2012) 1603)
    - – extension: DZ10 predictions
      (J. Duflo, A.P. Zuker, Phys. Rev. C 52 (1995) R23)



Generalized Relativistic Density Functional

- **grand canonical approach**
  - ◦ extension of relativistic mean-field models with density-dependent meson-nucleon couplings
    $\Rightarrow$ grand canonical potential density $\omega(T, \{\mu_i\})$
  - ◦ chemical equilibrium $\Rightarrow$ chemical potentials μ_i of particles not all independent



- selected **model features**
  - ◦ extended set of constituents: nucleons, light clusters (^{2}H, ^{3}H, ^{3}He, ^{4}He) and heavy nuclei
    - – experimental binding energies: AME 2012
      (M. Wang et al., Chinese Phys. 36 (2012) 1603)
    - – extension: DZ10 predictions
      (J. Duflo, A.P. Zuker, Phys. Rev. C 52 (1995) R23)
  - ◦ medium modifications of composite particles (mass shifts, internal excitations)
  - ◦ scattering correlations considered (essential for correct low-density limit)
  - ◦ thermodynamically consistent approach ($\Rightarrow$ "rearrangement" contributions)
  - ◦ model parameters from fit to properties of finite nuclei

Effective Interaction

exchange of

- Lorentz scalar mesons $m \in \mathcal{S} = \{\sigma, \delta, \sigma_*, \ldots\}$
- Lorentz vector mesons $m \in \mathcal{V} = \{\omega, \rho, \phi, \ldots\}$

Effective Interaction

exchange of

- Lorentz scalar mesons $m \in \mathcal{S} = \{\sigma, \delta, \sigma_*, \ldots\}$
- Lorentz vector mesons $m \in \mathcal{V} = \{\omega, \rho, \phi, \ldots\}$

◦ represented by (classical) fields A_m with mass m_m

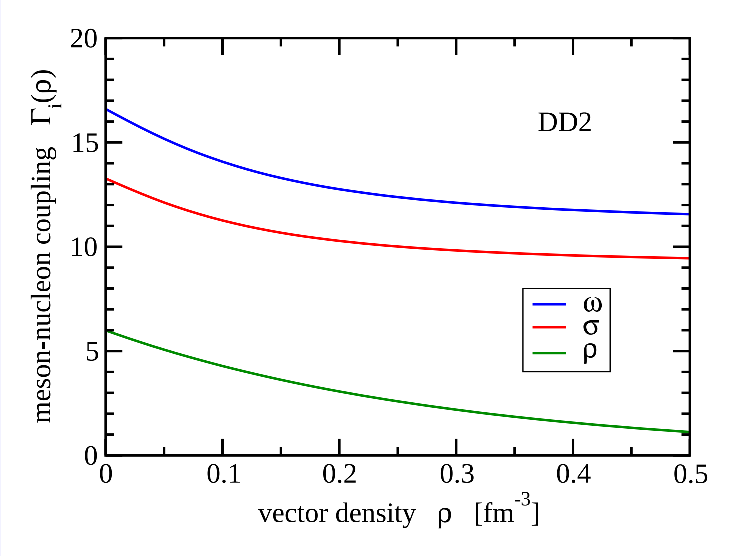
◦ coupling to constituents: $\Gamma_{im} = g_{im}\Gamma_m$

– scaling factors g_{im}

– density dependent $\Gamma_m = \Gamma_m(\varrho)$

$\varrho = \sum_i (N_i + Z_i) n_i$ with parametrization DD2

(S. Typel et al., Phys. Rev. C 81 (2010) 015803)



nuclear matter parameters

$n_{\rm sat} = 0.149$ fm^{-3}

$a_V = 16.02$ MeV

$K = 242.7$ MeV

$J = 31.67$ MeV

$L = 55.04$ MeV

Effective Interaction

exchange of

- Lorentz scalar mesons $m \in \mathcal{S} = \{\sigma, \delta, \sigma_*, \ldots\}$
- Lorentz vector mesons $m \in \mathcal{V} = \{\omega, \rho, \phi, \ldots\}$

○ represented by (classical) fields A_m with mass m_m

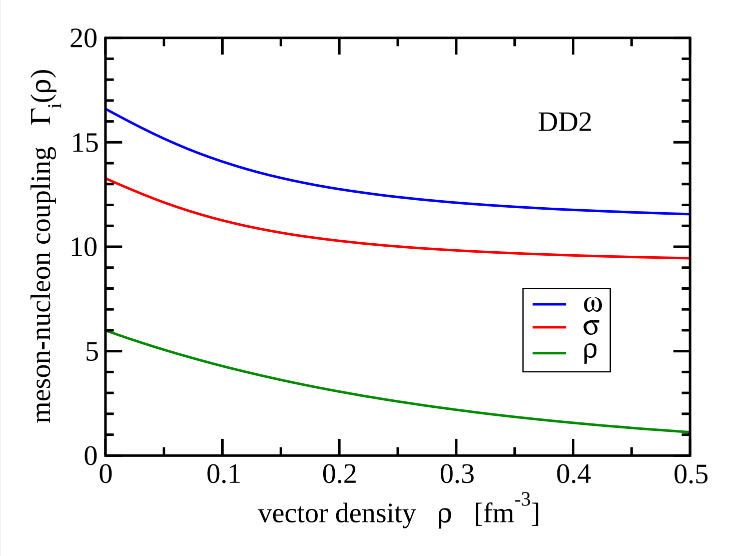
○ coupling to constituents: $\Gamma_{im} = g_{im}\Gamma_m$

– scaling factors g_{im}

– density dependent $\Gamma_m = \Gamma_m(\varrho)$

$\varrho = \sum_i (N_i + Z_i) n_i$ with parametrization DD2

(S. Typel et al., Phys. Rev. C 81 (2010) 015803)



○ scalar potential $S_i = \sum_{m \in \mathcal{S}} \Gamma_{im} A_m - \Delta m_i$

with medium-dependent mass shift $\Delta m_i(T, n_j)$

– from microscopic calculations

– mainly action of Pauli principle

$\Rightarrow$ dissolution of clusters at high densities

nuclear matter parameters

$n_{\text{sat}} = 0.149$ fm^{-3}

$a_V = 16.02$ MeV

$K = 242.7$ MeV

$J = 31.67$ MeV

$L = 55.04$ MeV

Effective Interaction

exchange of

- Lorentz scalar mesons $m \in \mathcal{S} = \{\sigma, \delta, \sigma_*, \ldots\}$
- Lorentz vector mesons $m \in \mathcal{V} = \{\omega, \rho, \phi, \ldots\}$

◦ represented by (classical) fields A_m with mass m_m

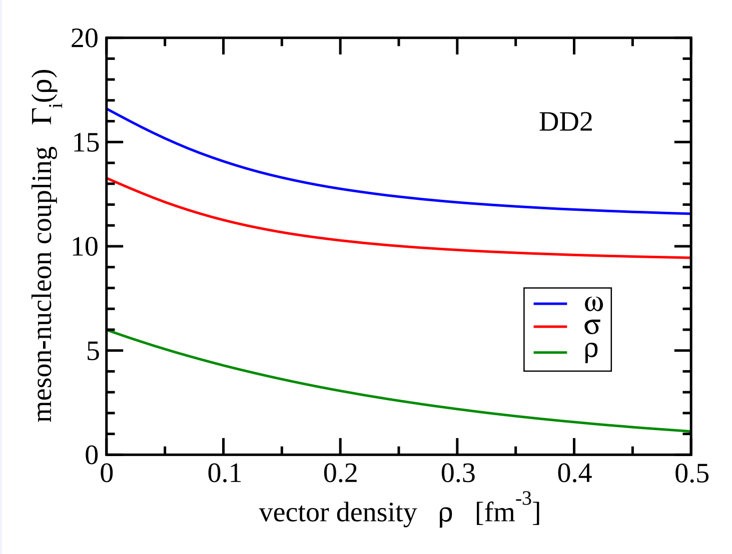
◦ coupling to constituents: $\Gamma_{im} = g_{im}\Gamma_m$

– scaling factors g_{im}

– density dependent $\Gamma_m = \Gamma_m(\varrho)$

$\varrho = \sum_i (N_i + Z_i) n_i$ with parametrization DD2

(S. Typel et al., Phys. Rev. C 81 (2010) 015803)



◦ scalar potential $S_i = \sum_{m\in\mathcal{S}} \Gamma_{im} A_m - \Delta m_i$

with medium-dependent mass shift $\Delta m_i(T, n_j)$

– from microscopic calculations

– mainly action of Pauli principle

$\Rightarrow$ dissolution of clusters at high densities

◦ vector potential $V_i = \sum_{m\in\mathcal{V}} \Gamma_{im} A_m + V_i^{(\mathrm{r})}$

with "rearrangement" contribution $V_i^{(r)}$

nuclear matter parameters

$n_{\mathrm{sat}} = 0.149$ fm^{-3}

$a_V = 16.02$ MeV

$K = 242.7$ MeV

$J = 31.67$ MeV

$L = 55.04$ MeV

Effective Interaction

exchange of

- Lorentz scalar mesons $m \in \mathcal{S} = \{\sigma, \delta, \sigma_*, \ldots\}$
- Lorentz vector mesons $m \in \mathcal{V} = \{\omega, \rho, \phi, \ldots\}$

∘ represented by (classical) fields A_m with mass m_m

∘ coupling to constituents: $\Gamma_{im} = g_{im}\Gamma_m$

– scaling factors g_{im}

– density dependent $\Gamma_m = \Gamma_m(\varrho)$

$\varrho = \sum_i (N_i + Z_i) n_i$ with parametrization DD2

(S. Typel et al., Phys. Rev. C 81 (2010) 015803)

∘ scalar potential $S_i = \sum_{m \in \mathcal{S}} \Gamma_{im} A_m - \Delta m_i$

with medium-dependent mass shift $\Delta m_i(T, n_j)$

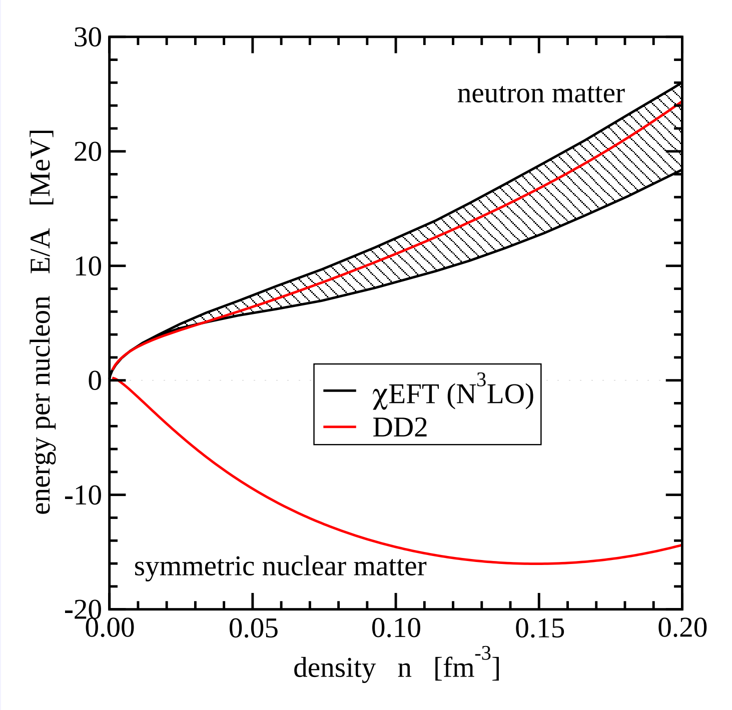
– from microscopic calculations

– mainly action of Pauli principle

⇒ dissolution of clusters at high densities

∘ vector potential $V_i = \sum_{m \in \mathcal{V}} \Gamma_{im} A_m + V_i^{(\mathrm{r})}$

with "rearrangement" contribution $V_i^{(r)}$



χEFT(N^{3}LO):

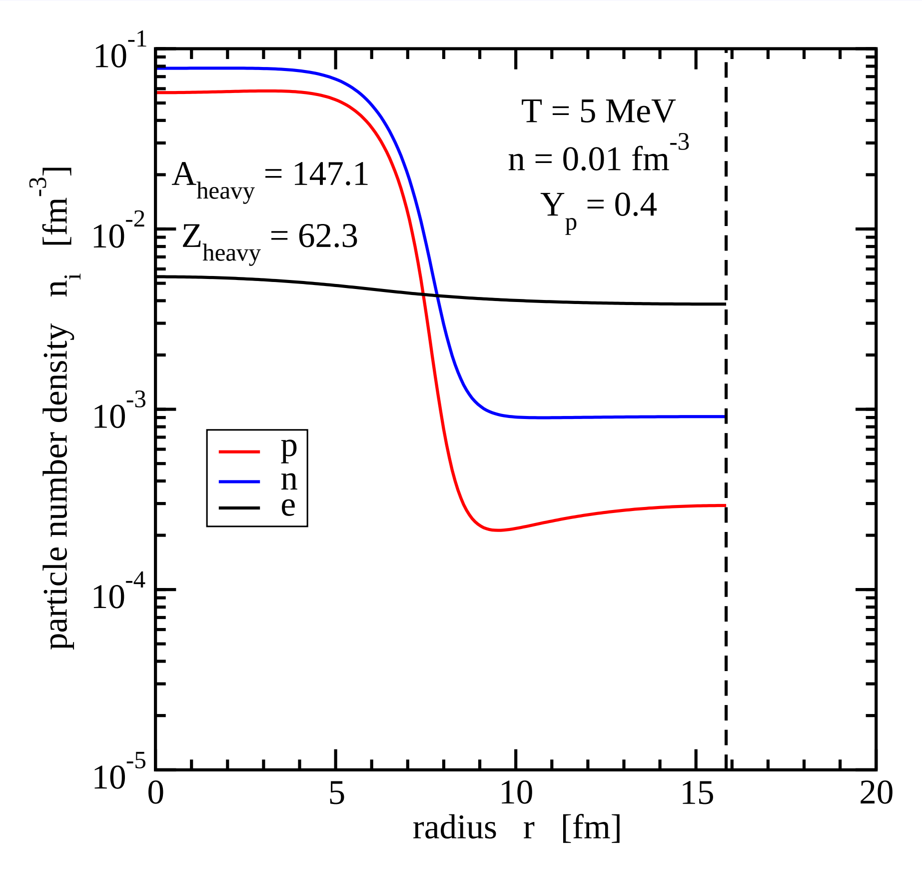
I. Tews et al., Phys. Rev. Lett 110 (2013) 032504

T. Krüger et al., Phys. Rev. C 88 (2013) 025802

α-Clusters on the Surface of Nuclei

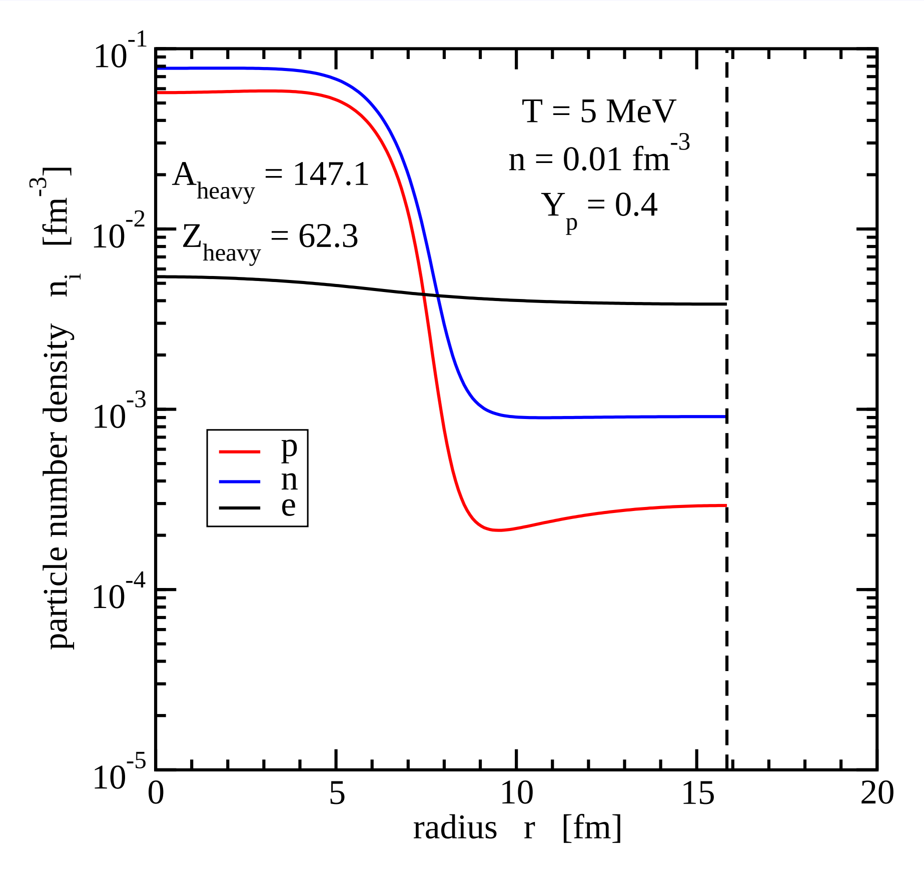
Application of gRDF Model

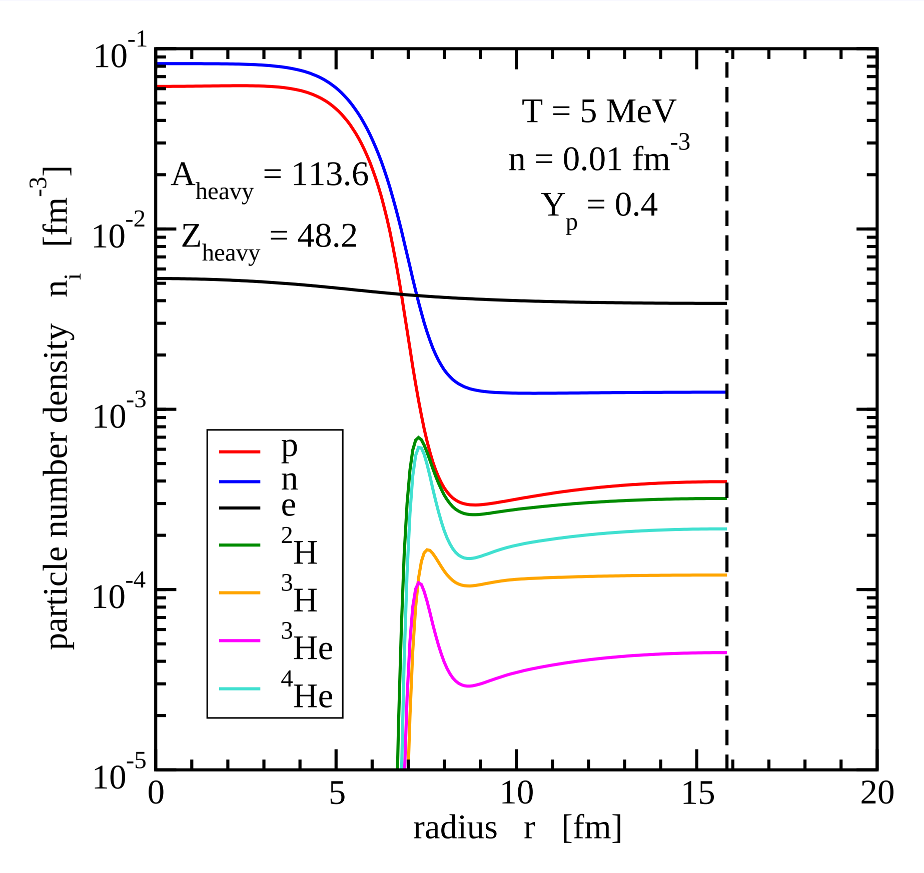
- finite temperature gRDF calculations in spherical Wigner-Seitz cell, extended Thomas-Fermi approximation without light clusters



Application of gRDF Model

- finite temperature gRDF calculations in spherical Wigner-Seitz cell, extended Thomas-Fermi approximation without and with light clusters
  $\Rightarrow$ enhanced cluster probability at surface of heavy nuclei, effects for **heavy nuclei in vacuum at zero temperature**?





Application of gRDF Model

- finite temperature gRDF calculations in spherical Wigner-Seitz cell, extended Thomas-Fermi approximation
- zero temperature: only α-particles relevant
  $\Rightarrow$ density distribution from ground-state wave function (WKB approximation)

Application of gRDF Model

- finite temperature gRDF calculations in spherical Wigner-Seitz cell, extended Thomas-Fermi approximation
- zero temperature: only α-particles relevant
  $\Rightarrow$ density distribution from ground-state wave function (WKB approximation)
- variation with neutron excess of nuclei $\Rightarrow$ chain of Sn nuclei

Application of gRDF Model

- finite temperature gRDF calculations in spherical Wigner-Seitz cell, extended Thomas-Fermi approximation
- zero temperature: only α-particles relevant
  $\Rightarrow$ density distribution from ground-state wave function (WKB approximation)
- variation with neutron excess of nuclei $\Rightarrow$ chain of Sn nuclei
- variation of isovector interaction
  $\Rightarrow$ modified parametrizations, ^{208}Pb nucleus

parametrization	symmetry energy J [MeV]	slope coefficient L [MeV]	ρ-meson coupling $\Gamma_\rho(n_{\text{ref}})$	ρ-meson parameter a_ρ
$DD2^{+++}$	35.34	100.00	4.109251	0.063577
$DD2^{++}$	34.12	85.00	3.966652	0.193151
$DD2^{+}$	32.98	70.00	3.806504	0.342181
DD2	31.67	55.04	3.626940	0.518903
$DD2^{-}$	30.09	40.00	3.398486	0.742082
$DD2^{--}$	28.22	25.00	3.105994	1.053251

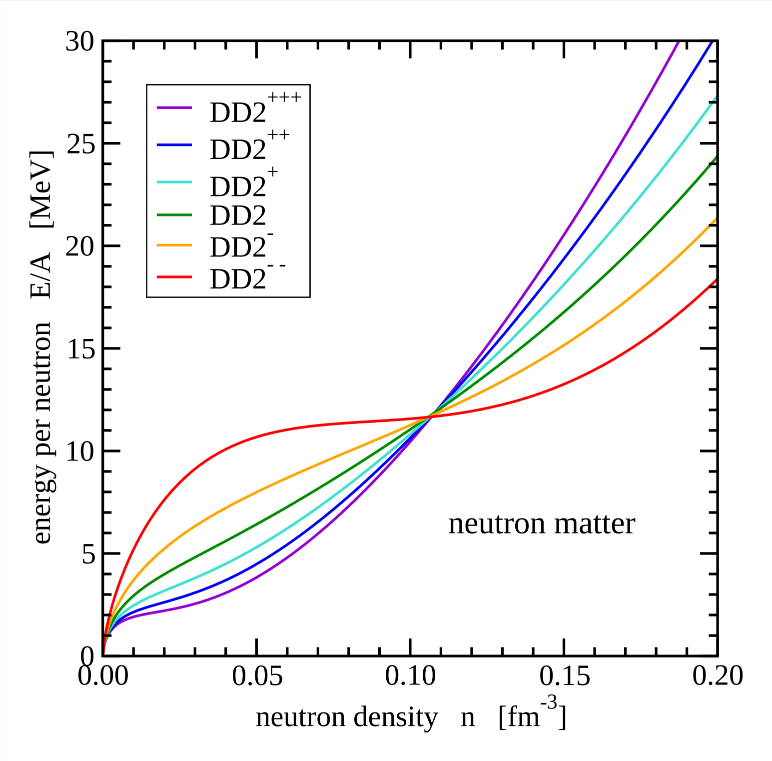
$$\Gamma_\rho(n) = \Gamma_\rho(n_{\text{ref}}) \exp\left[-a_\rho\left(\frac{n}{n_{\text{ref}}} - 1\right)\right]$$

Application of gRDF Model

- finite temperature gRDF calculations in spherical Wigner-Seitz cell, extended Thomas-Fermi approximation
- zero temperature: only α-particles relevant
  $\Rightarrow$ density distribution from ground-state wave function (WKB approximation)
- variation with neutron excess of nuclei $\Rightarrow$ chain of Sn nuclei
- variation of isovector interaction
  $\Rightarrow$ modified parametrizations, ^{208}Pb nucleus

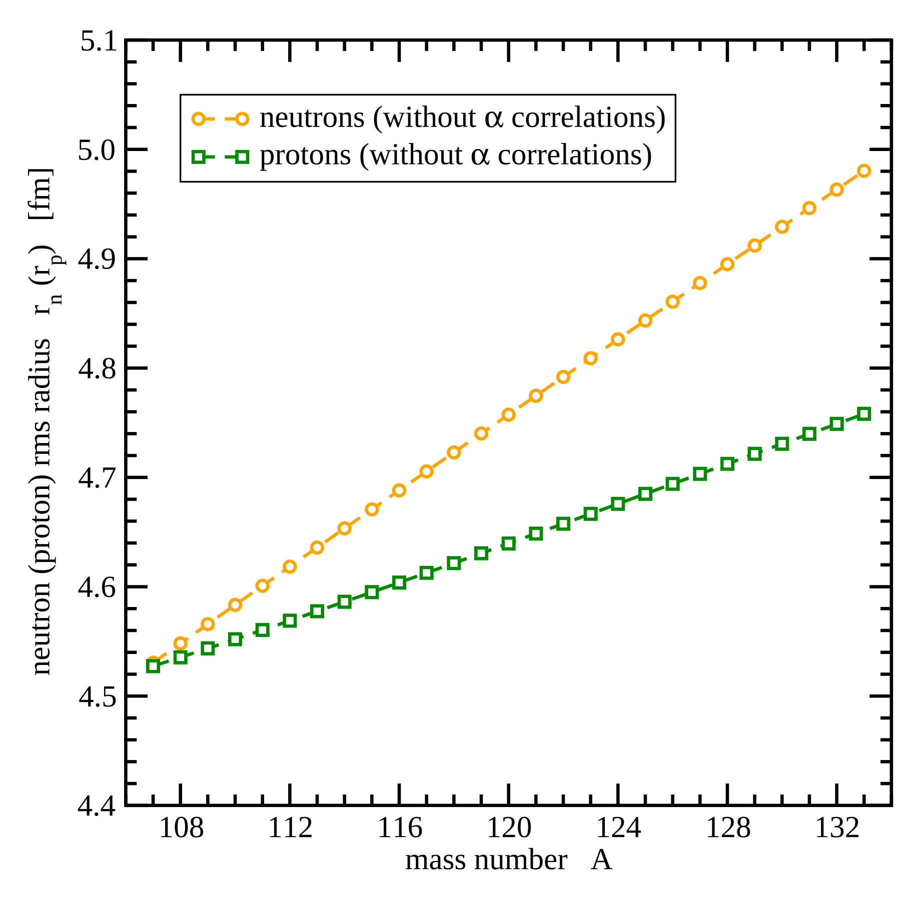
parametrization	symmetry energy J [MeV]	slope coefficient L [MeV]	ρ-meson coupling $\Gamma_\rho(n_{\rm ref})$	ρ-meson parameter a_ρ
DD2^{+++}	35.34	100.00	4.109251	0.063577
DD2^{++}	34.12	85.00	3.966652	0.193151
DD2^{+}	32.98	70.00	3.806504	0.342181
DD2	31.67	55.04	3.626940	0.518903
DD2^{-}	30.09	40.00	3.398486	0.742082
DD2^{--}	28.22	25.00	3.105994	1.053251

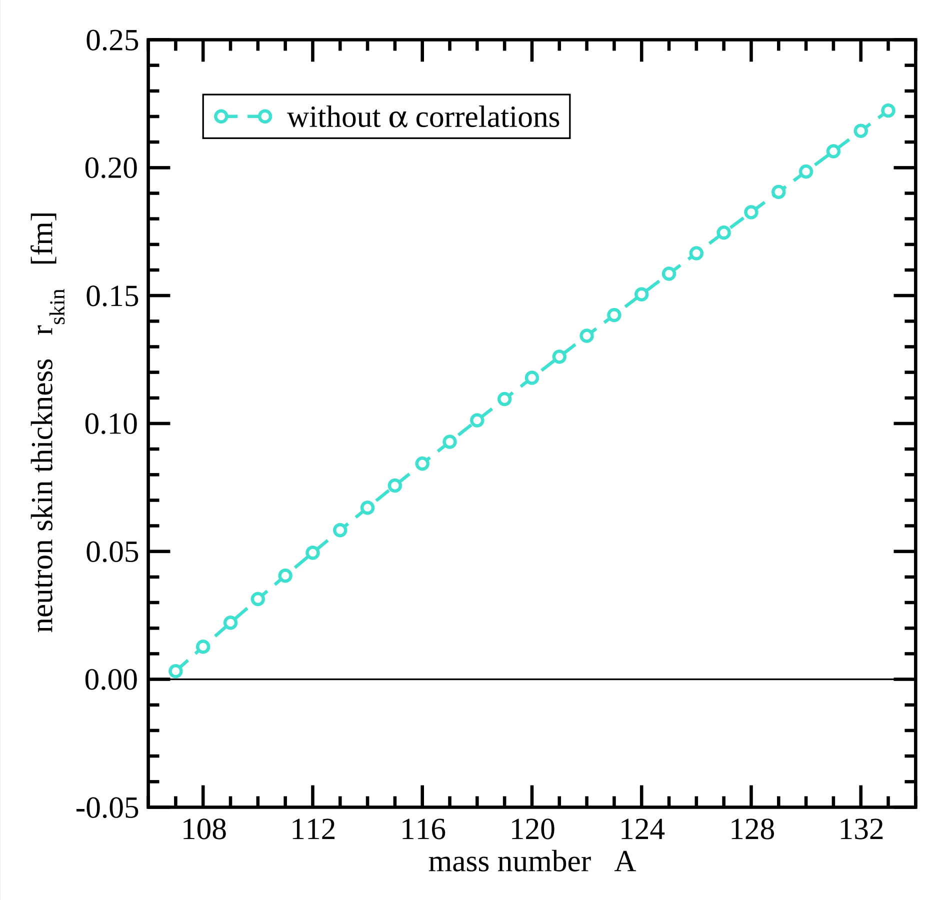
$$\Gamma_\rho(n) = \Gamma_\rho(n_{\rm ref}) \exp\left[-a_\rho\left(\frac{n}{n_{\rm ref}} - 1\right)\right]$$



Neutron Skin of Sn Nuclei

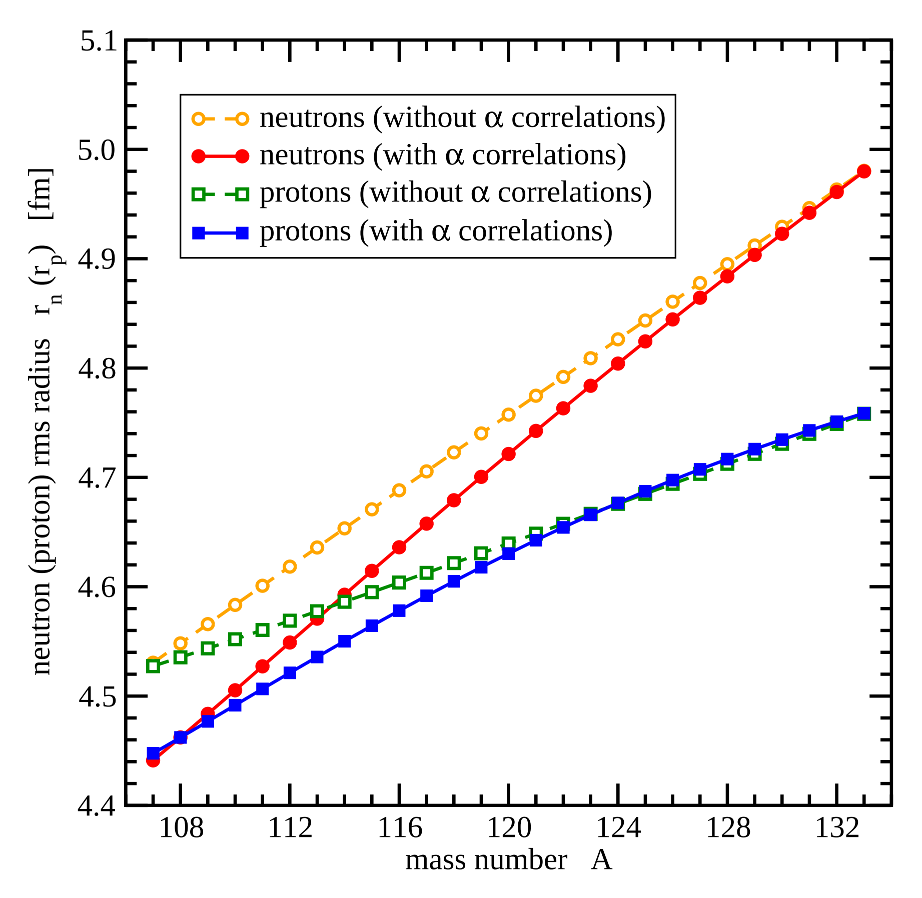
- neutron and protons rms radii r_n and r_p
- neutron skin thickness $r_{\text{skin}} = r_n - r_p$

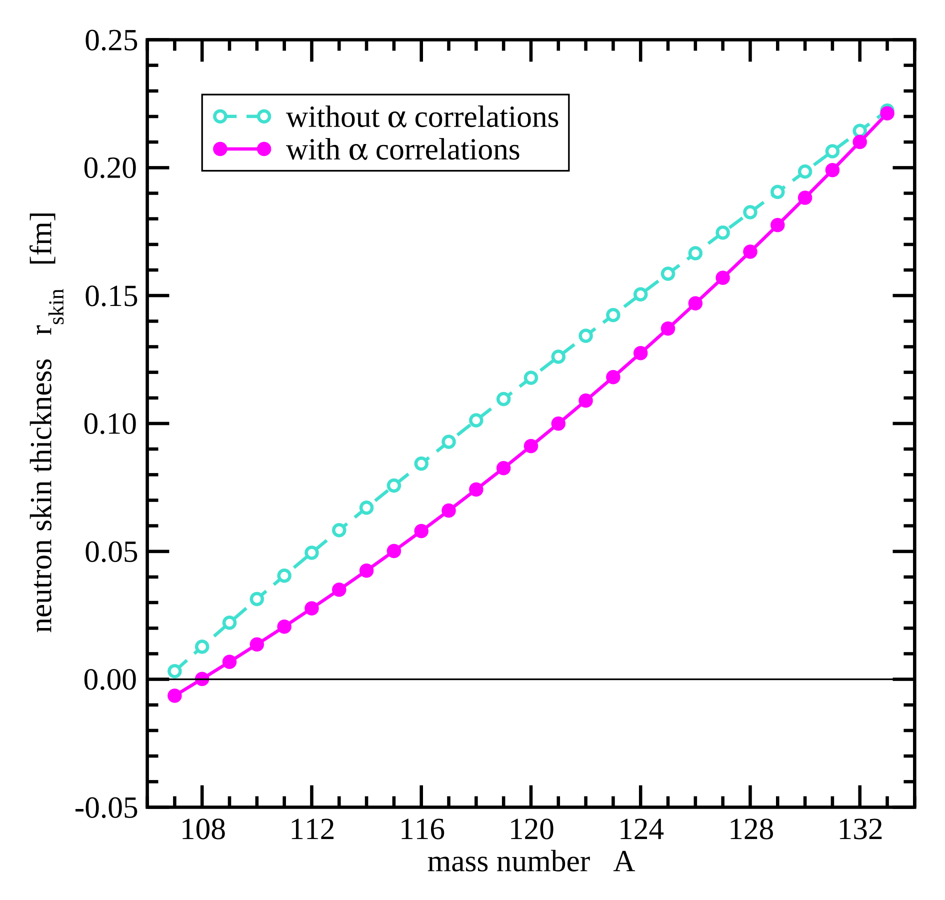




Neutron Skin of Sn Nuclei

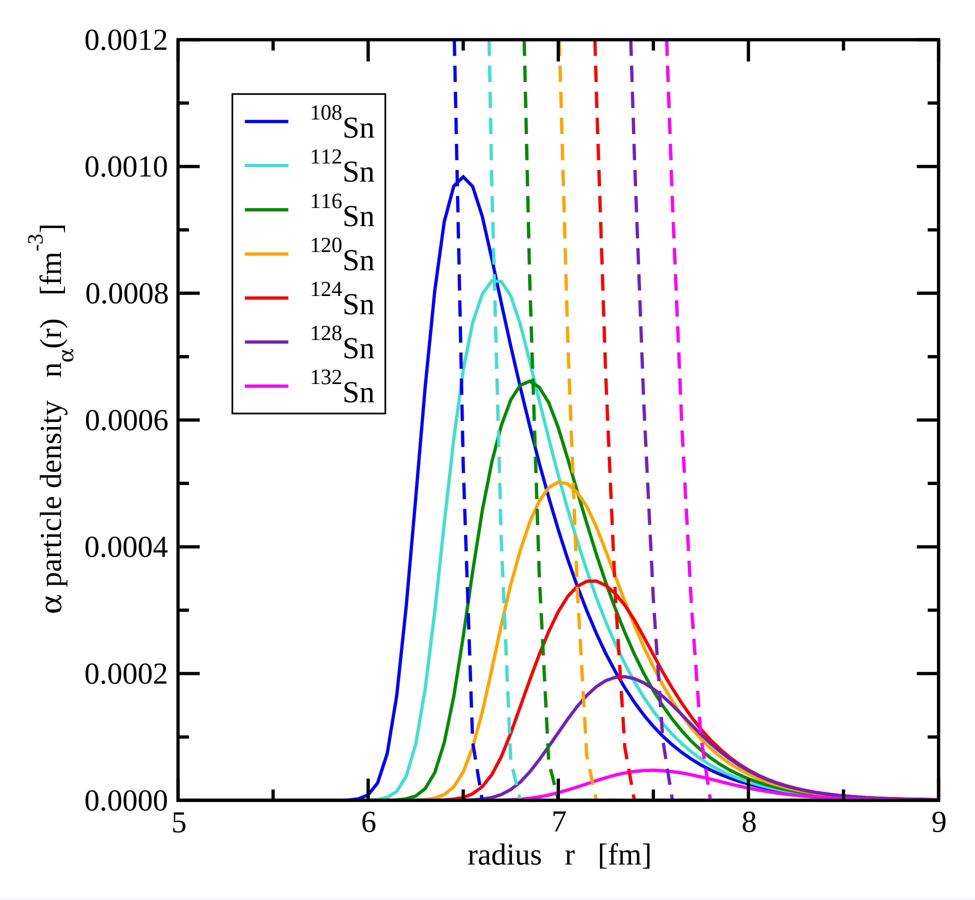
- neutron and protons rms radii r_n and r_p
- neutron skin thickness $r_{\text{skin}} = r_n - r_p$

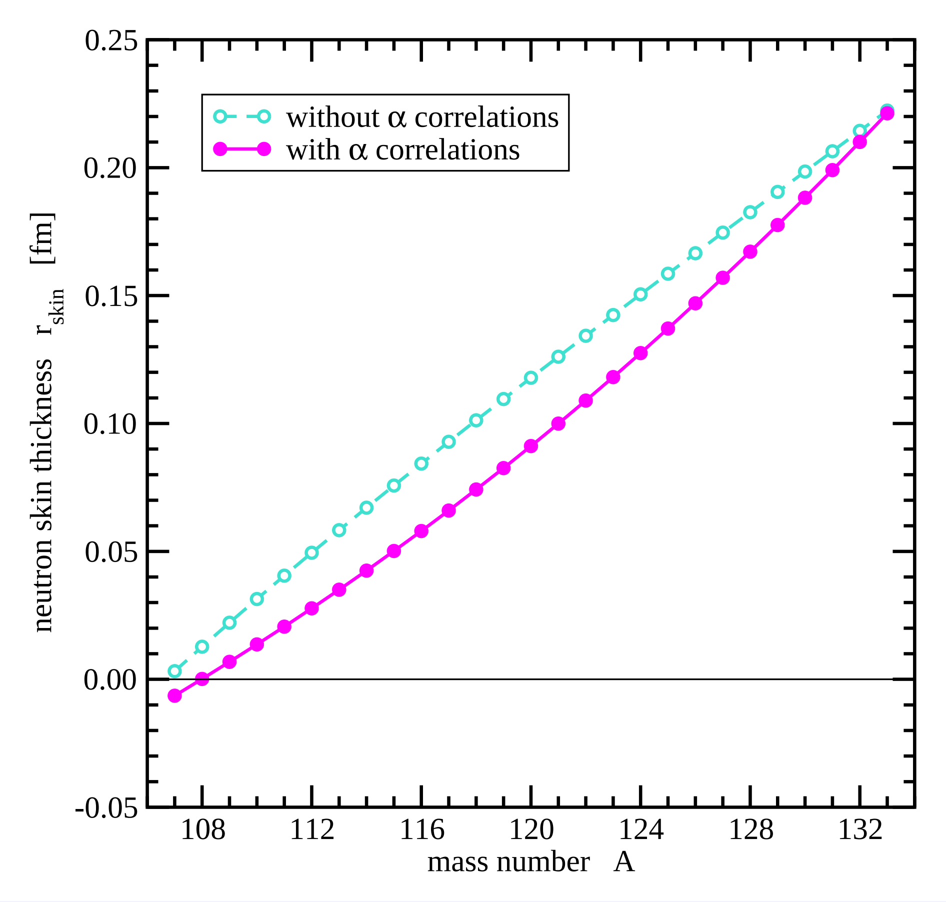




Neutron Skin of Sn Nuclei

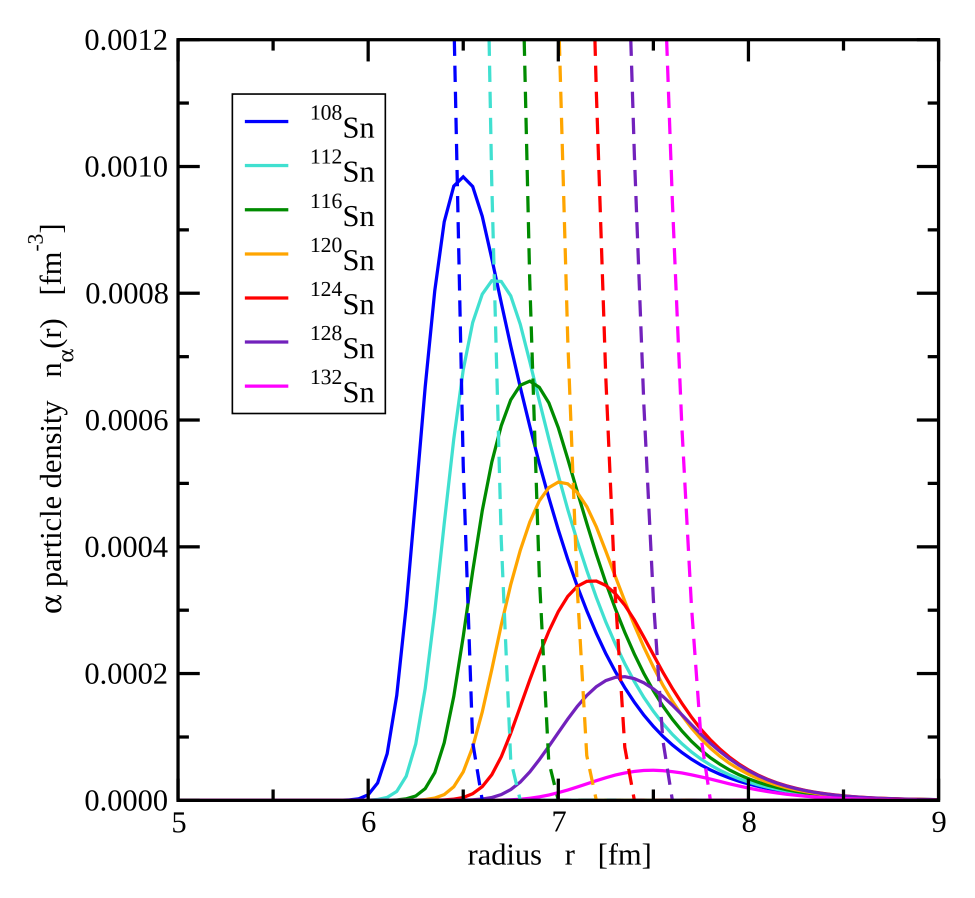
- density distributions of neutrons (dashed lines) and α particles (full lines)
- neutron skin thickness $r_{\text{skin}} = r_n - r_p$

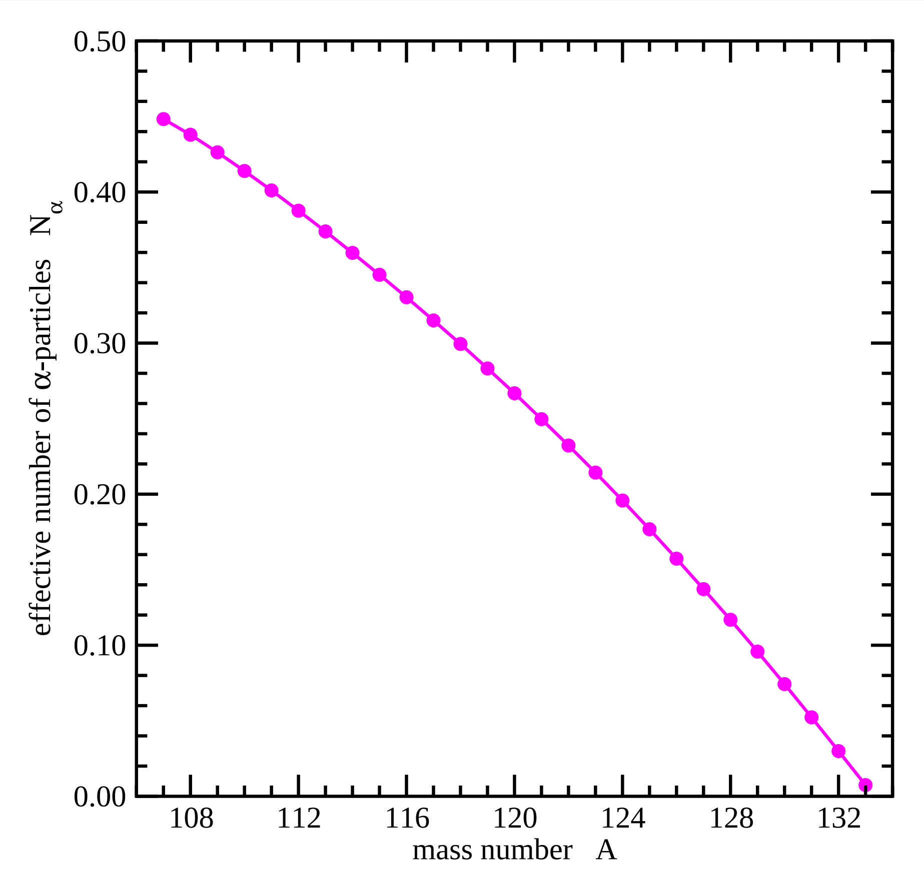




Neutron Skin of Sn Nuclei

- density distributions of neutrons (dashed lines) and α particles (full lines)
- effective α-particle number N_α

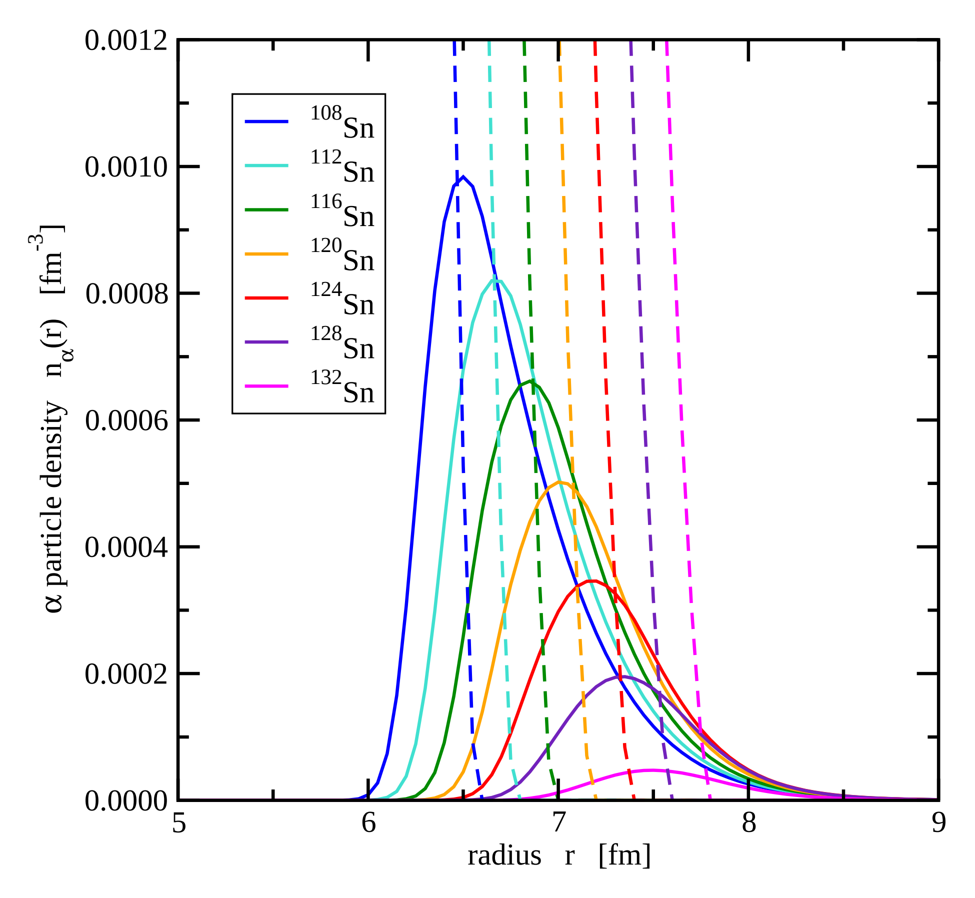


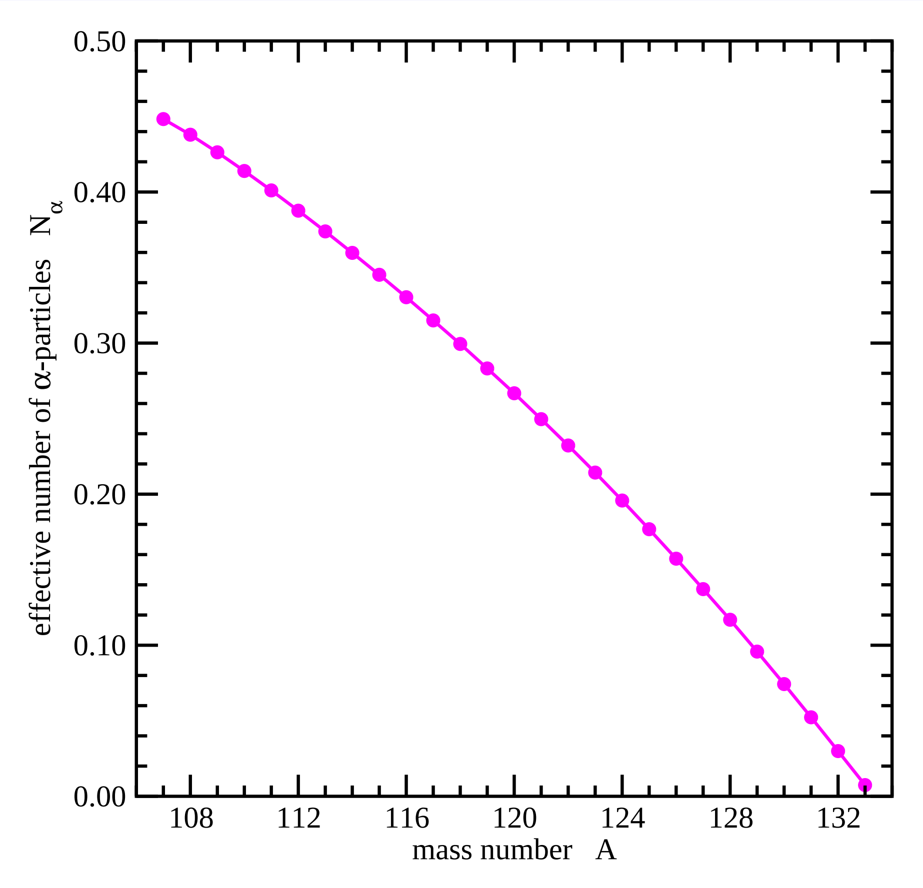


Neutron Skin of Sn Nuclei

- density distributions of neutrons (dashed lines) and α particles (full lines)
- effective α-particle number N_α

experimental test of predictions?

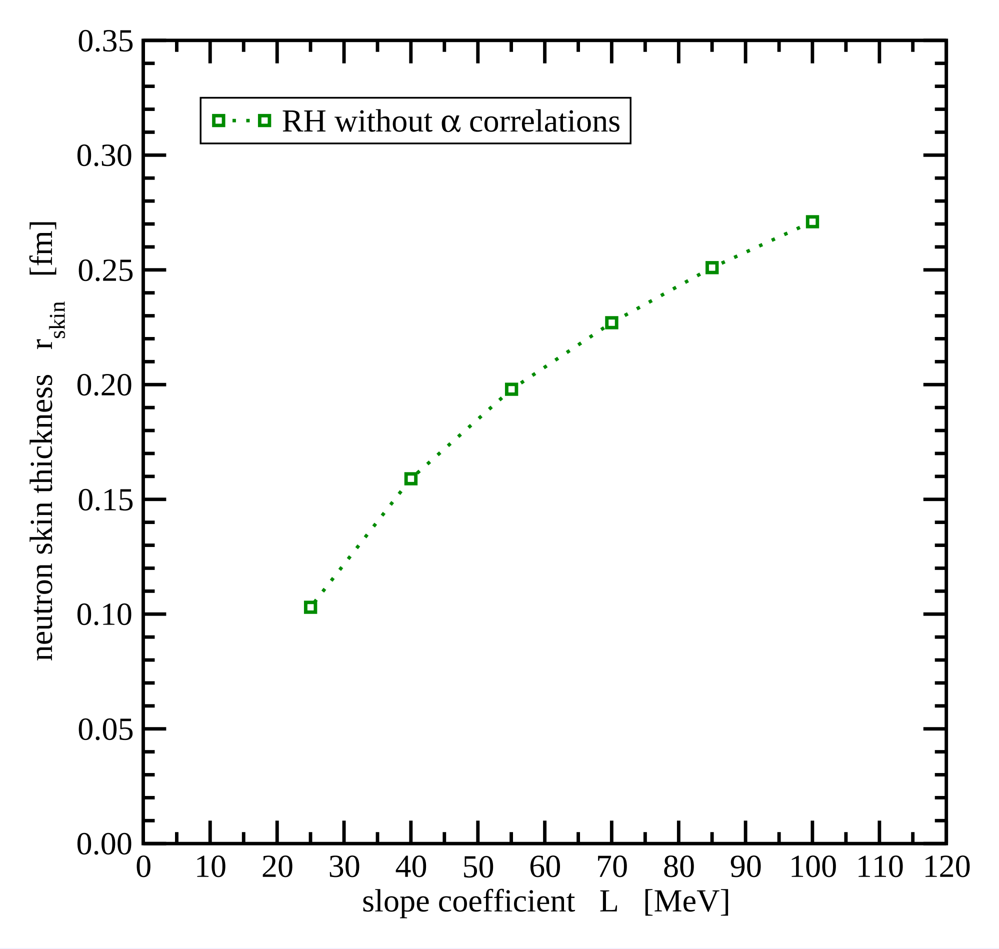




Neutron Skin of ^{208}Pb

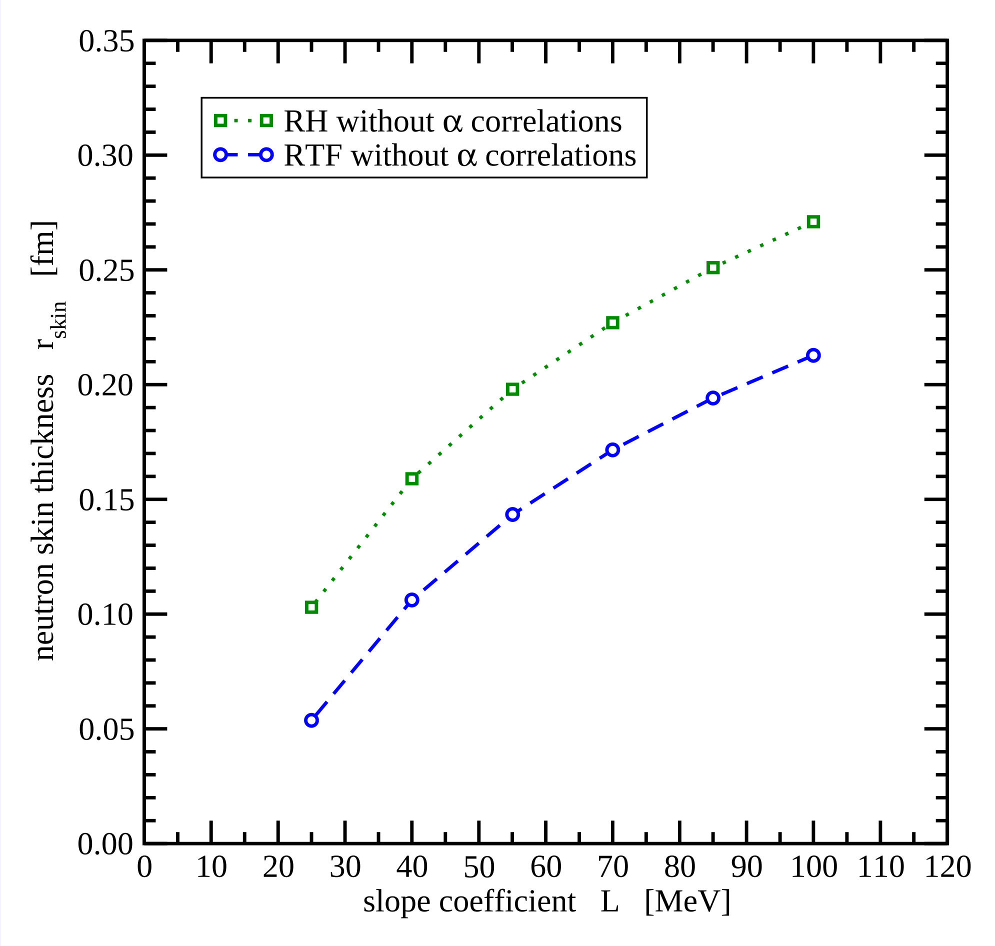
- dependence on symmetry energy slope coefficient L
  $\Rightarrow$ use parametrizations
  DD2^{+++}, . . . , DD2^{--}
- relativistic Hartree (RH) calculation used in original fit of model parameters

  (correlation $r_{\text{skin}} \leftrightarrow L$ not linear because no complete refit of model parameters, only of effective isovector interaction)



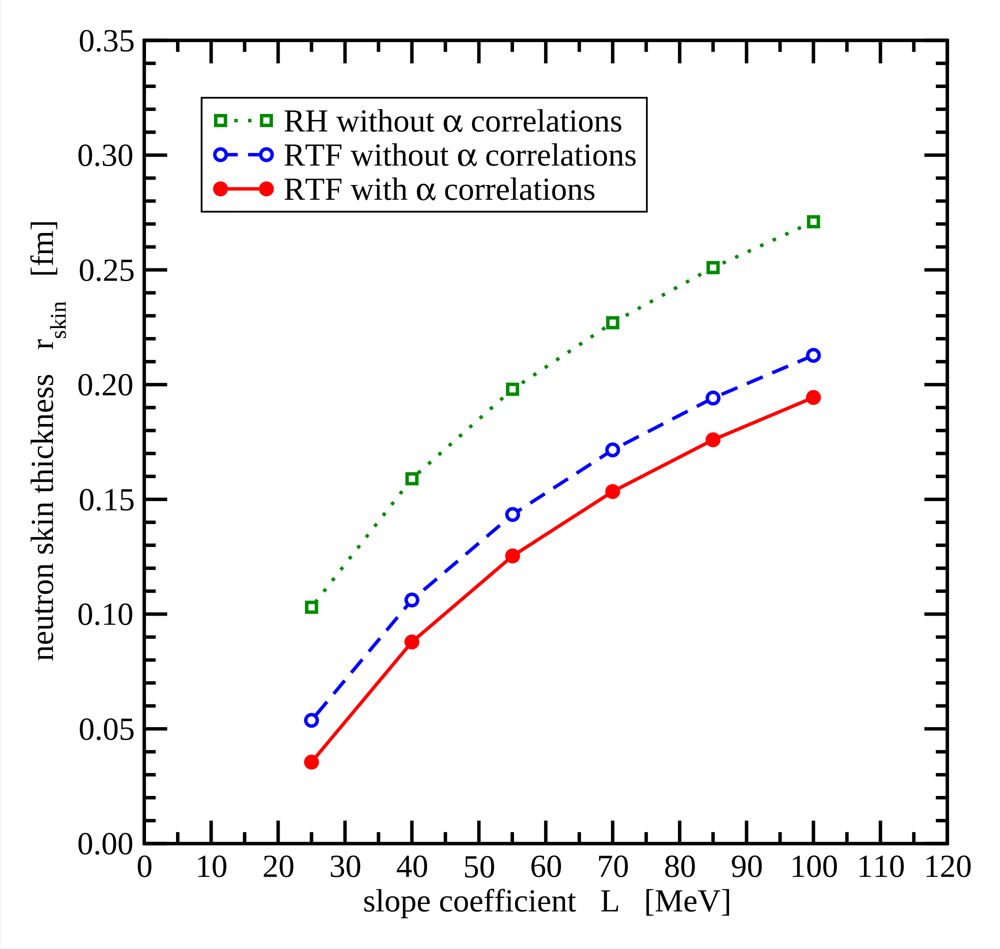
Neutron Skin of ^{208}Pb

- dependence on symmetry energy slope coefficient L
  $\Rightarrow$ use parametrizations
  DD2^{+++}, . . . , DD2^{--}
- relativistic Hartree (RH) calculation used in original fit of model parameters
- relativistic Thomas-Fermi (RTF) calculation for description of nuclei with generalized relativistic density functional
  $\Rightarrow$ underestimate of neutron skin thickness but similar correlation as in RH calculation



Neutron Skin of ^{208}Pb

- dependence on symmetry energy slope coefficient L
  $\Rightarrow$ use parametrizations
  DD2^{+++}, . . . , DD2^{--}
- relativistic Hartree (RH) calculation used in original fit of model parameters
- relativistic Thomas-Fermi (RTF) calculation for description of nuclei with generalized relativistic density functional
  $\Rightarrow$ underestimate of neutron skin thickness but similar correlation as in RH calculation
- with α-particles at surface
  $\Rightarrow$ systematic reduction of neutron skin



Experimental Test

Experimental Study of α-Clustering at Nuclear Surface

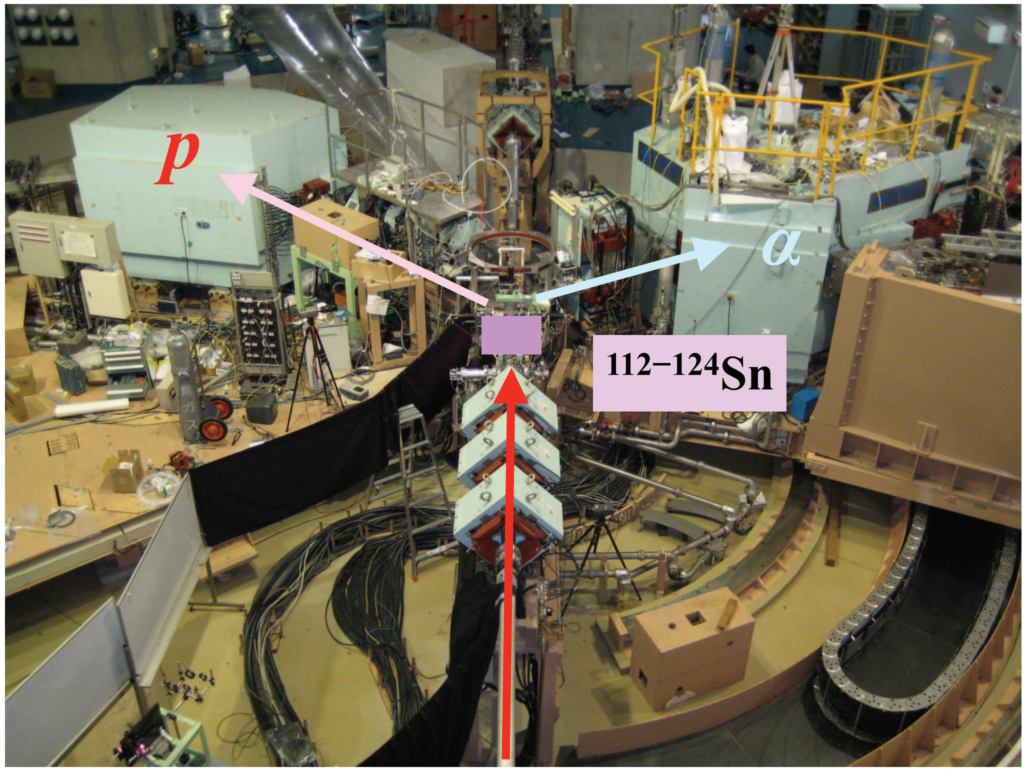
- clean probe for α-particles in nuclei: quasi-free (p,pα) knockout reactions

Experimental Study of α-Clustering at Nuclear Surface

- clean probe for α-particles in nuclei: quasi-free (p,pα) knockout reactions
- experiment at RCNP Cyclotron Facility, Osaka, Japan
  - collaboration with T. Aumann (TU Darmstadt), T. Uesaka (RIKEN) et al.
  - proposal accepted in PAC evaluation March 2014, experiment planned for 2015

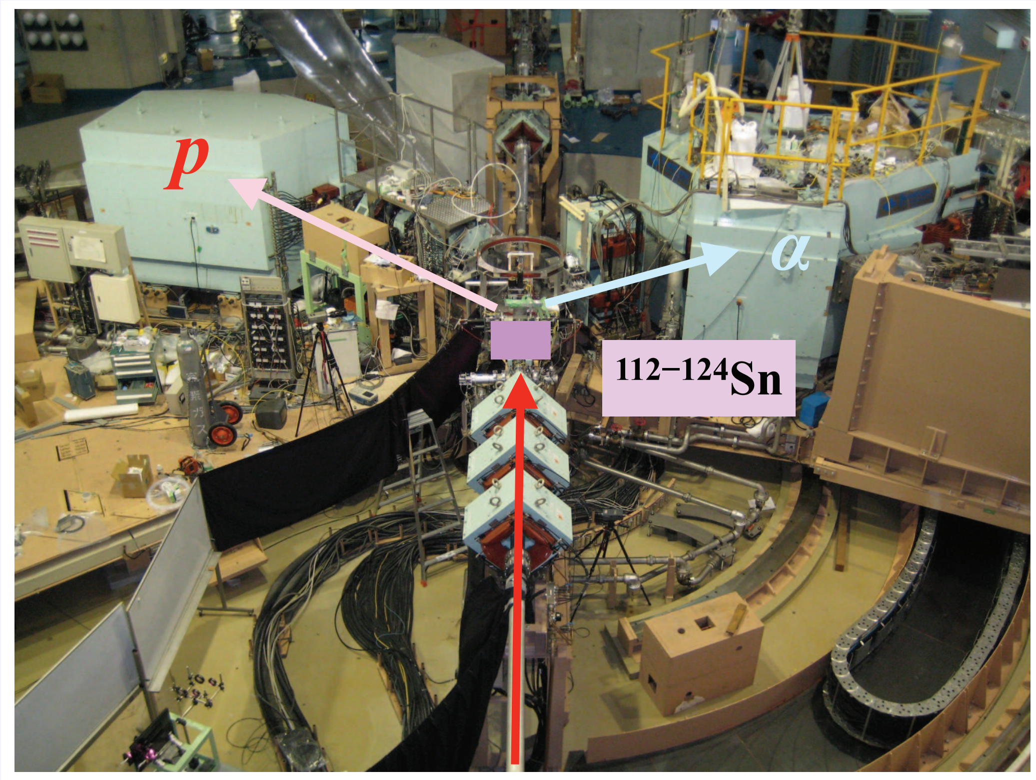
Experimental Study of α-Clustering at Nuclear Surface

- clean probe for α-particles in nuclei: quasi-free (p,pα) knockout reactions
- experiment at RCNP Cyclotron Facility, Osaka, Japan
  - collaboration with T. Aumann (TU Darmstadt), T. Uesaka (RIKEN) et al.
  - proposal accepted in PAC evaluation March 2014, experiment planned for 2015
  - 300 MeV proton beam
  - targets: ^{112}Sn, ^{116}Sn, ^{120}Sn, ^{124}Sn
  - proton detection: Grand Raiden
  - α detection: LAS
  - several spectrometer settings



Experimental Study of α-Clustering at Nuclear Surface

- clean probe for α-particles in nuclei: quasi-free (p,pα) knockout reactions
- experiment at RCNP Cyclotron Facility, Osaka, Japan
  - collaboration with T. Aumann (TU Darmstadt), T. Uesaka (RIKEN) et al.
  - proposal accepted in PAC evaluation March 2014, experiment planned for 2015
  - 300 MeV proton beam
  - targets: ^{112}Sn, ^{116}Sn, ^{120}Sn, ^{124}Sn
  - proton detection: Grand Raiden
  - α detection: LAS
  - several spectrometer settings
  - experimental signatures:
    - dependence of effective α-particle number ($\Rightarrow$ cross sections) on neutron excess $N - Z$
    - localisation of α-particles on surface of nucleus $\Rightarrow$ broad momentum distribution



Quasi-Free (p,pα) Reactions on Sn Nuclei @ 300 MeV

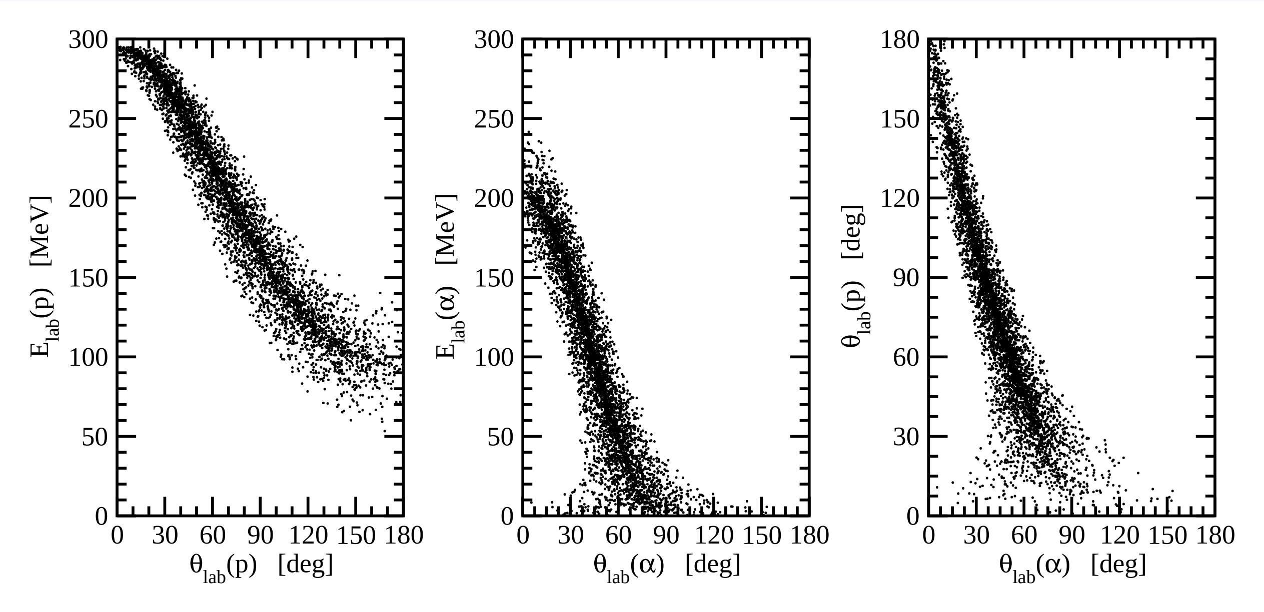
kinematics

- low momentum transfer to residual Cd nucleus

Quasi-Free (p,pα) Reactions on Sn Nuclei @ 300 MeV

kinematics

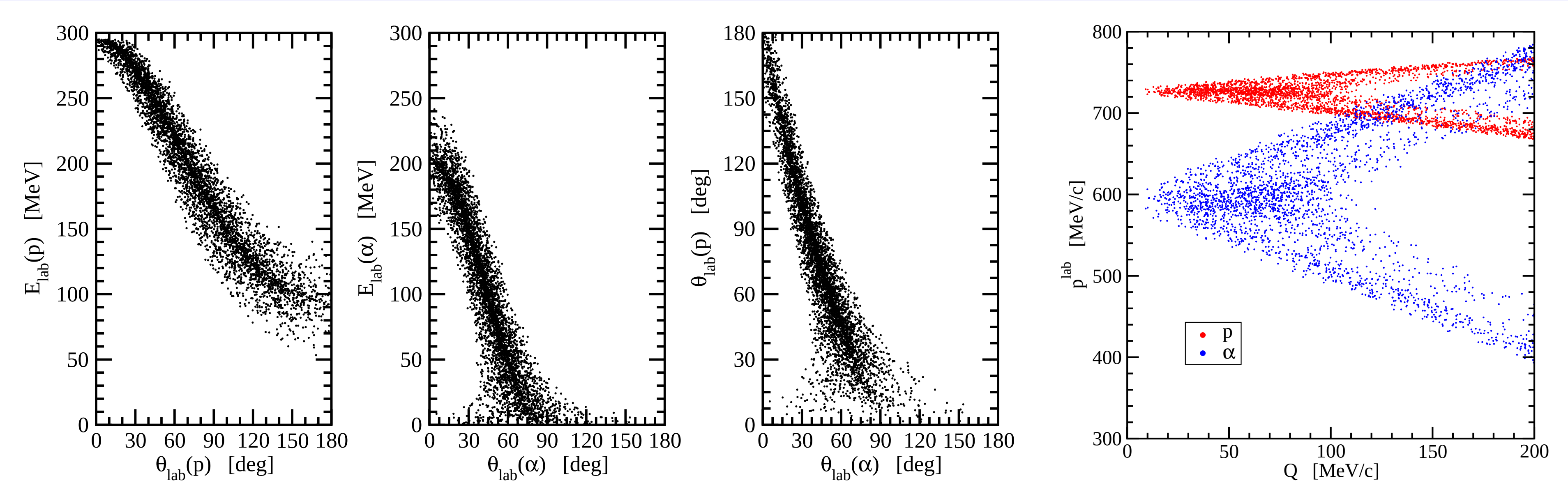
- low momentum transfer to residual Cd nucleus $\Rightarrow$
  - strong correlation of angles/energies of emitted protons and α-particles



Quasi-Free (p,pα) Reactions on Sn Nuclei @ 300 MeV

kinematics

- low momentum transfer to residual Cd nucleus $\Rightarrow$
  - strong correlation of angles/energies of emitted protons and α-particles
  - select pair of angles, e.g., $\theta_{\rm lab}(p) = 45^{\circ}$ and $\theta_{\rm lab}(\alpha) = 60^{\circ}$
  - choose spectrometer settings to cover different ranges of intrinsic α-particle momenta Q within acceptance (p, Grand Raiden: 5%, α, LAS: 30%)



Quasi-Free (p,pα) Reactions on Sn Nuclei @ 300 MeV

cross sections

- relativistic distorted-wave impulse approximation

Quasi-Free (p,pα) Reactions on Sn Nuclei @ 300 MeV

cross sections

- relativistic distorted-wave impulse approximation
  $\Rightarrow$ factorization

$$\frac{d^5\sigma}{dQ\,d\Omega_Q\,d\Omega_p'} = K \times \frac{d^2\sigma}{d\Omega_p'} \times W_\alpha(\vec{Q}) \times R$$

  - kinematic factor K

Quasi-Free (p,pα) Reactions on Sn Nuclei @ 300 MeV

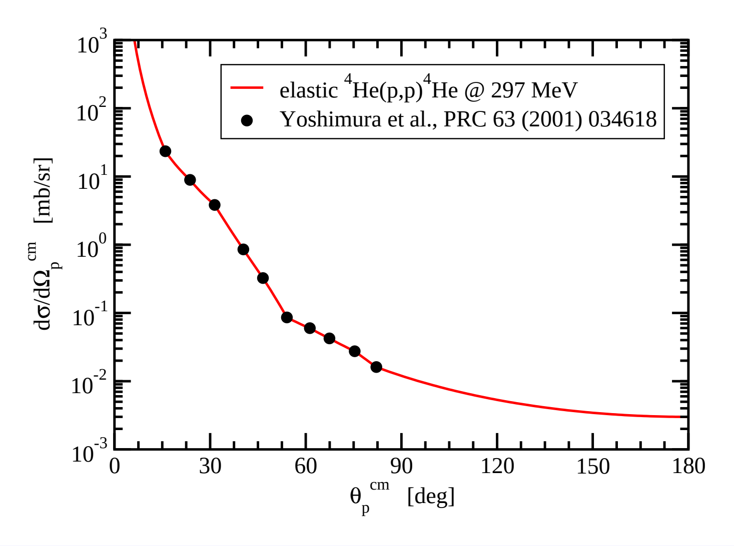
cross sections

- relativistic distorted-wave impulse approximation
  $\Rightarrow$ factorization

$$\frac{d^5\sigma}{dQ\,d\Omega_Q\,d\Omega'_p} = K \times \frac{d^2\sigma}{d\Omega'_p} \times W_\alpha(\vec{Q}) \times R$$

  - kinematic factor K
  - half-off-shell p-α scattering cross section $\frac{d^2\sigma}{d\Omega'_p}$

    $\Rightarrow$ use parametrized experimental elastic p-α scattering cross section



Quasi-Free (p,pα) Reactions on Sn Nuclei @ 300 MeV

cross sections

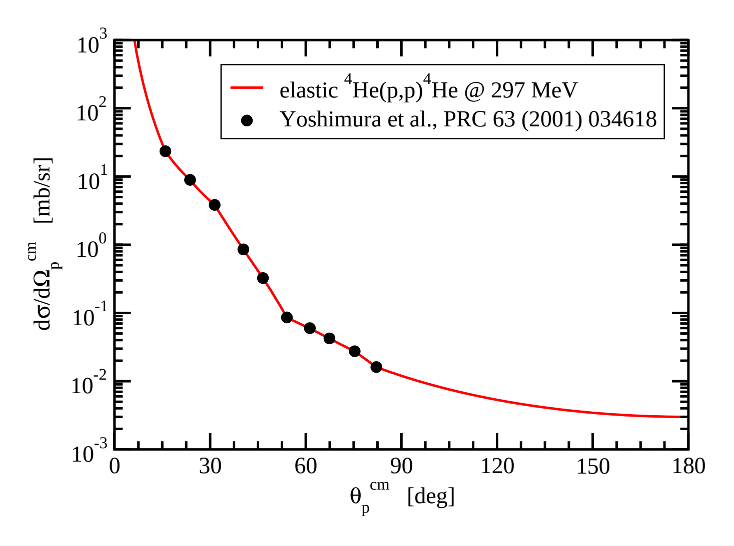
- relativistic distorted-wave impulse approximation
  $\Rightarrow$ factorization

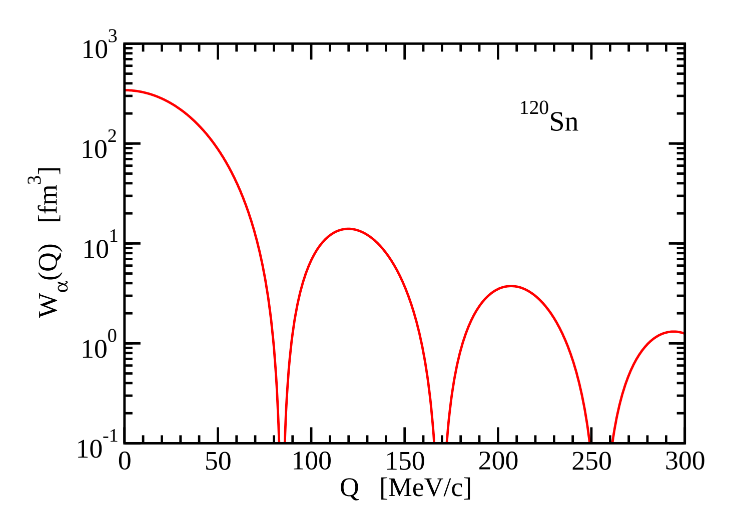
$$\frac{d^5\sigma}{dQ\,d\Omega_Q\,d\Omega'_p} = K \times \frac{d^2\sigma}{d\Omega'_p} \times W_\alpha(\vec{Q}) \times R$$

  - kinematic factor K
  - half-off-shell p-α scattering cross section $\frac{d^2\sigma}{d\Omega'_p}$
    $\Rightarrow$ use parametrized experimental elastic p-α scattering cross section
  - intrinsic momentum distribution

$$W_\alpha(\vec{Q}) = \left|\chi_{\alpha-\mathrm{Cd}}(\vec{Q})\right|^2$$ with $\vec{Q} = \vec{k}_{\alpha-\mathrm{Cd}}$

    of α-particle in Sn nucleus
  - reduction factor R due to absorption





Quasi-Free (p,pα) Reactions on Sn Nuclei @ 300 MeV

cross sections

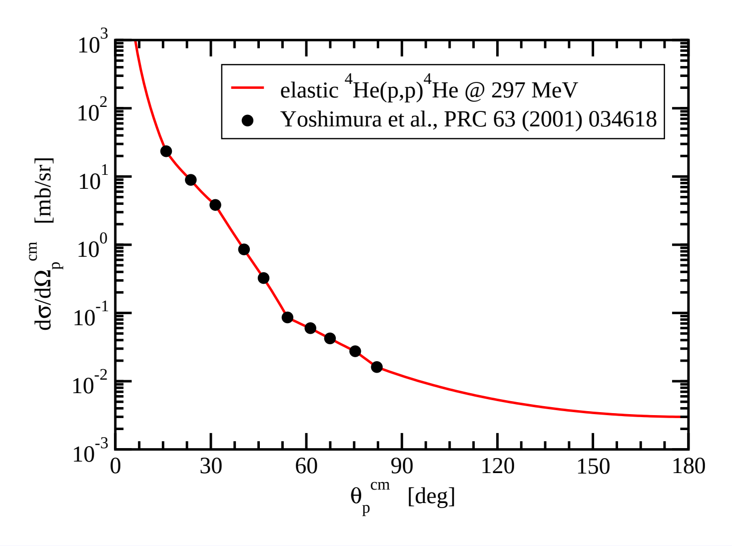
- relativistic distorted-wave impulse approximation
  $\Rightarrow$ factorization

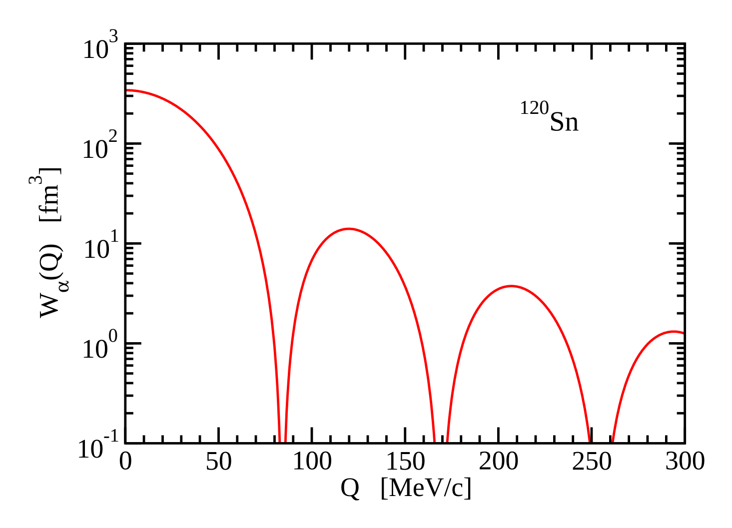
$$\frac{d^5\sigma}{dQ\, d\Omega_Q\, d\Omega'_p} = K \times \frac{d^2\sigma}{d\Omega'_p} \times W_\alpha(\vec{Q}) \times R$$

  - kinematic factor K
  - half-off-shell p-α scattering cross section $\frac{d^2\sigma}{d\Omega'_p}$
    $\Rightarrow$ use parametrized experimental elastic p-α scattering cross section
  - intrinsic momentum distribution

$$W_\alpha(\vec{Q}) = \left|\chi_{\alpha-\mathrm{Cd}}(\vec{Q})\right|^2$$ with $\vec{Q} = \vec{k}_{\alpha-\mathrm{Cd}}$

    of α-particle in Sn nucleus
  - reduction factor R due to absorption
- Monte Carlo simulation of experiment
  $\Rightarrow$ estimate of count rates





Conclusions

Conclusions

- many-body correlations essential in low-density nuclear matter
  - formation of clusters/nuclei
  - conditions at surface of heavy nuclei
  - prerequisite for explanation of α-decay
- generalized relativistic density functional (gRDF) for equation of state calculations
  - model with explicit cluster degrees of freedom, quasiparticles with medium-dependent properties
  - effective interaction with density-dependent couplings, well-constrained parameters
- application of gRDF approach to heavy nuclei
  - predicts formation of α-clusters at surface of heavy nuclei
    - $\Rightarrow$ reduction of neutron skin thickness
    - $\Rightarrow$ affects correlation with slope coefficient of symmetry energy
    - $\Rightarrow$ systematic variation of effect with neutron excess of nucleus and with isovector part of effective interaction
- experimental test of predictions
  - quasi-free (p,pα) knockout reactions
    - $\Rightarrow$ experiment with Sn nuclei planned at RCNP, Osaka