Halo Systems in Medium-Mass Nuclei : A New Analysis Method

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INT, Seattle, 11/16/2007

Outline

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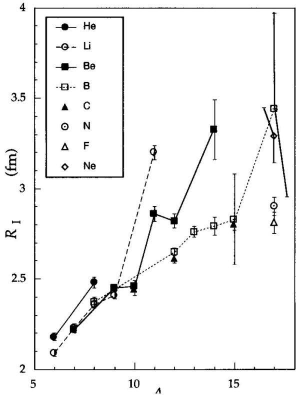
Halos in Light Nuclei

- Low density tail extending out to large distance
- Direct consequence of small nucleon separation energy / drip-line physics
- First observed experimentally in ^{11}Li and ^{11}Be

  [I. Tanihata *et al*, Phys. Rev. Lett. **55** (1985) 2676 ; Phys. Lett. **206B** (1988) 592]
- Various experimental signatures

- Interaction radii/cross sections
- Momentum distribution
- . . .

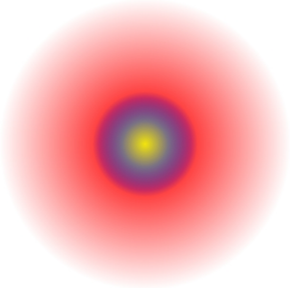


800 MeV/n

[I. Tanihata, Nucl. Phys. **A520** (1990) 411c-425c]
[B. Blank *et al.*, Z. Phys. **A343** (1992) 343-375]
[E. Arnold *et al.*, Phys. Lett. **B281** (1992) 16]

Light Nuclei : Few-Body Models

- Halo degrees of freedom decoupled from the core
- Problem reduces to 2 or 3-body interacting clusters
- Exact dynamics through Schrödinger or Faddeev equations



Rule of thumb characterization for halo states :
[A.S. Jensen, M.V. Zhukov, Nucl. Phys. **A693** (2001), 411]

- Halo extension:

  $>$ 50% probability in classically forbidden region

- Dominating cluster structure:

  $>$ 50% of the actual configuration

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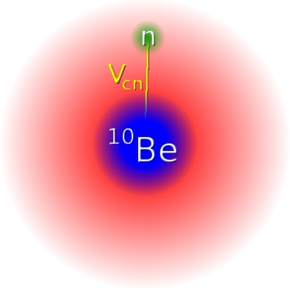

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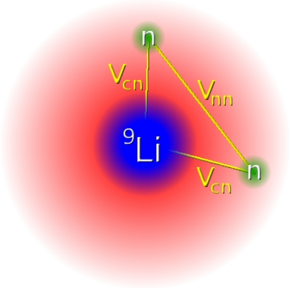

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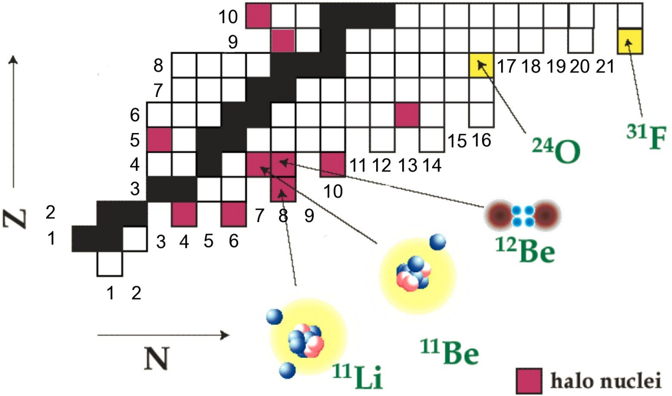
Known Light Halo Nuclei

- Experimental evidence for several proton and neutron light halo nuclei
- Ground and excited states



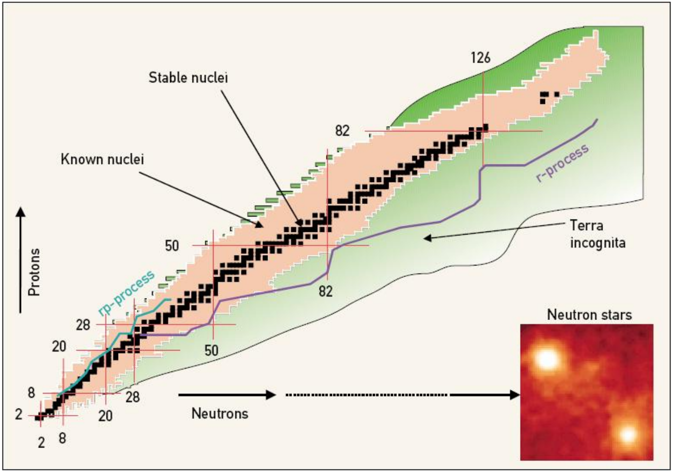
[RIA White Paper, 2005]

Cluster vision for light systems : valid for heavier masses ?

Outline

Challenges for Nuclear Energy Density Functional (EDF)

- EDF theory : appropriate for mid- to heavy mass nuclei ($A > 40$)
- EDF behavior at small/surface density / large asymmetry not under control



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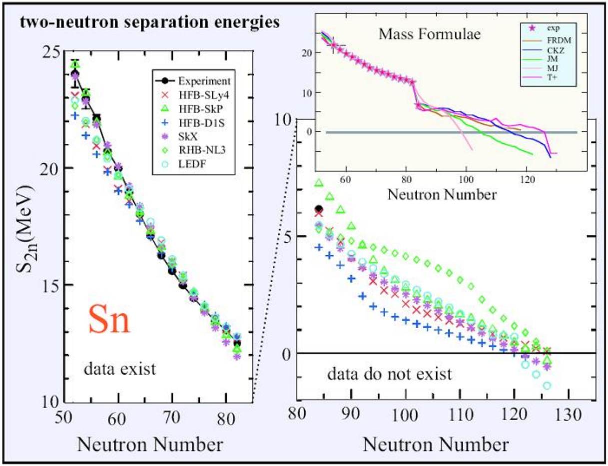

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- Potential use of halo structures to constrain current EDF ?
  - Surface physics: low density configurations
  - Surface physics : gradient versus density dependence
  - Drip-line phenomenon : large isospin asymmetry
  - Drip-line phenomenon : shell evolution at low separation energy
  - Pairing functional : constraints at low density/large asymmetry
- Collective behaviors: Cluster vision not really expected

Halo definition expected to change...

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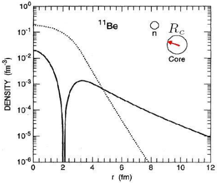
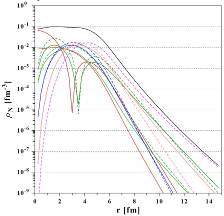




Halo definition expected to change...

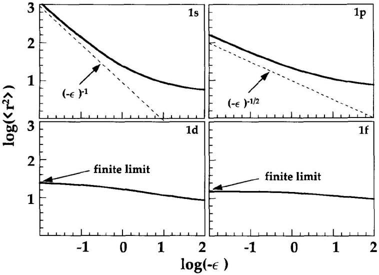
HFB calculations in spherical symmetry

- **LyHF** spherical HFB code [K. Bennaceur, INPL/ESNT, France]
- Discrete continuum in 40 fm spherical box
- Even-even nuclei : no time-reversal invariance breaking

- Particle-hole channel : SLy4 functional
  [E. Chabanat *et al.*, Nucl. Phys. **A635** (1998) 231-256]
- Particle-particle channel : DDDI functional

Importance of low-ℓ states

- Divergence of r.m.s. radii for $\ell = 0, 1$ weakly bound systems
  [K. Riisager *et al.*, Nucl. Phys. **A548** (1992) 393] - [T. Misu *et al.*, Nucl. Phys. **A614** (1997) 44]
- Focus on the evolution of the r.m.s. radius to predict halos
- Prerequisites : presence + occupation of s/p orbitals
- Higher order moments $< r^n >$ diverge for higher ℓ in weak binding limit $\epsilon \to 0$



- $< r^n >$ diverges as $\epsilon^{\frac{2\ell-1-n}{2}}$ for $n > 2\ell - 1$
- $< r^n >$ diverges as $\ln(\epsilon)$ for $n = 2\ell - 1$
- $< r^n >$ remains finite for $n \leq 2\ell - 1$

Possible contributions from $\ell > 1$ states to nuclear halos...

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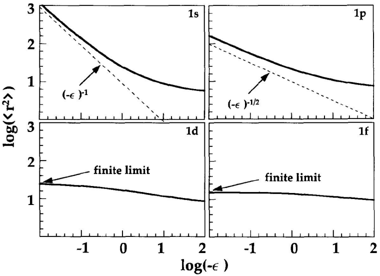

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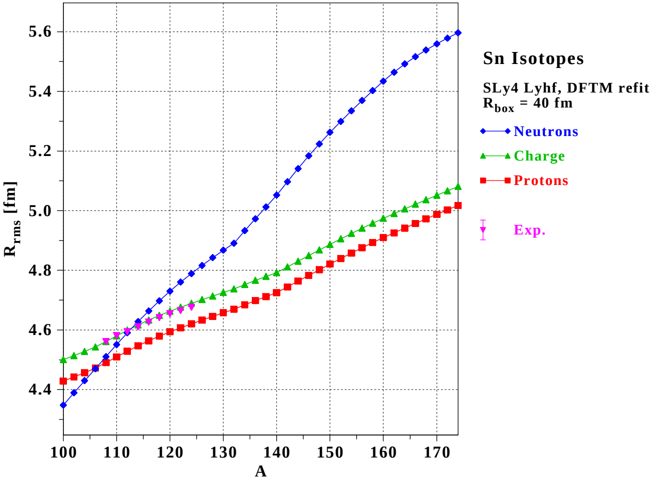
Results for Sn Isotopes ($Z = 50$)

- Root-mean-square radii



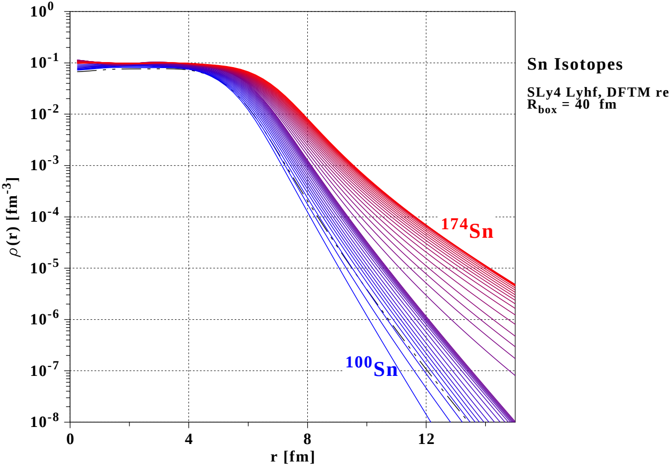
- Weak kink of neutron r.m.s.

Results for Sn Isotopes ($Z = 50$)

- Kink of neutron r.m.s. : halo signature / neutron skin ?

$N \leq 82$
Neutron skin growth

$N > 82$
Anomalous extension ?

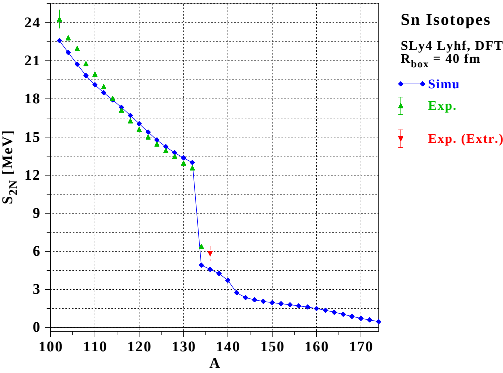


- Anomalous neutron skin growth / halo ?

Results for Sn Isotopes ($Z = 50$)

- Kink of neutron r.m.s. : halo signature / shell effect ?
- Two-neutrons separation energy S_{2N} (drives asymptotic behavior)

  - Drops at $N = 82$
  - No close from 0 for $N > 82$

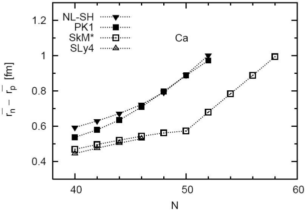


- Kink at $N = 82$ may be due to shell effects only

Detailed Analysis Methods

- Qualitative analysis misleading : "giant halo" ?

[M. Grasso *et al.*, Phys. Rev. **C74** (2006) 064317] - [J. Terasaki *et al.*, Phys. Rev. **C74** (2006) 054318]



- Naive counting of nucleons
- Proton/neutron r.m.s. radii difference
- Missing part : halo neutrons decorrelated from
  - protons
  - core neutrons

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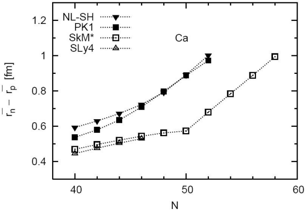

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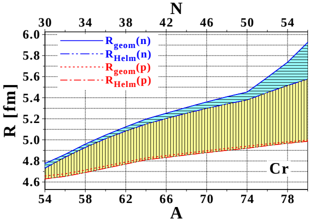
- Quantitative analysis inadequate : Helm model

  [S. Mizutori *et al.*, Phys. Rev. **C61** (2000) 044326]



- Anzatz for core density
- Extracts halo contribution to r.m.s. radius
- Model- and fit-dependent
- Halo in proton-rich / stable / doubly magic nuclei

Roadmap

- Limits of existing methods
- Shell effects may explain part/all of neutron r.m.s. radii kinks

- Need of a robust + quantitative framework
- Lessons from previous attempts :
  - Halo region : decorrelated from protons AND core neutrons
  - One-body density : contains enough relevant information for characterization

Goals

- Non ambiguous / model-independent definition of halos
- Extraction of meaningful criteria
- Separation of skin / shell / halo effects

Outline

Intrinsic One-Body Density

- Self-bound system : separation of center-of-mass and intrinsic d.o.fs.

$$\Psi^N_{i,\vec{K}}(\vec{r}_1 \dots \vec{r}_N) = e^{\imath \vec{K}.\vec{R}_N}\, \Phi^N_i(\vec{r}_1 \dots \vec{r}_N) \equiv e^{\imath \vec{K}.\vec{R}_N}\, \ddot{\Phi}^N_i(\vec{\xi}_1 \dots \vec{\xi}_{N-1})$$

- Uniform laboratory density : need to consider intrinsic one-body density
- Relevant degrees of freedom : intrinsic spectroscopic amplitudes

[D. Van Neck *et al.*, Phys. Rev. **C57** (1998) 2308] - [J. Escher *et al.*, Phys. Rev. **C64** (2001) 065801]

$$\varphi_i(\vec{r}\,) = \sqrt{N} \int d\vec{r}_1 \dots \vec{r}_{N-1} \Phi^{N-1\,*}_i(\vec{r}_1 \dots \vec{r}_{N-1})\delta(\vec{R}_{N-1})\Phi^N_0(\vec{r}_1 \dots \vec{r}_{N-1}, \vec{r}\,)$$

  - Definition w/ respect to center-of-mass of $(N-1)$-body frame
  - Natural definition for knock-out

- Normalization : spectroscopic factors

$$S_i = \int d\vec{r}\, |\varphi_i(\vec{r}\,)|^2 \qquad \Leftrightarrow \qquad \sum\!\!\!\!\!\!\int_i S_i = N$$

- Decomposition of one-body intrinsic density

$$\rho^{[i]}(\vec{r}, \vec{r}\,') = \sum\!\!\!\!\!\!\int_i \varphi^*_i(\vec{r}\,')\varphi_i(\vec{r}\,)$$

Asymptotic Behavior for φ_i

- Asymptotic solution (vanishing interaction) : free Schrödinger equation

$$\left(\frac{d^2}{d\,r^2} + \frac{2}{r}\,\frac{d}{d\,r} - \frac{\ell_i\,(\ell_i+1)}{r^2} - \kappa_i^2 \right) \varphi_i^\infty(\vec{r}\,) = 0$$

- Asymptotic intrinsic overlap functions

$$\varphi_i^\infty(\vec{r}\,) = B_i\,h_{\ell_i}(\imath\kappa_i r)\,Y_{\ell_i}^{m_i}(\theta,\varphi)$$

  - B_i: Asymptotic Normalization Coefficient (ANC)
  - h_{ℓ_i}: Hankel functions
  - κ_i related to one-nucleon separation energy

$$\kappa_i = \sqrt{\frac{2m\epsilon_i}{\hbar^2}} \qquad \epsilon_i = E_i^{N-1} - E_0^N$$

Asymptotic Behavior for ρ

- Asymptotics of one-body intrinsic density in spherical case

$$\rho^{\infty}(r) = \sum_i \frac{B_i^2}{4\pi} (2\ell_i + 1) \left| h_{\ell_i}(\imath\kappa_i r) \right|^2$$

- Leading order : nucleon separation energy prevails for large r, regardless of ℓ

$$\left| h_{\ell_i}(\imath\kappa_i r) \right|^2 \underset{r\to+\infty}{\longrightarrow} \frac{e^{-2\kappa_i r}}{(\kappa_i r)^2} \qquad \rho(r) \underset{r\to+\infty}{\longrightarrow} \frac{B_0}{4\pi}(2\ell_0 + 1)\frac{e^{-2\kappa_0 r}}{(\kappa_0 r)^2}$$

- Energy ordering of i components
- Corrections
  - ℓ-dep. of h_ℓ : centrifugal barrier
    $\Rightarrow$ favors low ℓ states
  - $(2\ell + 1)$ degeneracy factor
  - Overall : low ℓ favored

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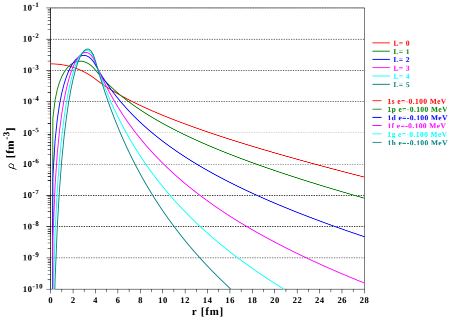

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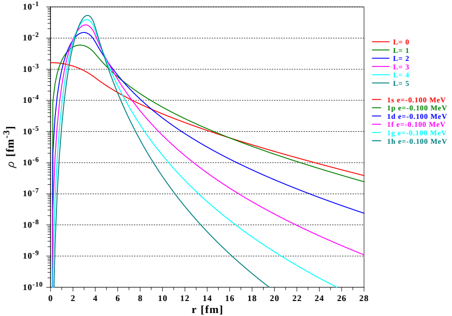

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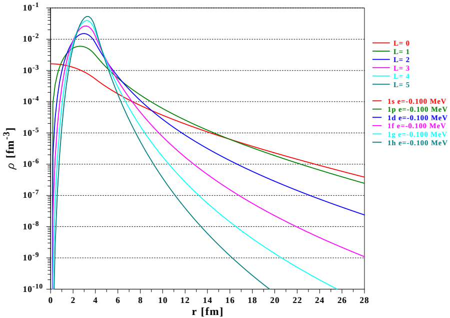

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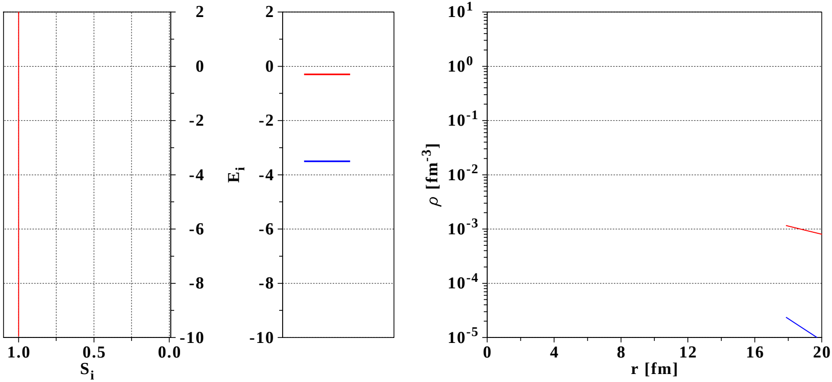
Consequences of Asymptotic Ordering

- Density with normalized radial overlaps $\psi_i(r) \Rightarrow \rho(\vec{r}) = \sum_i \frac{S_i}{4\pi}(2\ell_i + 1)|\psi_i(r)|^2$
- Assume (for now) $S_i = 1$
  - Asymptotic ordering induces crossings between normalized components
  - Crossing sharpness depending on energy difference, angular momenta...
  - Crossing between $i = 0$ and sum of higher components



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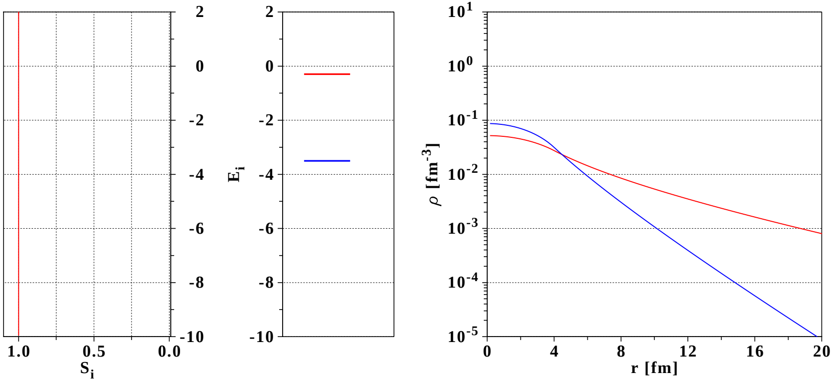

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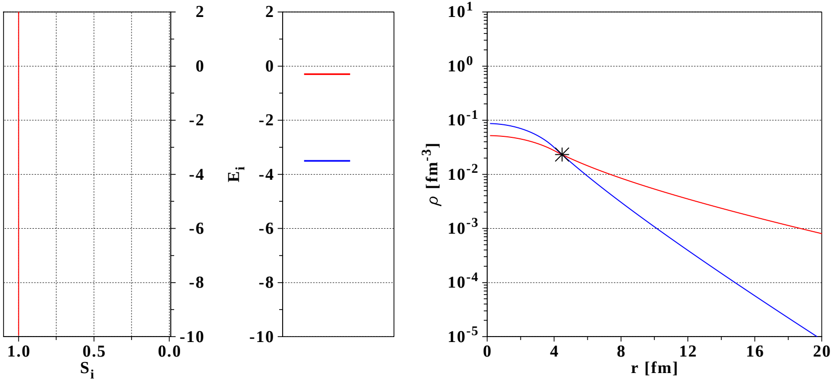

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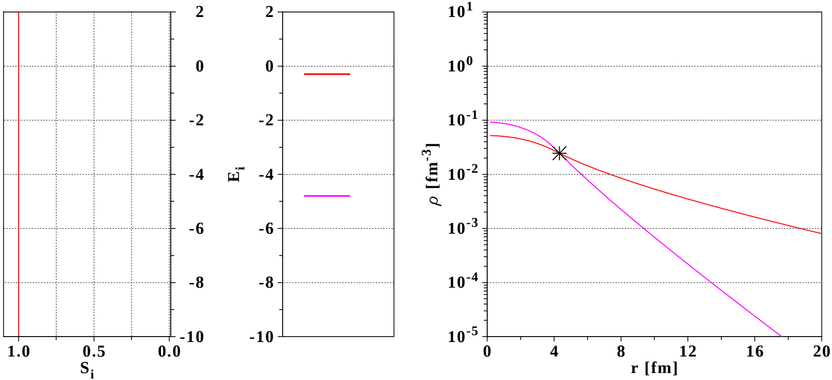

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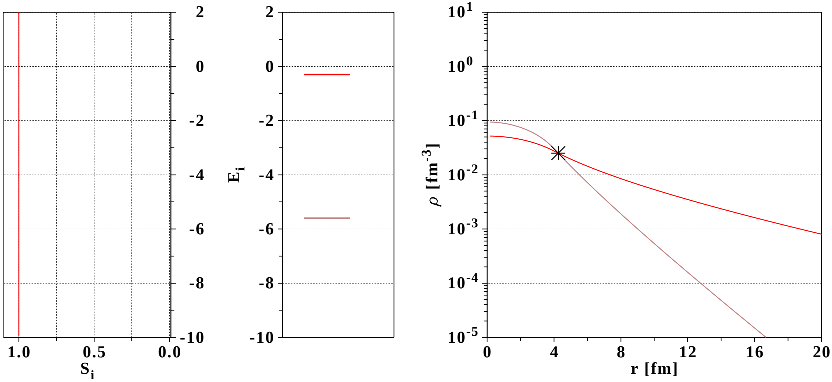

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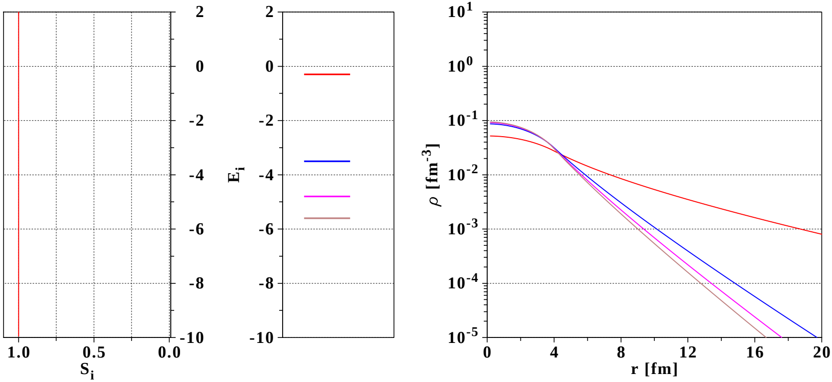

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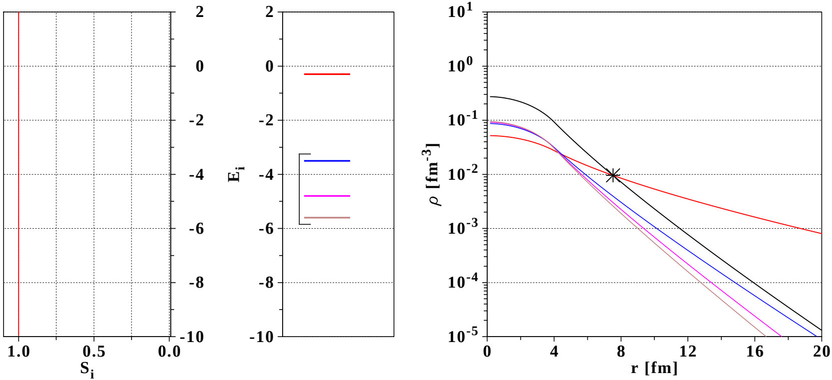

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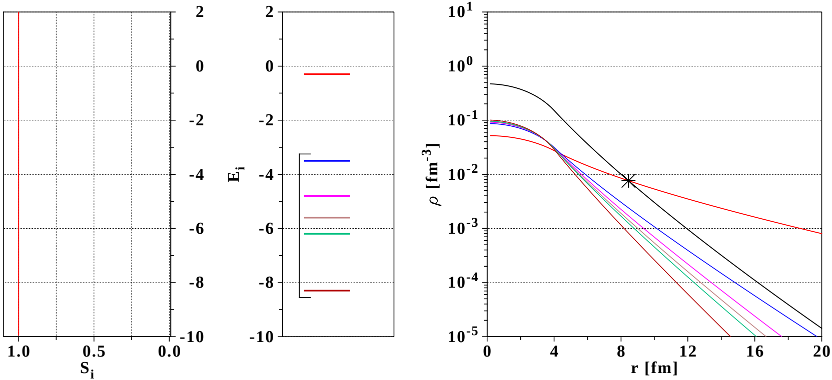

Consequences of Asymptotic Ordering

- Density with normalized radial overlaps $\psi_i(r) \Rightarrow \rho(\vec{r}) = \sum_i \frac{S_i}{4\pi}(2\ell_i + 1)|\psi_i(r)|^2$
- Spectroscopic factors increase with excitation energy in $(N-1)$ system
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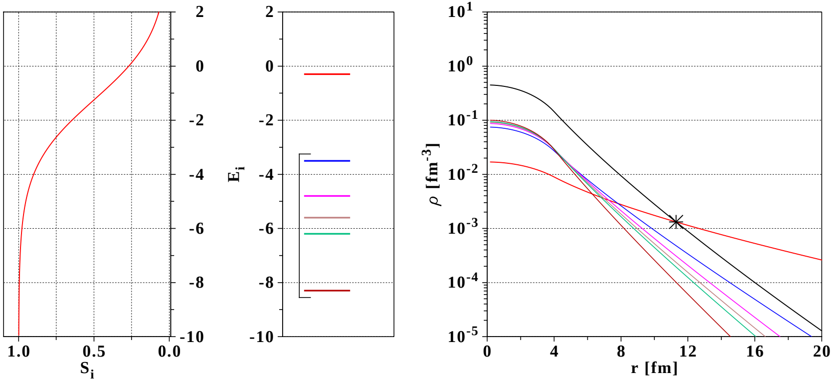

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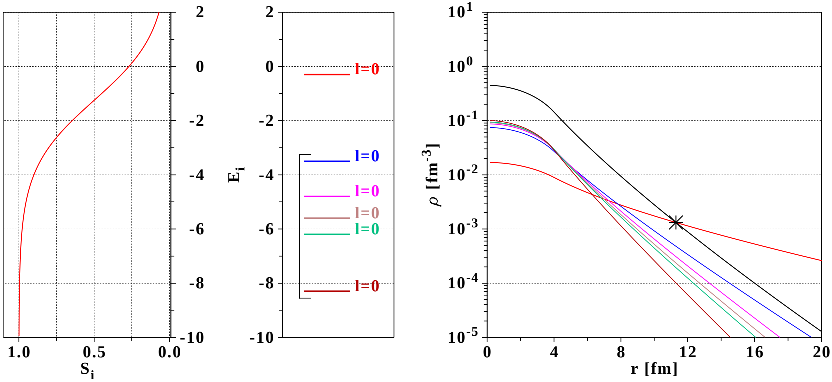

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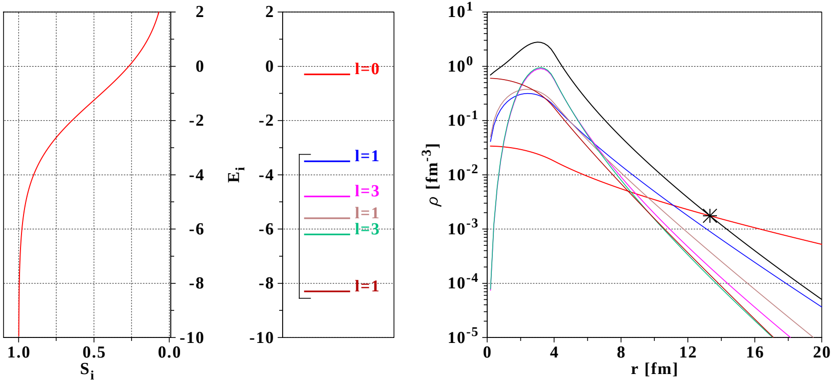

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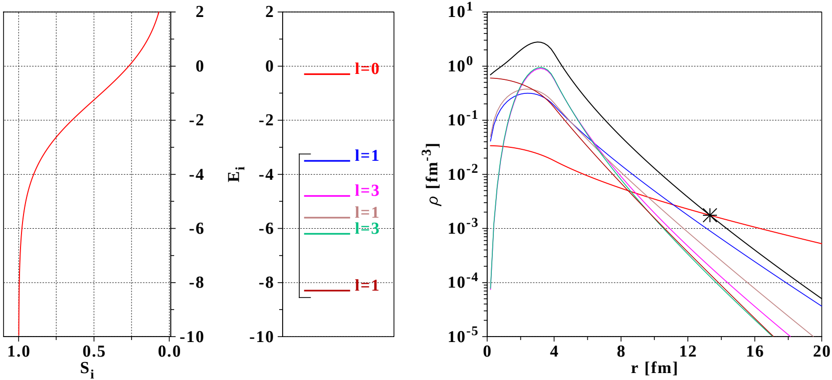
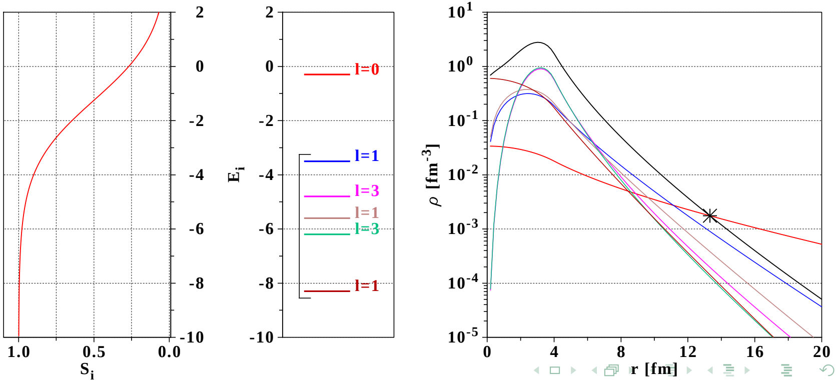


Model-Independent Definition of Halos

Halo = region where nucleons are spatially decorrelated from the others

- Need to extend out : long tail (of course)
- Existence of sharp crossing between weakly bound states and remaining ones

A posteriori notion of core and tail orbitals



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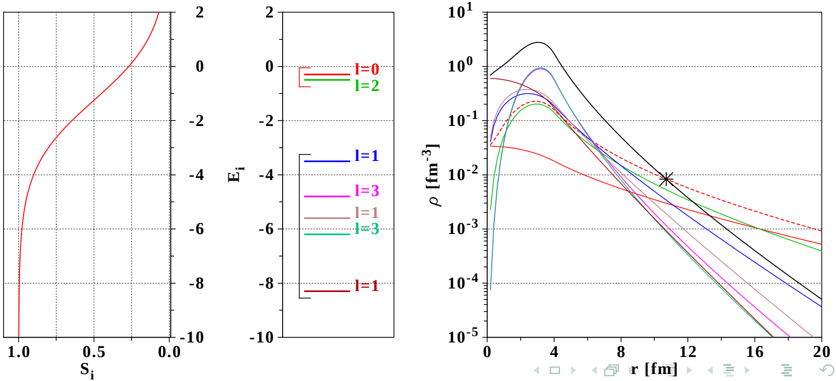

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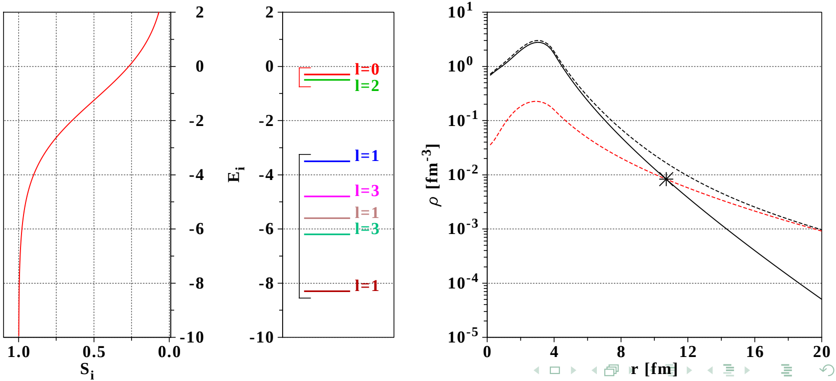

Energy Spectrum of Halo Systems

- Translation in terms of excitation spectrum of the $(N-1)$ system
- Long tail
  $\Rightarrow \kappa_0 \ll 1$: small separation energy / low-lying states
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  $\Rightarrow$ sharp crossing in the density profile between core and halo components

Halo energy scales

- Separation energy E
- Bunch spread ΔE of low-lying states
- Core Excitation energy E'

- Similar scales for "Halo EFT"
  [C. Bertulani *et al.*, Nucl. Phys. **A712** (2002) 37]
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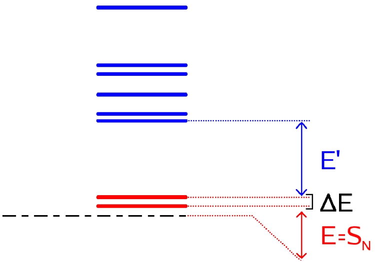

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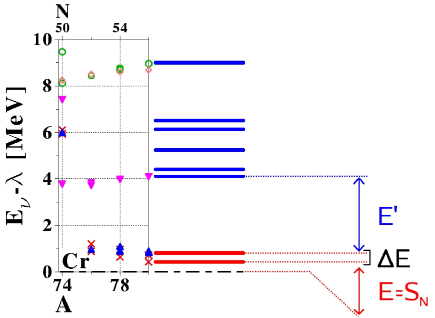

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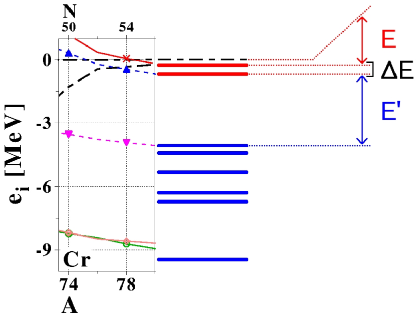

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Definition of Halo Region

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- Significant curvature of the log-density
- Second log-derivative separates regions where core/halo components dominate

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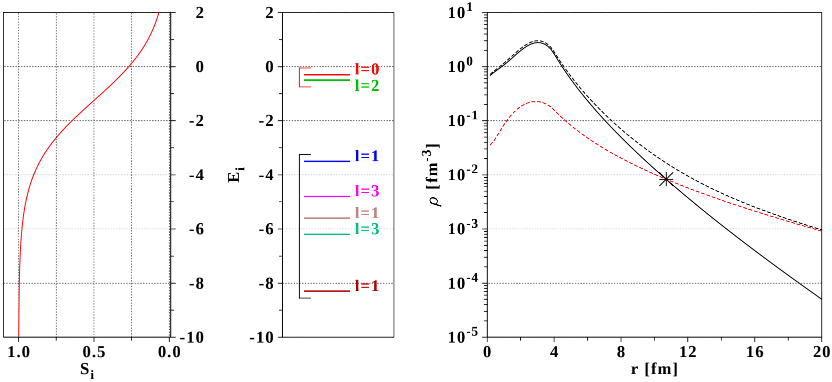
Halo = region where tail components dominate by at least one order of magnitude



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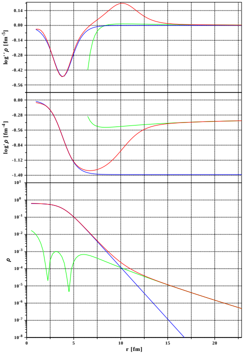

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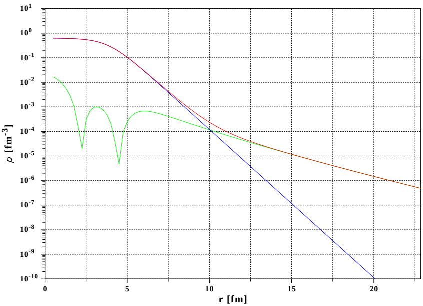

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  - Toy models
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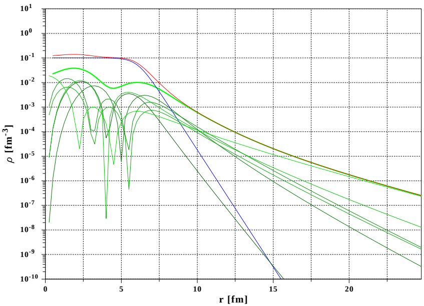

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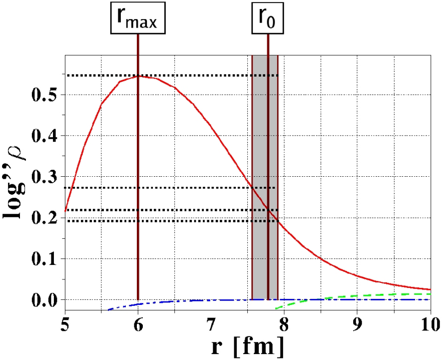

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- Error bars

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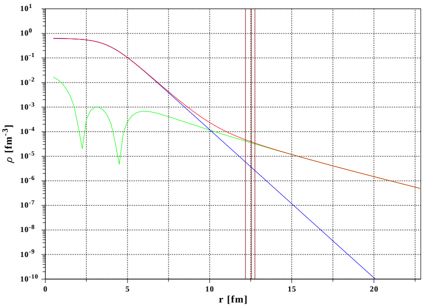

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- Negligible core contribution in the outer $r > r_0$ region
- Need of quantitative description of halo region

Average number of nucleons in the halo

$$N_{halo} = 4\pi \int_{r>r_0} r^2 \rho(r)\, dr$$

Effect of halo region on nuclear extension

$$\begin{aligned} \delta R_{halo} &= R_{rms,tot} - R_{rms,inner} \\ &= \sqrt{\frac{< r^2 >}{< r^0 >}} - \sqrt{\frac{\int_{r<r_0} r^4 \rho(r)\, dr}{\int_{r<r_0} r^2 \rho(r)\, dr}} \end{aligned}$$

- Extensions to all radial moments possible as an extension
- Correlated within a single isotopic series / decoupled for systematics
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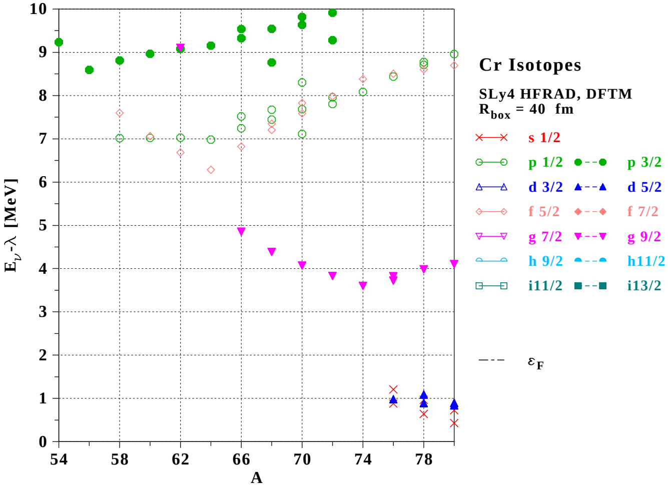
Outline

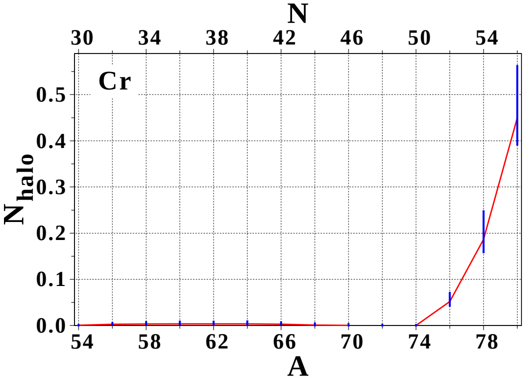
Cr Isotopes

- QP energies: excitation spectrum of $(N-1)$-body system
- Low-lying $3s_{1/2}$ and $2d_{5/2}$ states / ideal conditions regarding energy scales



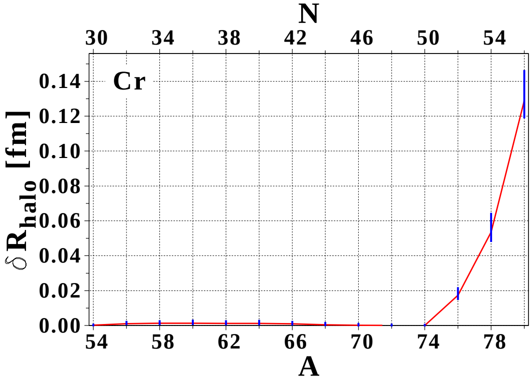
Cr Isotopes

- Average number of nucleons in the halo region
- No effect before $N = 50$ shell closure / sharp increase beyond
- Small value Vs N BUT same order as in light halo nuclei



Cr Isotopes

- Influence of the halo region on the nuclear extension
- No effect before $N = 50$ shell closure / sharp increase beyond
- Important contribution to total r.m.s. radius + separation of shell effects



Evidence of halo formation

Cr Isotopes

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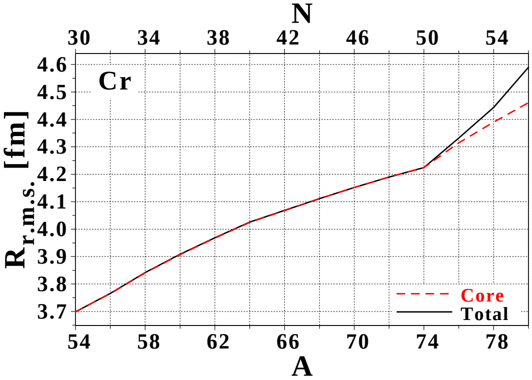
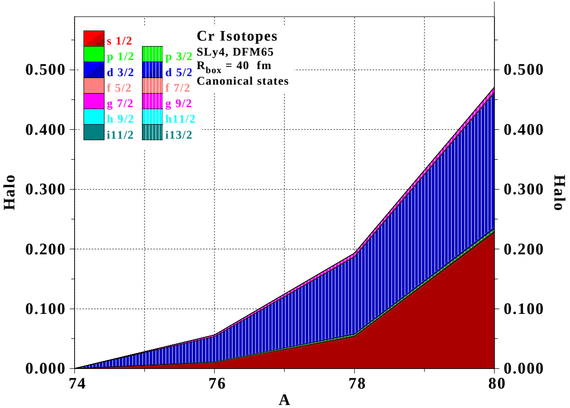


Only relevant physics extracted

Cr Isotopes

- Individual contributions to the halo (canonical basis)
- Only least-bound states contribute
- Major contribution from $2d_{5/2}$ state (degeneracy + v^2)



Formation of a Collective halo

Cr Isotopes : Conclusion

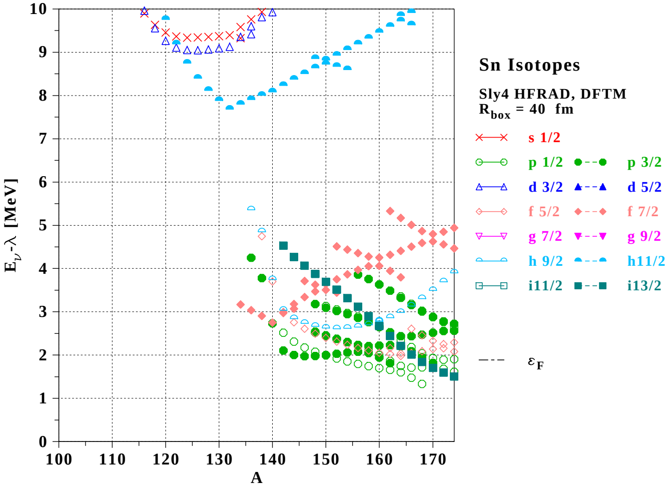
- Small relative effect : $N_{halo} \sim 0.5$ for ^{80}Cr
- Significant contribution from halo to the nuclear extension
- Contributions from multiple states, including $\ell = 2$
- Absolute values of N_{halo} comparable with situation in light halo nuclei

  $\Rightarrow$ s-wave halo nucleus (^{11}Be) : $N_{halo} \approx .35$
- No "Giant" halo...

Converging leads for formation of collective halo in drip-line Cr isotopes

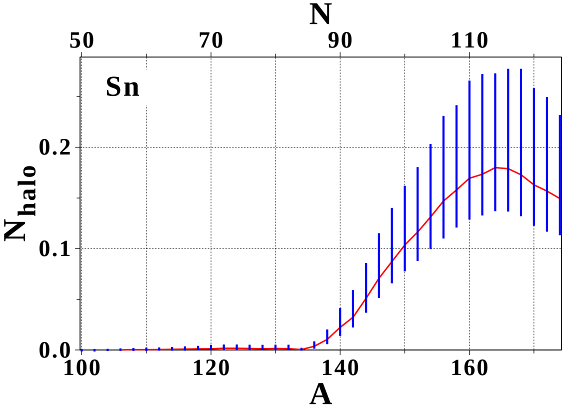
Sn Isotopes

- Lot of collectivity / large bunch of high-ℓ states at drip-line
- Not favorable energy scales



Sn Isotopes

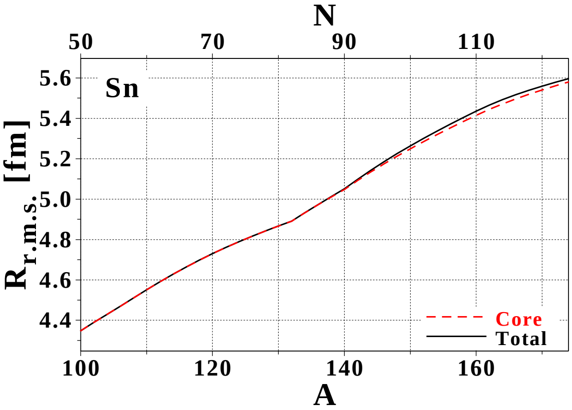
- Number of nucleons in the halo region
- No effect before $N = 82$ shell closure
- Small absolute contribution: one third of Cr isotopes



- Hindrance from filling high-ℓ state at the drip-line

Sn Isotopes

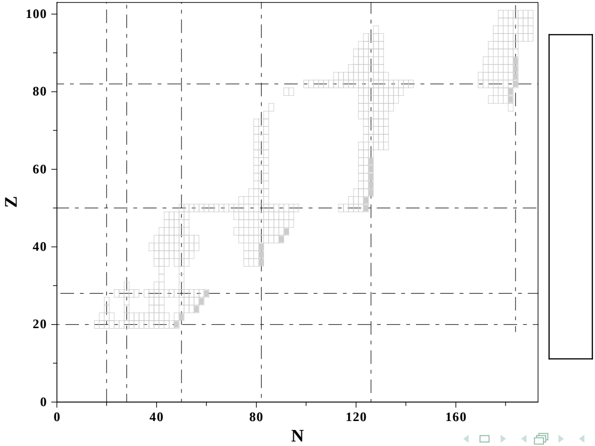
- Influence of the halo region on the nuclear extension
- Very small effect on nuclear extension



No halo seen

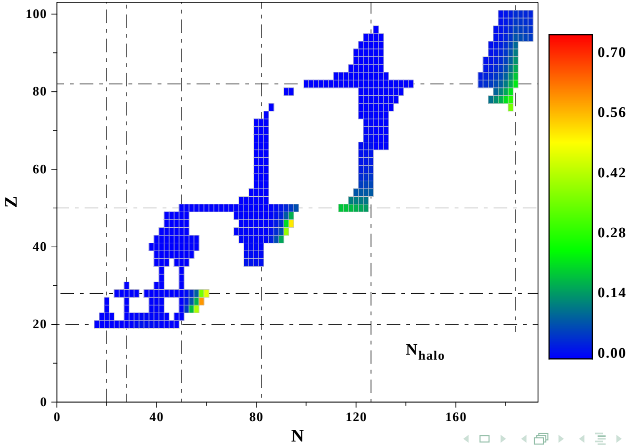
Systematics

- Systematics over ∼ 500 spherical nuclei given by CEA-D1S online database



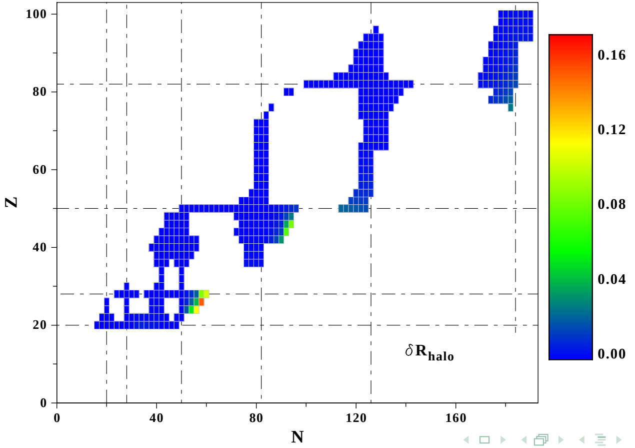
Systematics

- Systematics over ∼ 500 spherical nuclei given by CEA-D1S online database
- Number of nucleons in the halo region
- Decorrelated nucleons at the very drip line for several isotopes



Systematics

- Systematics over ∼ 500 spherical nuclei given by CEA-D1S online database
- Influence on total extension
- Different information from N_{halo}: reduced impact for heavy nuclei (collectivity)
- Best candidates: Fe, Cr, Ni, Pd, Ru



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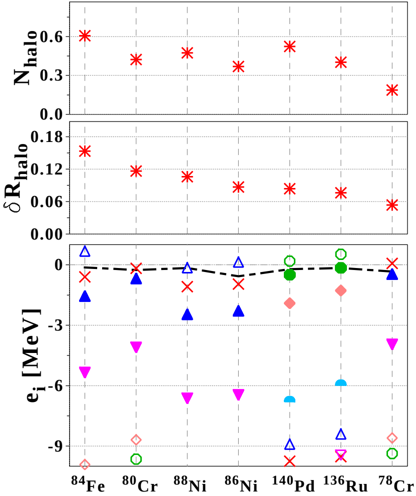
Common denominator :
low-lying $\ell = 0, 1$ states



Influence of EDF characteristics on halo formation

Role of pairing correlations

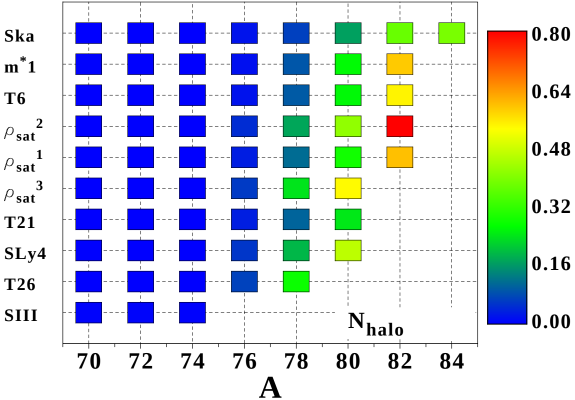
- Effect of surface Vs volume-type pairing on weakly bound states
- Pairing anti-halo effect
  [K. Bennaceur *et al.*, Phys. Lett. **B496** (2000) 154]
  - Extra localization of QP states from pairing field
  - Prevents divergences of r.m.s. radius from weakly bound states
- Particular role of *s*-waves
  [I. Hamamoto, B. Mottelson, Phys. Rev. **C68** (2003) 034312]
  - Extreme situations : $\lambda \longrightarrow 0$, $e_s \longrightarrow 0$
  - Decoupling of *s*-wave from pairing field : classical halo
  - Not encountered in realistic situations

Influence of the particle-hole energy functional

- Role of new terms: tensor interaction. . .
- Influence of INM properties: effective mass, compressibility, saturation point. . .
- Influence of the parametrization

Limits of current energy functionals

- Constrain low-density behavior of EDF using halo data ?



N_{halo} :
Average number of nucleons

δR_{halo} :
Influence on spatial extension

S_{2N} :
2n separation energy

- Strong dependence of halo features on EDF parametrization
  - Already known for other basic observables / drip-lines
- Predictivity of current EDF models for exotic systems ?

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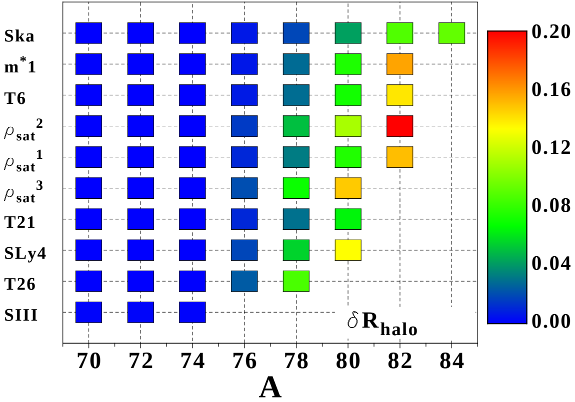

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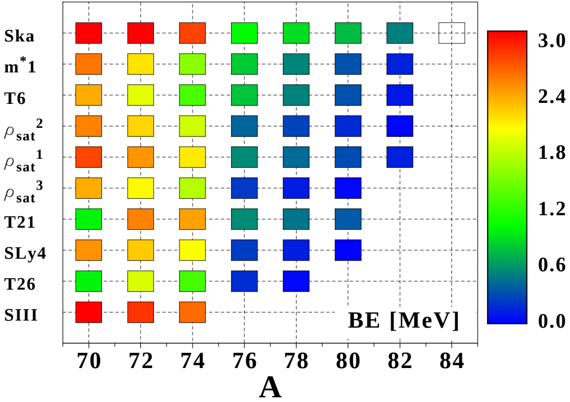

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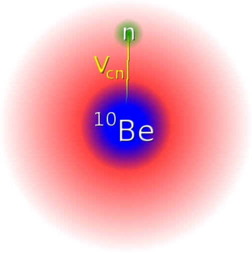
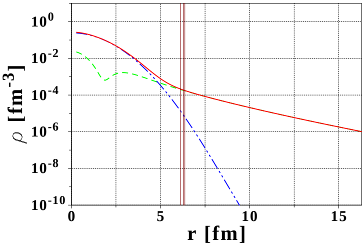
Application to Other Halo Systems

- Model-independent analysis: can be used for other systems
- Light nuclei from Coupled-Channels calculations (2-body clusters only)

  [F. Nunes *et al.*, Nucl. Phys. **596** (1996) 171 - Nucl. Phys. **A609** (1996) 43]





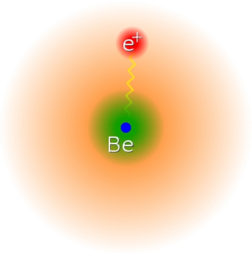
	N_{halo}	δR_{halo} [fm]	R_{rms} [fm]
^{13}C	$0.66.10^{-3}$	$0.74.10^{-3}$	2.487
^{11}Be	0.270	0.394	2.908

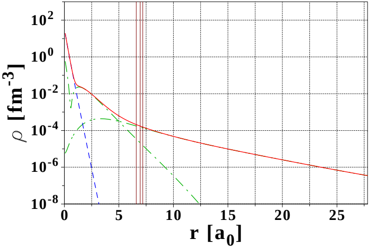
- Good separation between halo/non-halo systems
- Absolute value for δR_{halo}: much bigger Vs medium-mass nuclei (collectivity)

Application to Other Halo Systems

- Model-independent analysis: can be used for other systems
- Atom-positron complexes: e^+ binding to neutral atom by polarization potential

[J. Mitroy, Phys. Rev. Lett. **94** (2005) 033402]





- Asymptotics: $e^+ + A$ or $Ps + A^+$

	N_{e-}	N_{halo}	$R_{r.m.s.}$	δR_{halo}	P_{e+}	P_{e-}
Be	4	0.624	5.661	3.194	98.1	01.9
Mg	12	0.669	2.298	0.826	80.3	19.7
Cu	29	0.754	1.777	0.975	88.6	11.4
He	2	1.982	15.472	14.568	50.3	49.7
Li	3	1.972	7.781	7.088	50.8	49.2

- P_X (%): proportion of X in halo outer region
- Positron ($P_{e^+} \gg P_{e^-}$) and positronium ($P_{e^+} \approx P_{e^-}$) halos identified

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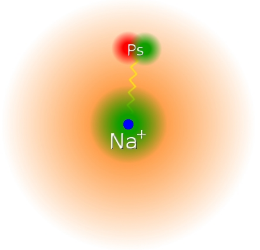
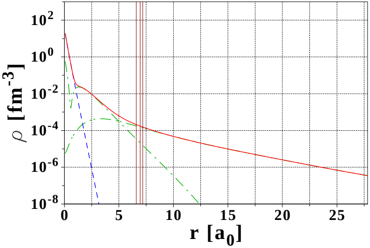
- Model-independent analysis: can be used for other systems
- Atom-positron complexes: e^+ binding to neutral atom by polarization potential
  [J. Mitroy, Phys. Rev. Lett. **94** (2005) 033402]





- Asymptotics:
  $e^+ + A$ or $Ps + A^+$

	N_{e-}	N_{halo}	$R_{r.m.s.}$	δR_{halo}	P_{e+}	P_{e-}
Be	4	0.624	5.661	3.194	98.1	01.9
Mg	12	0.669	2.298	0.826	80.3	19.7
Cu	29	0.754	1.777	0.975	88.6	11.4
He	2	1.982	15.472	14.568	50.3	49.7
Li	3	1.972	7.781	7.088	50.8	49.2

- P_X (%): proportion of X in halo outer region
- Positron ($P_{e^+} \gg P_{e^-}$) and positronium ($P_{e^+} \approx P_{e^-}$) halos identified

Outline

Conclusion

- New analysis method based on analysis of intrinsic one-body density
- Model-independent criteria for halo formation

- Cr Isotopes
  - Small relative number of nucleons in halo region / Comparable with light systems
  - Large influence of halo region on nuclear extension
  - Contribution from several weakly bound states, including $l = 2$
  - Notion of "giant halo" : meaningless...

Formation of a collective halo in Cr isotopes

- Systematics over spherical nuclei
  - Good candidates : drip-line Fe, Cr, Ni, Pd, Ru
  - Experimental validation in drip-line medium-mass region ?

- Successful application to light nuclei and atom-positron complexes
  - Correct extraction of halo factors
  - Proves model-independence

Conclusion

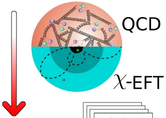
- Extension of the method
  - Deformed nuclei : multipolar moments of the density
  - Multi-reference EDF effects : PNP, GCM on breathing modes...
  - Inclusion of cluster correlations: hindrance to halo formation?
  - Study of correlations: two-body density
- Link with experimental studies: open question
  - Neutron drip-lines beyond reach for medium-mass nuclei
  - Robust method BUT no robust predictions
  - High sensitivity to EDF parametrization

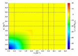
Fine tuning of EDF based on experimental data: not yet

  - Halo: (very) rare exotic phenomenon
  - Missing terms in current functionals
- Lot of work needed first on EDF used in single/multi-vacua calculations

Long-range plan

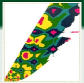
- Microscopic vertex from χ-EFT / low-momentum interactions + nuclei properties





Ground state

Mass, deformation

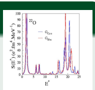


Spectroscopy

Excited states

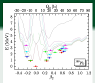
Collective modes

RPA, QRPA, GCM



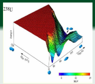
Symmetry restoration

J Projection, PNP



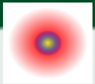
Heavy elements

Fission, superheavy



Exoticity

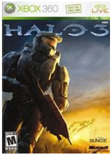
Drip-lines, halos



Astrophysics

r-process, SN

Commercial break



V. R. and T. Duguet
Halo phenomenon in medium-mass nuclei.
I. New analysis method and first applications
nucl-th/0702050

V. R., K. Bennaceur and T. Duguet
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II. Impact of correlations and large scale analysis
arXiv:0711.1275

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