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Halo & shape decoupling effect in deformed nuclei

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P. Ring (TU Munich & PKU), Xiang-Xiang Sun (ITP)
Jie Zhao (ITP), En-Guang Zhao (ITP)

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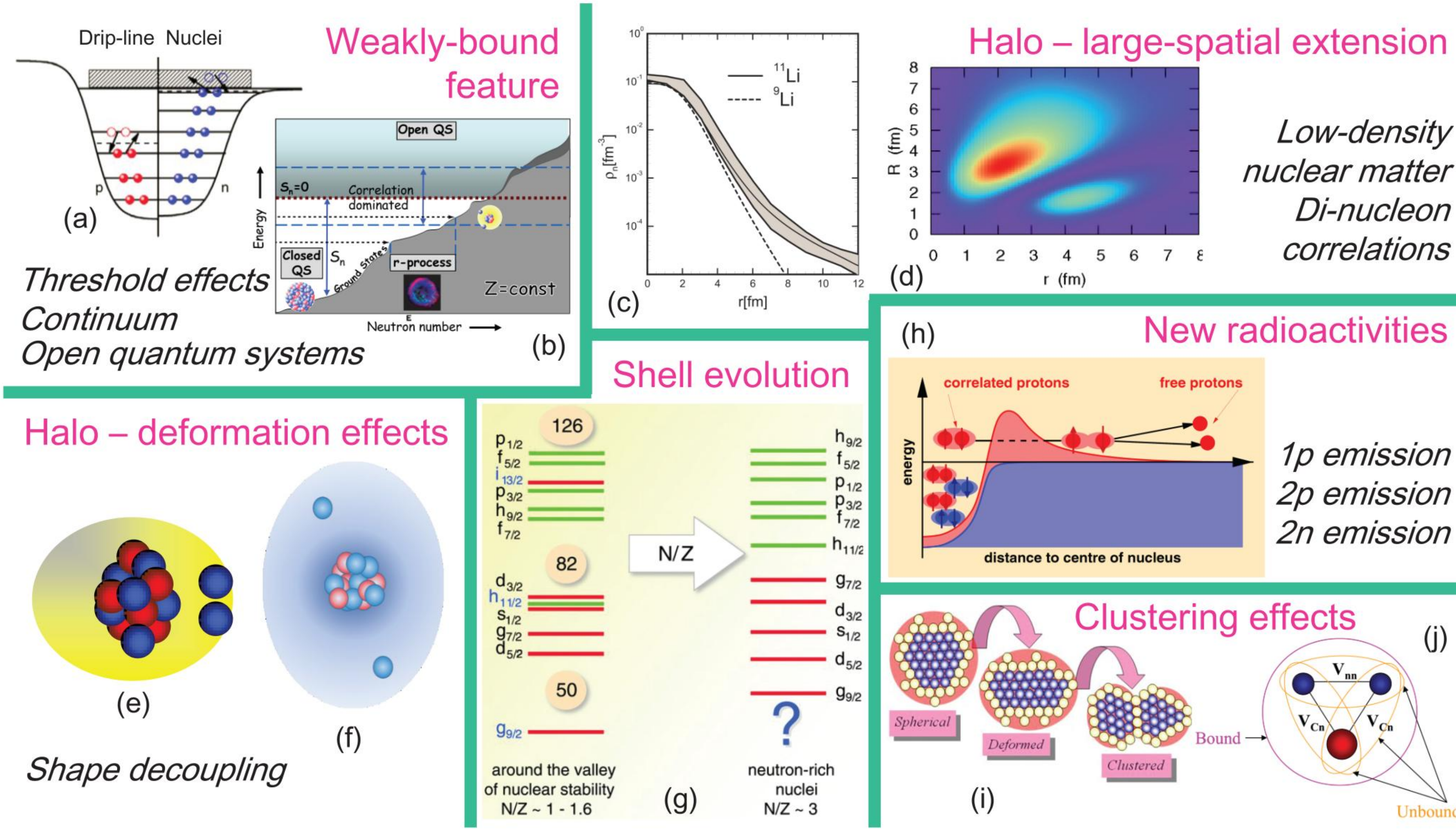
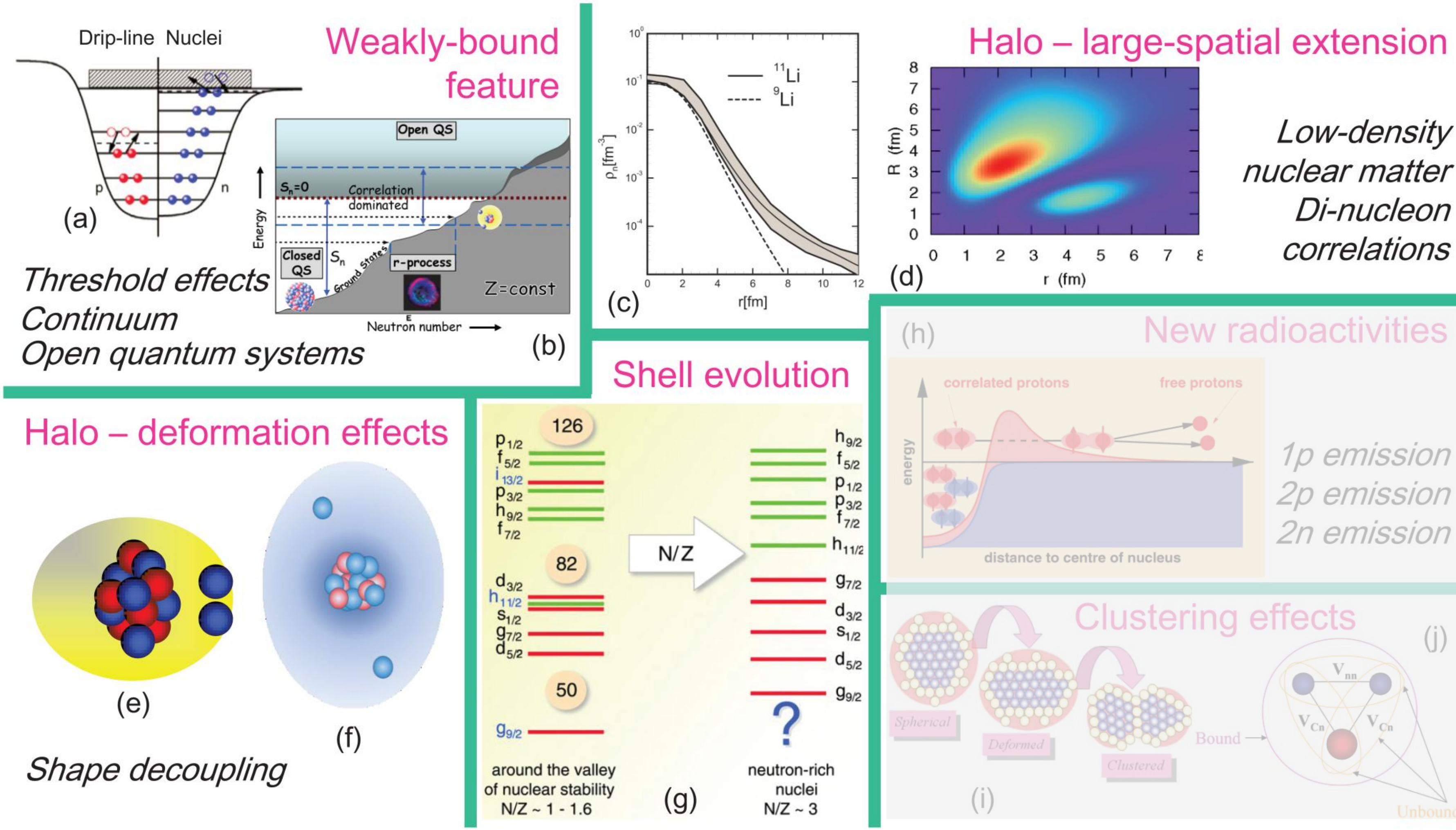
Physics in exotic nuclear structure



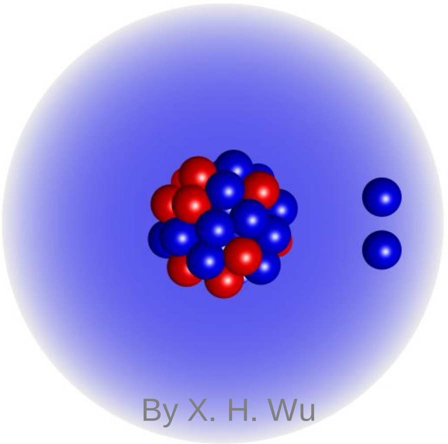
SGZ, PoS (INPC2016) 373

Physics in exotic nuclear structure

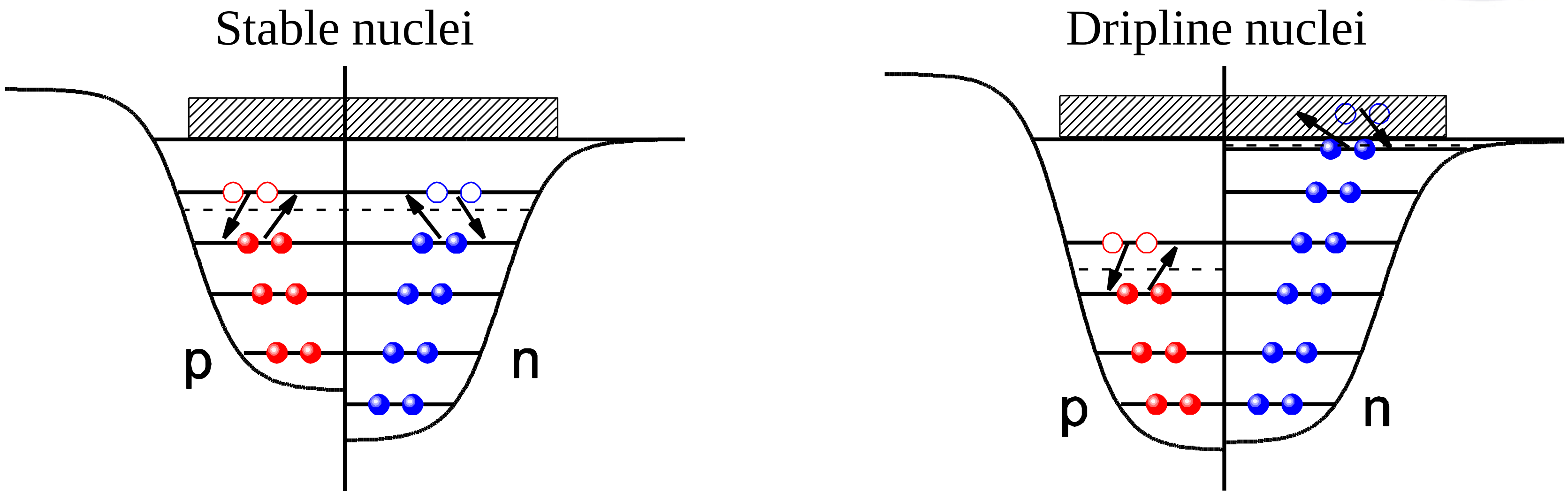


SGZ, PoS (INPC2016) 373

Characteristics of halo nuclei



- ☐ Weakly bound; large spatial extension
- ☐ Continuum can not be ignored



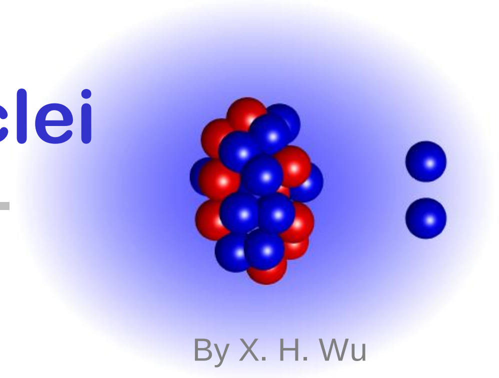
Self-consistent description:

- Weakly bound, continuum
- Large spatial distribution
- Couplings among …

Meng_Toki_SGZ_Zhang_Long_Geng2006
Prog. Part. Nucl. Phys. 57-470
Meng & SGZ 2015, J. Phys. G42-093101

Bulgac1980; nucl-th/9907088
Dobaczewski_Flocard_Treiner1984_NPA422-103

Characteristics of deformed halo nuclei



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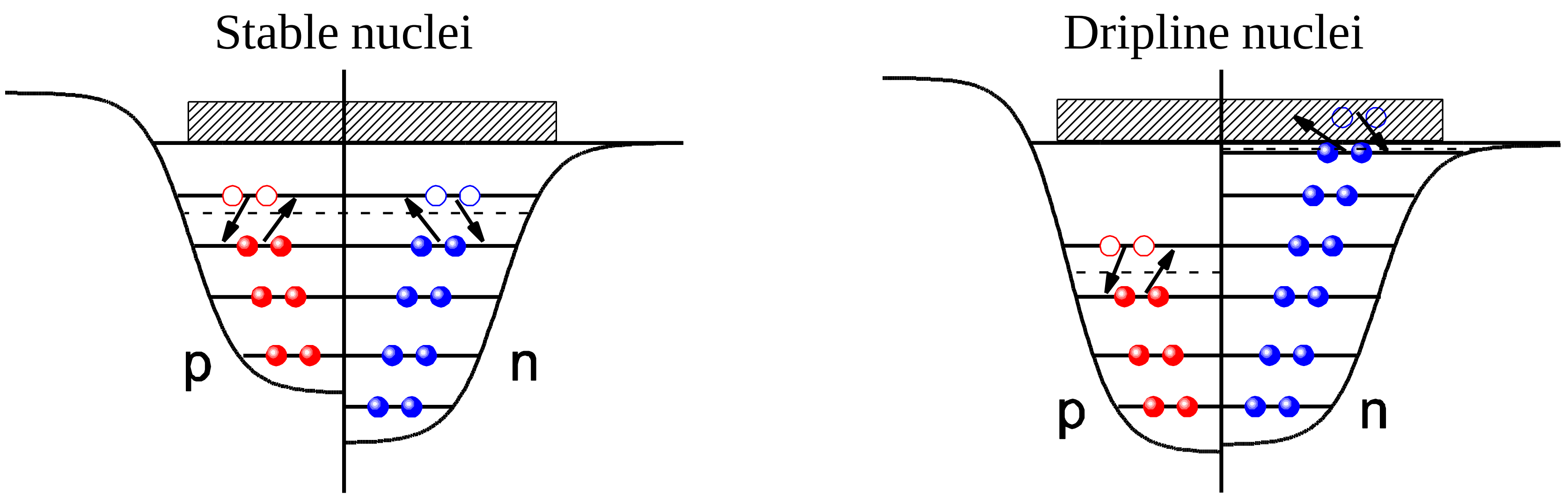

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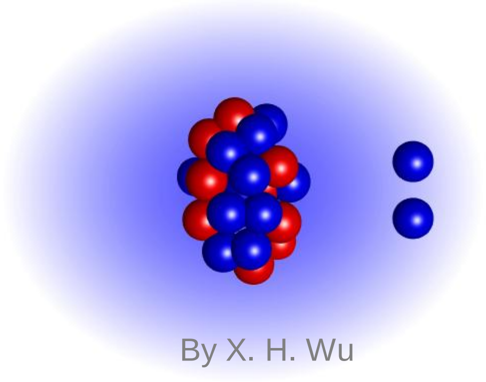
What we aim at



A self-consistent description of

- ✓ Deformation
- ✓ Continuum contribution
- ✓ Large spatial distribution
- ✓ Interplays among them

by developing a
relativistic Hartree-Bogoliubov model

Covariant Density Functional Theory (CDFT)

$$\begin{aligned}\mathcal{L} =& \bar{\psi}_i (i\partial\!\!\!/ - M)\psi_i + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - g_\sigma\bar{\psi}_i\sigma\psi_i \\ &- \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - g_\omega\bar{\psi}_i\omega\!\!\!/\psi_i \\ &- \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu - g_\rho\bar{\psi}_i\vec{\rho\!\!\!/}\vec{\tau}\psi_i \\ &- \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - e\bar{\psi}_i\frac{1-\tau_3}{2}A\!\!\!/\psi_i,\end{aligned}$$

Serot_Walecka1986_ANP16-1

Reinhard1989 RPP52-439

Ring1996_PPNP37-193

Vretenar_Afanasjev_Lalazissis_Ring2005_PR409-101

Meng_Toki_SGZ_Zhang_Long_Geng2006_PPNP57-470

Liang_Meng_SGZ2015_PR570-1

Meng_SGZ2015_JPG42-093101

$$(\boldsymbol{\alpha}\cdot\mathbf{p} + \beta(M + S(\mathbf{r})) + V(\mathbf{r}))\psi_i = \epsilon_i\psi_i$$

$$\left(-\nabla^2 + m_\sigma^2\right)\sigma = -g_\sigma\rho_S - g_2\sigma^2 - g_3\sigma^3$$

$$\left(-\nabla^2 + m_\omega^2\right)\omega = g_\omega\rho_V - c_3\omega^3$$

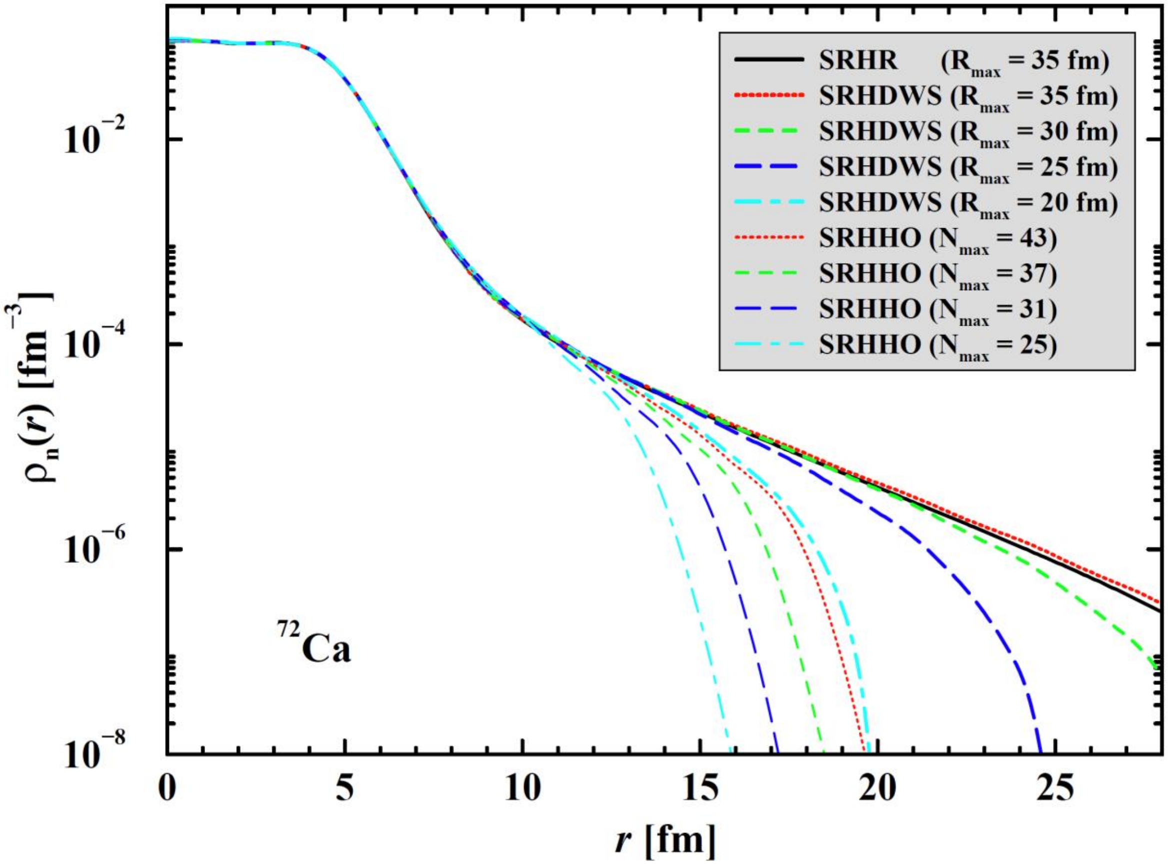
$$\left(-\nabla^2 + m_\rho^2\right)\rho = g_\rho\rho_3$$

$$-\nabla^2 A = e\rho_C$$

CDFTs in a Woods-Saxon basis

Shapes	Model	Schrödinger W-S basis	Dirac W-S basis	
Spherical	Rela. Hartree	SRH SWS	SRH DWS	√
		SGZ_Meng_Ring2003_PRC91-262501		

Why Woods-Saxon basis ?



Woods-Saxon basis is a reconciler between the HO basis & *r* space

- Reproduces results of *r* space
- Matrix diagonalization, numerically less complicated than HO

SGZ_Meng_Ring 2003_PRC91-262501

CDFTs in a Woods-Saxon basis

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Axially deformed	Rela. Hartree + BCS		DRH DWS	√
	SGZ_Meng_Ring2006_AIP Conf. Proc. 865-90			

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Woods-Saxon basis is a reconciler between the HO basis & *r* space

Density dependent DRHB theory in continuum

Chen_Li_Liang_Meng2012_PRC85-067301

Schunck_Egido2008_PRC77-011301R; PRC78-064305

Long_Ring_Giai_Meng2010_PRC81-024308

Deformed RHB theory in continuum

Kucharek_Ring1991_ZPA339-23

$$\sum_{\sigma'p'}\int d^3\boldsymbol{r}'\begin{pmatrix} h_D(\boldsymbol{r}\sigma p,\boldsymbol{r}\sigma'p')-\lambda & \Delta(\boldsymbol{r}\sigma p,\boldsymbol{r}'\sigma'p') \\ -\Delta^*(\boldsymbol{r}\sigma p,\boldsymbol{r}'\sigma'p') & -h_D(\boldsymbol{r}\sigma p,\boldsymbol{r}\sigma'p')+\lambda \end{pmatrix}\begin{pmatrix} U_k(\boldsymbol{r}'\sigma'p') \\ V_k(\boldsymbol{r}'\sigma'p') \end{pmatrix} = E_k\begin{pmatrix} U_k(\boldsymbol{r}\sigma p) \\ V_k(\boldsymbol{r}\sigma p) \end{pmatrix}$$

Axially deformed nuclei

Woods-Saxon basis

$$\varphi_{i\kappa m}(\boldsymbol{r}\sigma) = \frac{1}{r}\begin{pmatrix} iG_{i\kappa}(r)Y^{l}_{jm}(\Omega\sigma) \\ -F_{i\kappa}(r)Y^{\tilde{l}}_{jm}(\Omega\sigma) \end{pmatrix}$$

$$U_k(\boldsymbol{r}\sigma p) = \sum_{i\kappa}\begin{pmatrix} u^{(m)}_{k,(i\kappa)}\varphi_{i\kappa m}(\boldsymbol{r}\sigma p) \\ u^{(\bar{m})}_{k,(i\tilde{\kappa})}\tilde{\varphi}_{i\kappa m}(\boldsymbol{r}\sigma p) \end{pmatrix}$$

$$V_k(\boldsymbol{r}\sigma p) = \sum_{i\kappa}\begin{pmatrix} v^{(m)}_{k,(i\kappa)}\varphi_{i\kappa m}(\boldsymbol{r}\sigma p) \\ v^{(\bar{m})}_{k,(i\tilde{\kappa})}\tilde{\varphi}_{i\kappa m}(\boldsymbol{r}\sigma p) \end{pmatrix}$$

$$\begin{pmatrix} \mathcal{A} & \mathcal{B} \\ \mathcal{C} & \mathcal{D} \end{pmatrix}\begin{pmatrix} \mathcal{U} \\ \mathcal{V} \end{pmatrix} = E\begin{pmatrix} \mathcal{U} \\ \mathcal{V} \end{pmatrix}$$

$$\mathcal{U} = \left(u^{(m)}_{k,(i\kappa)}\right),\quad \mathcal{V} = \left(v^{(m)}_{k,(\widetilde{i\kappa})}\right)$$

Deformed RHB theory in continuum

Kucharek_Ring1991_ZPA339-23

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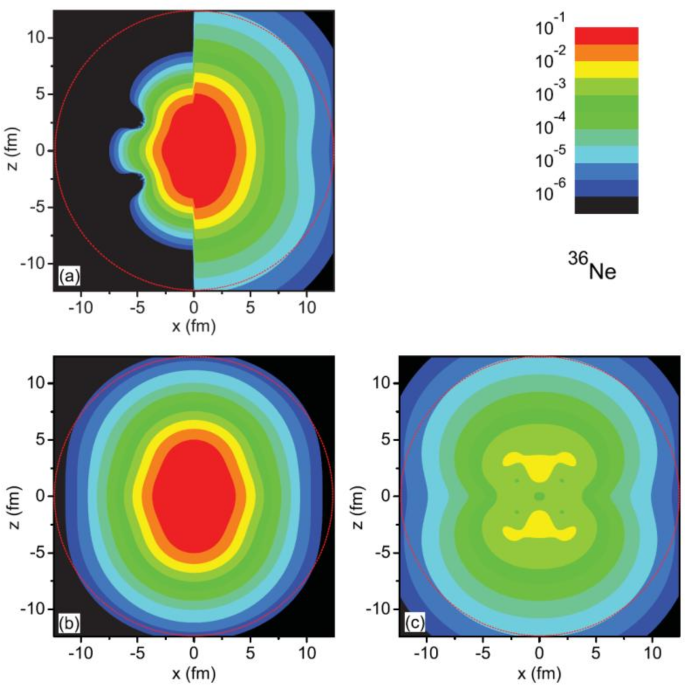
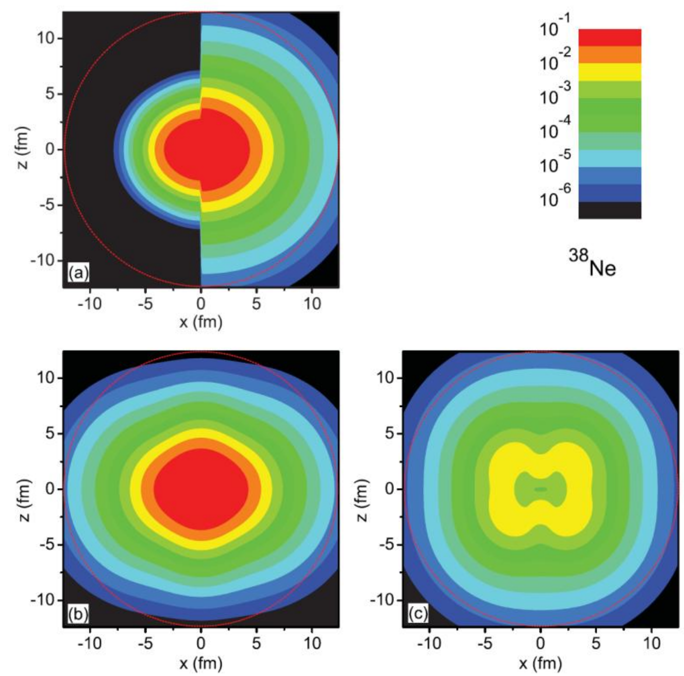
Conditions for occurrence of a halo & its shape

- Existence & deformation of neutron halo depend on quantum numbers of the main components of the s.p. orbits around Fermi surface
  - s levels with $\Lambda = 0 \Rightarrow$ spherical halos
  - p levels with $\Lambda = 0 \Rightarrow$ prolate halos
  - p levels with $\Lambda = 1 \Rightarrow$ oblate halos
  - d, f, ... levels: no halos

SGZ_Meng_Ring_Zhao 2010
PRC82-011301R
Li_Meng_Ring_Zhao_SGZ 2012
PRC85-024312





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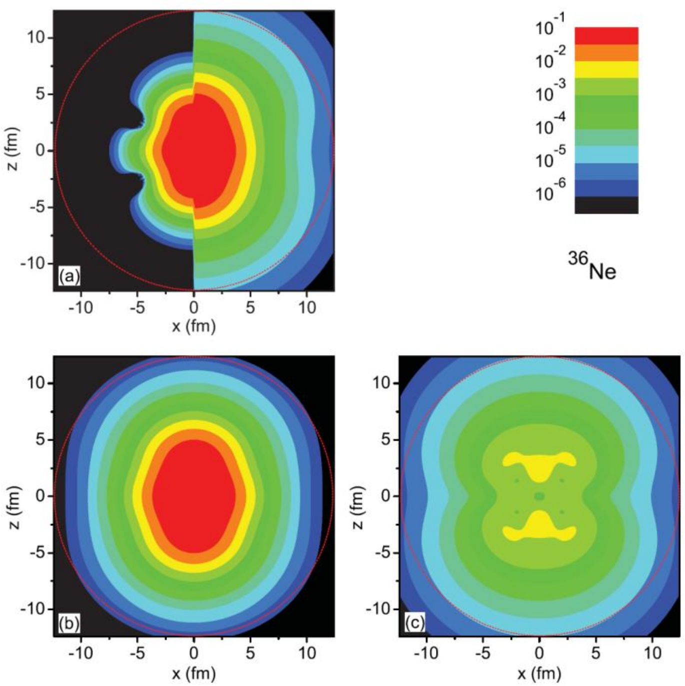
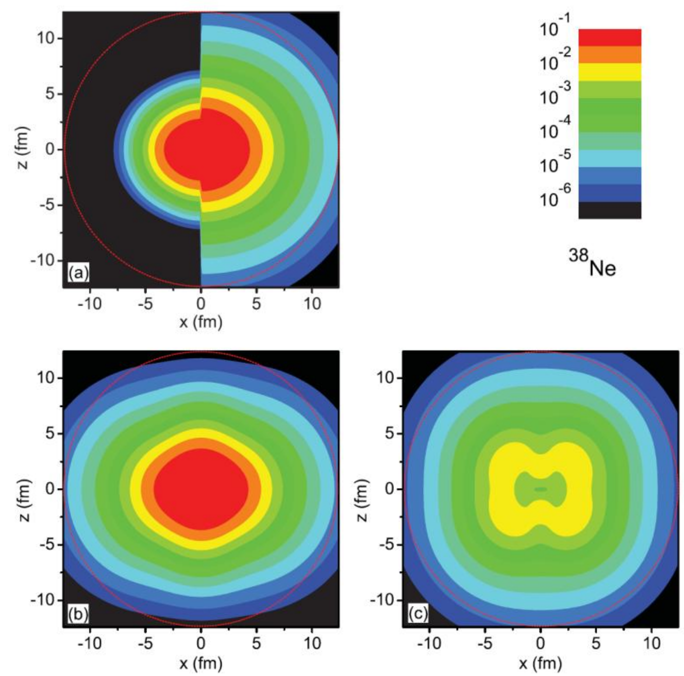
SGZ_Meng_Ring_Zhao 2010 PRC82-011301R
Li_Meng_Ring_Zhao_SGZ 2012 PRC85-024312

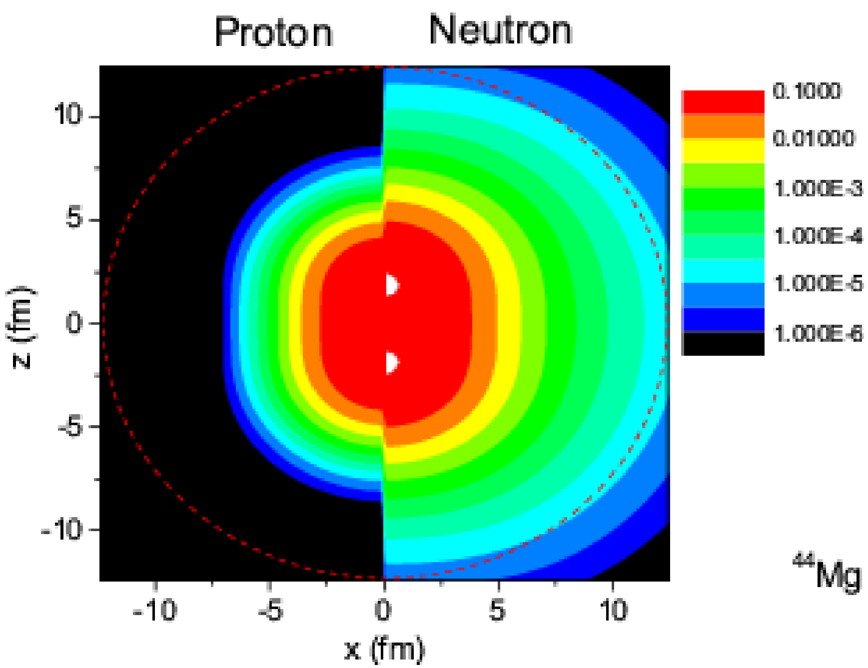
Pei_Zhang_Xu2013PRC87-051302R
Nakada_Takayama2018_PRC98-011301R

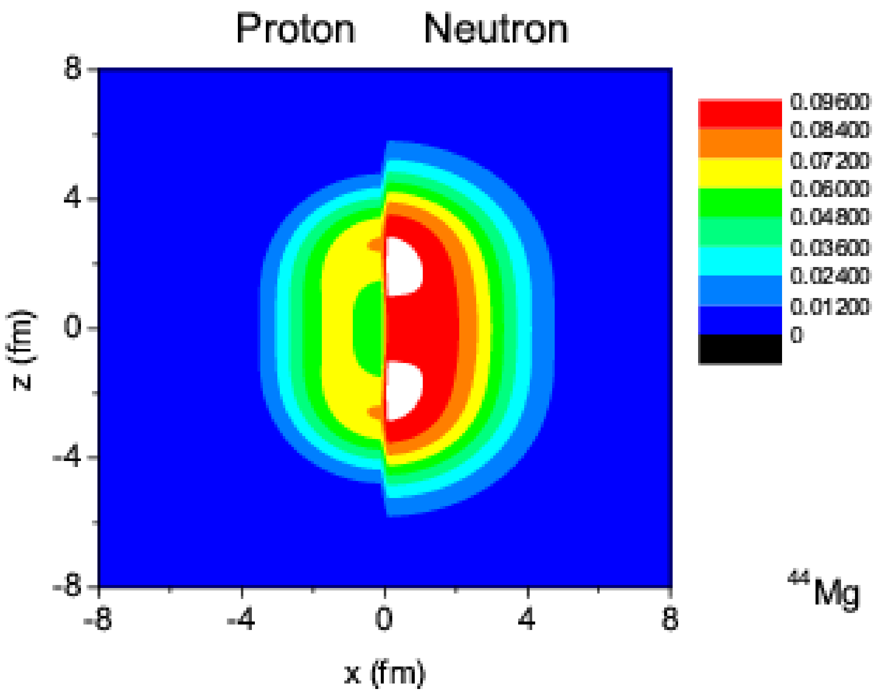




^{44}Mg: Density distributions

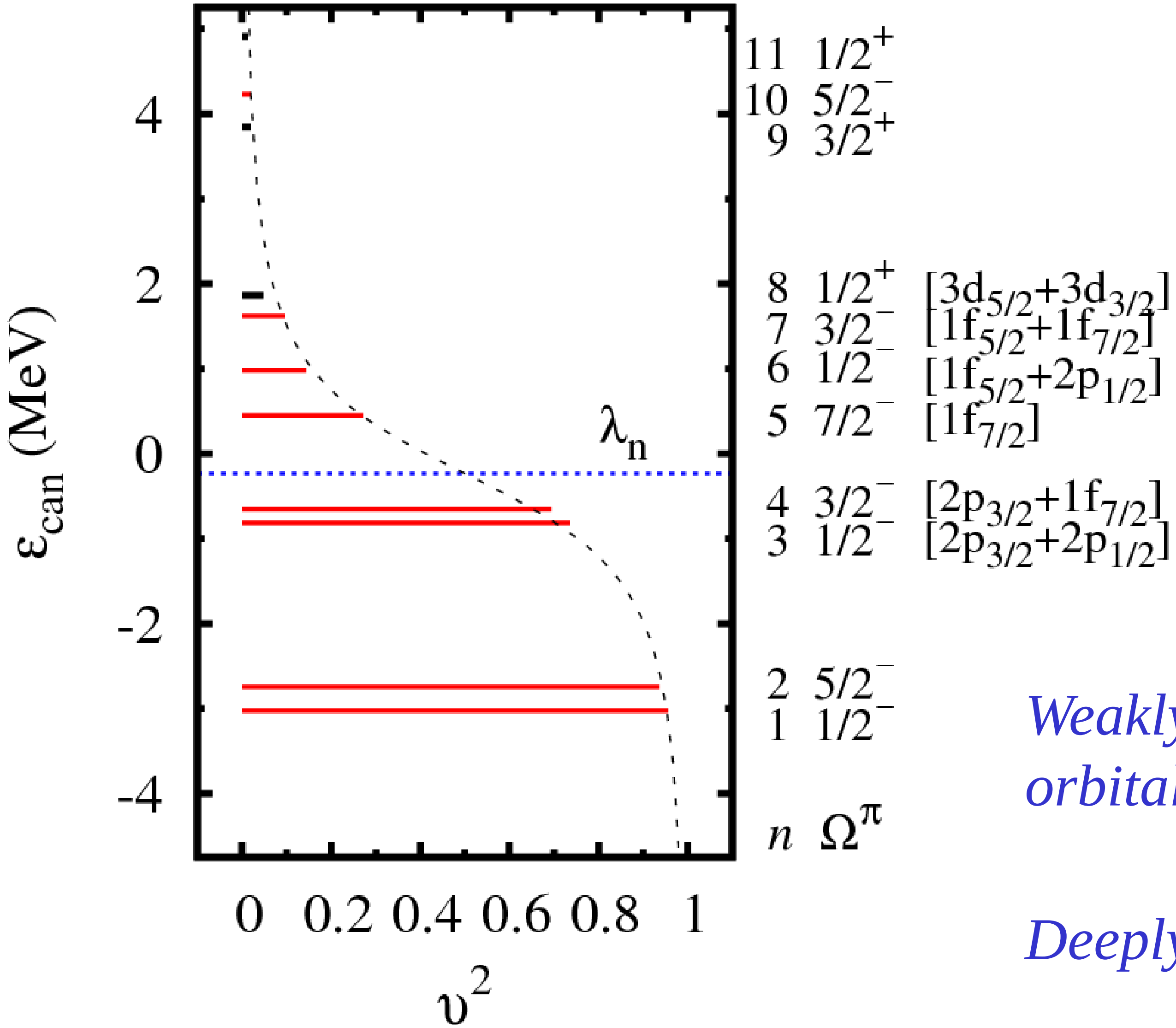
SGZ_Meng_Ring_Zhao 2010 PRC82-011301R
Li_Meng_Ring_Zhao_SGZ 2012 PRC85-024312





- Prolate deformation
- Large spatial extension in neutron density distribution

^{44}Mg: Single neutron states in canonical basis



Weakly bound & continuum orbitals

Deeply bound orbitals

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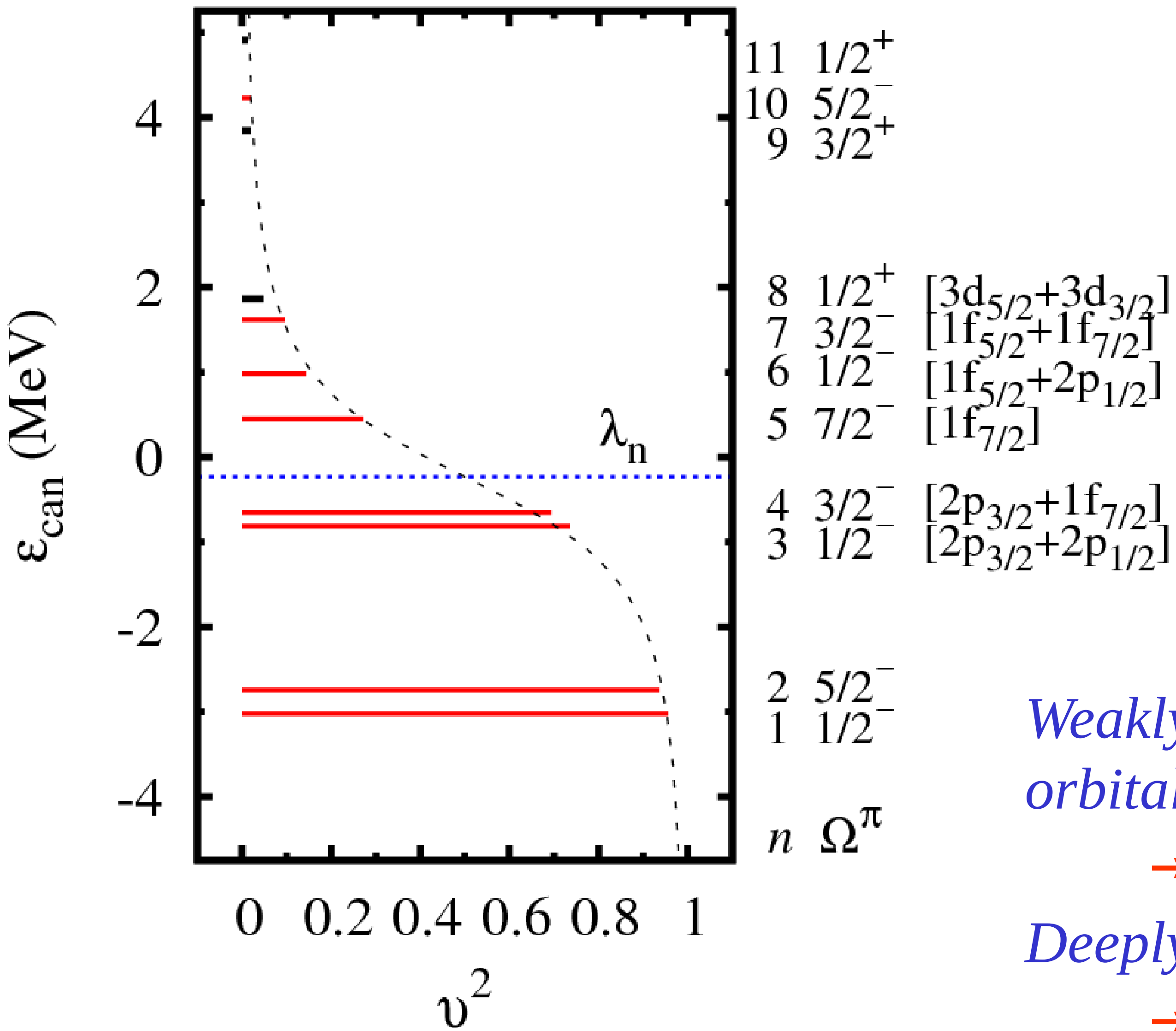


Weakly bound & continuum orbitals

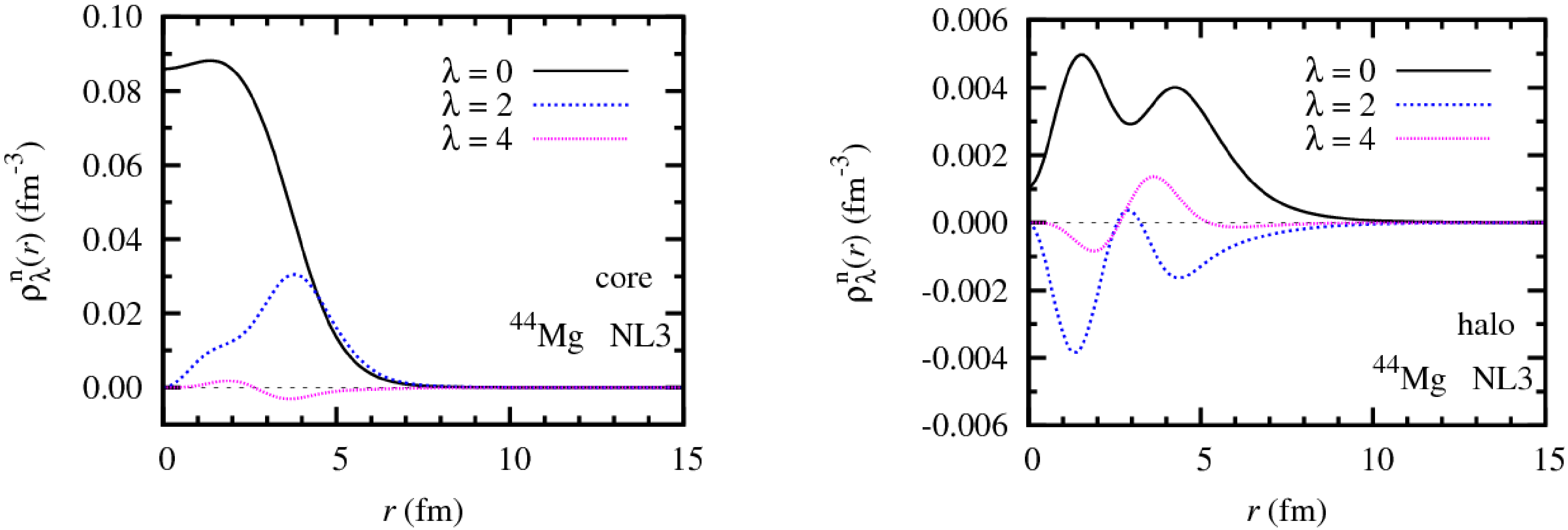
→ halo

Deeply bound orbitals

→ core

^{44}Mg: Density of core & halo---shape decoupling

$$\rho(\boldsymbol{r}) = \sum_{\lambda} \rho_\lambda(r) P_\lambda(\cos\theta), \ \ \lambda = 0, 2, 4, \cdots$$



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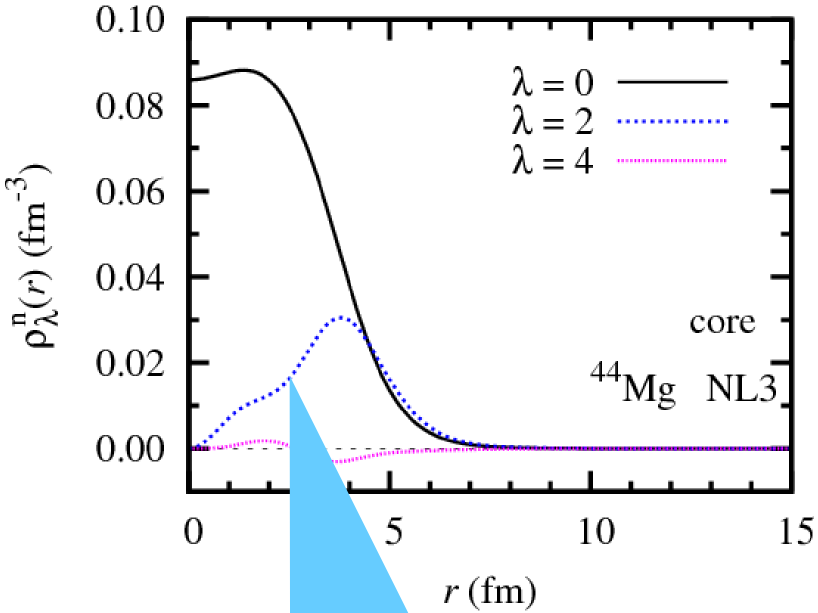

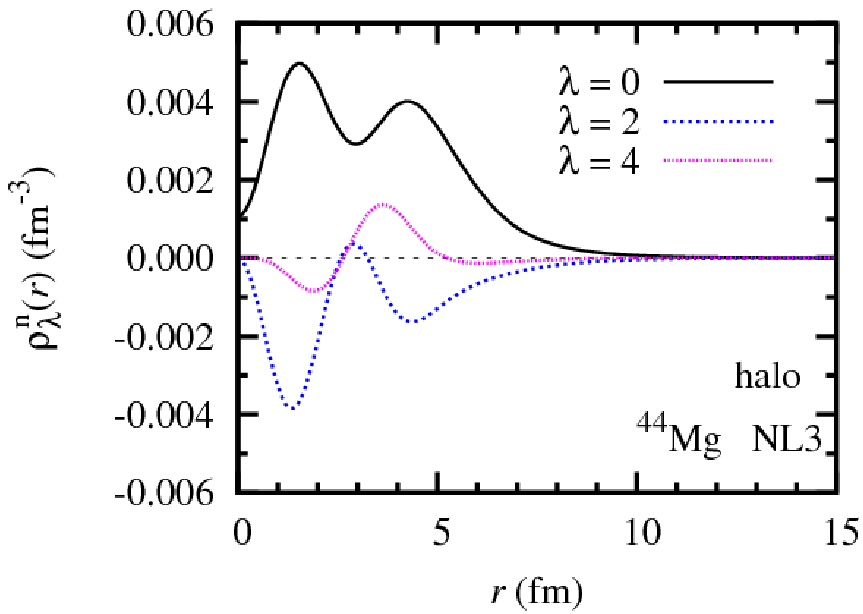

Core: prolate

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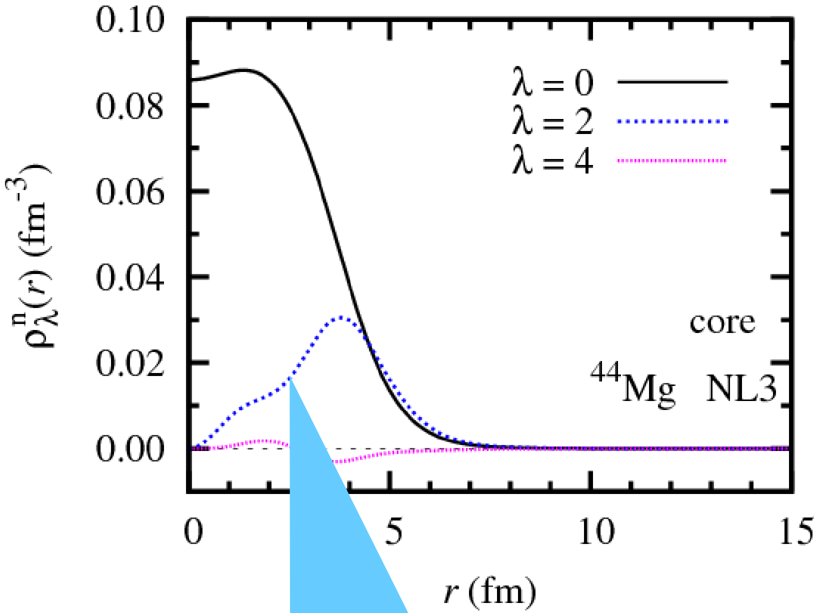
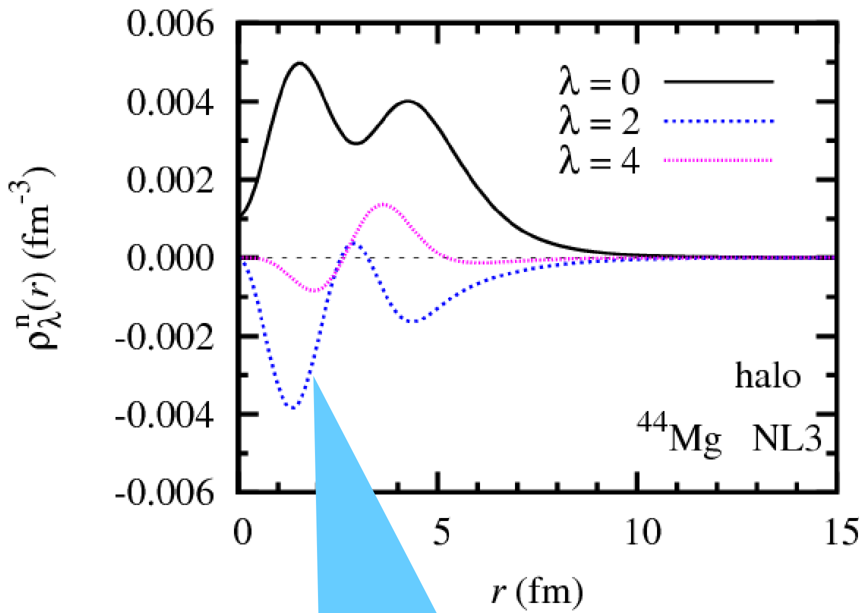
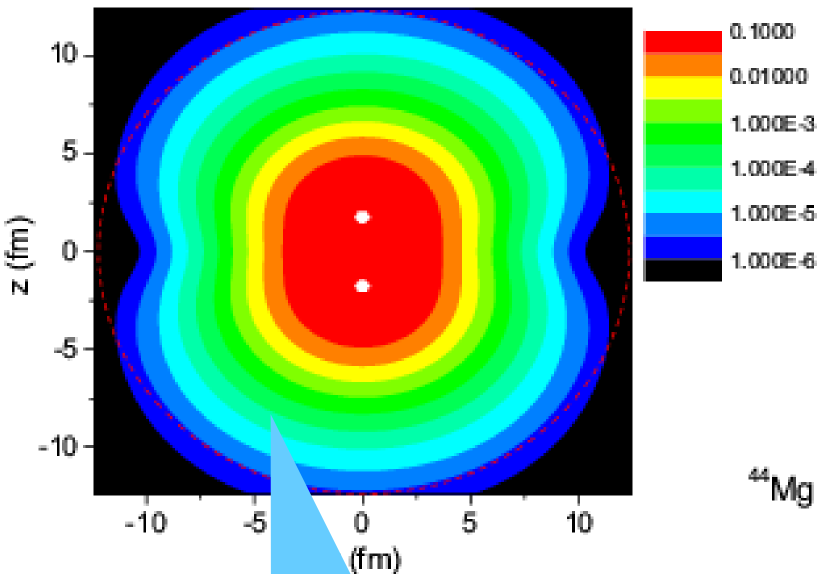


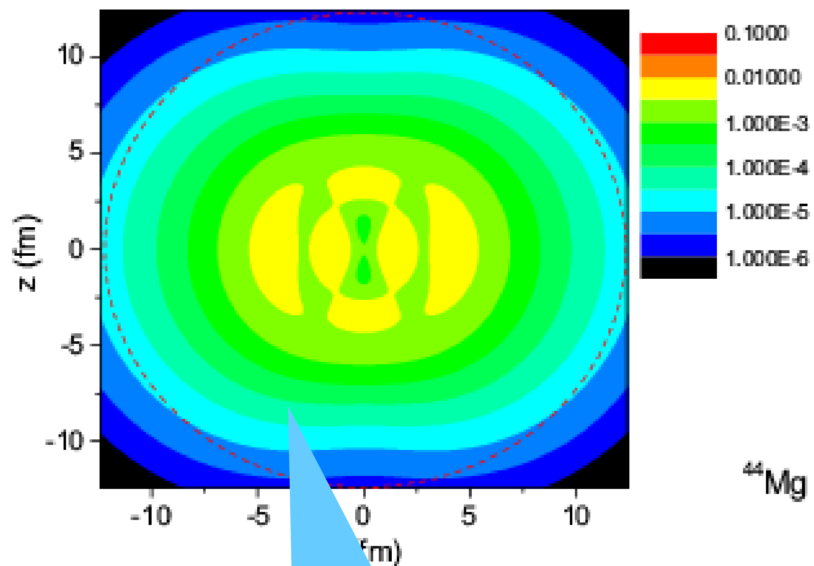


Core: prolate

halo: oblate

^{44}Mg: Density of core & halo---shape decoupling



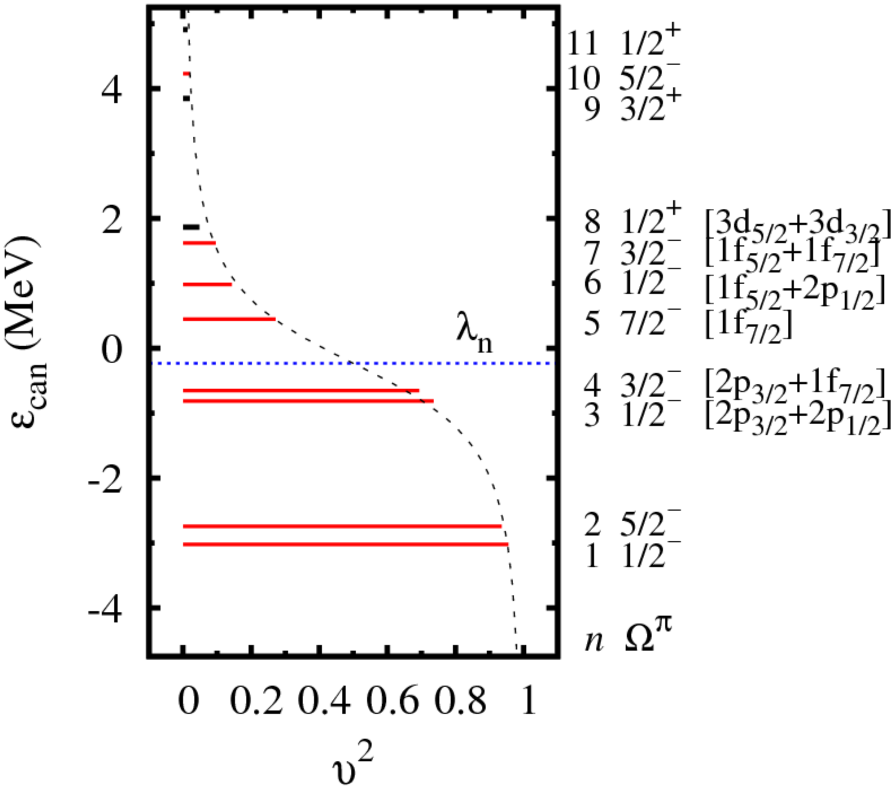


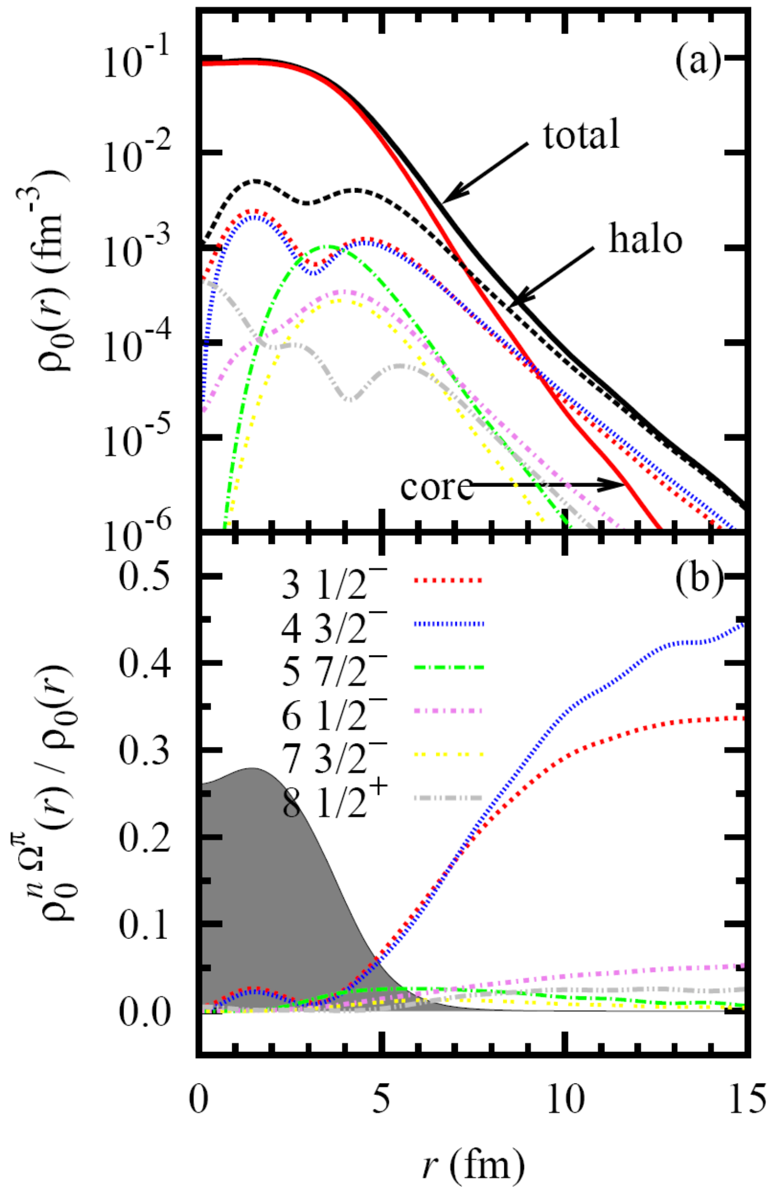
Core: prolate

halo: oblate

^{44}Mg: Decomposition of neutron density distribution

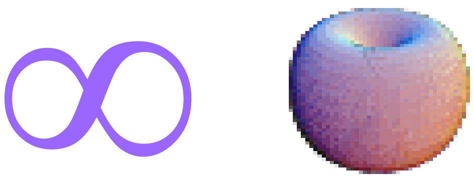
- The 3rd & 4th states contribute to tail part of neutron density distribution
- Main component: $2p_{3/2}$
- $R_{\mathrm{core}} = 3.72$ fm, $R_{\mathrm{halo}} = 5.86$ fm



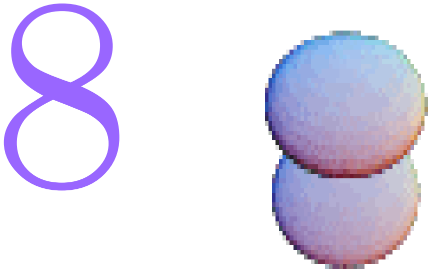


Shape of low-Λ single particle orbital

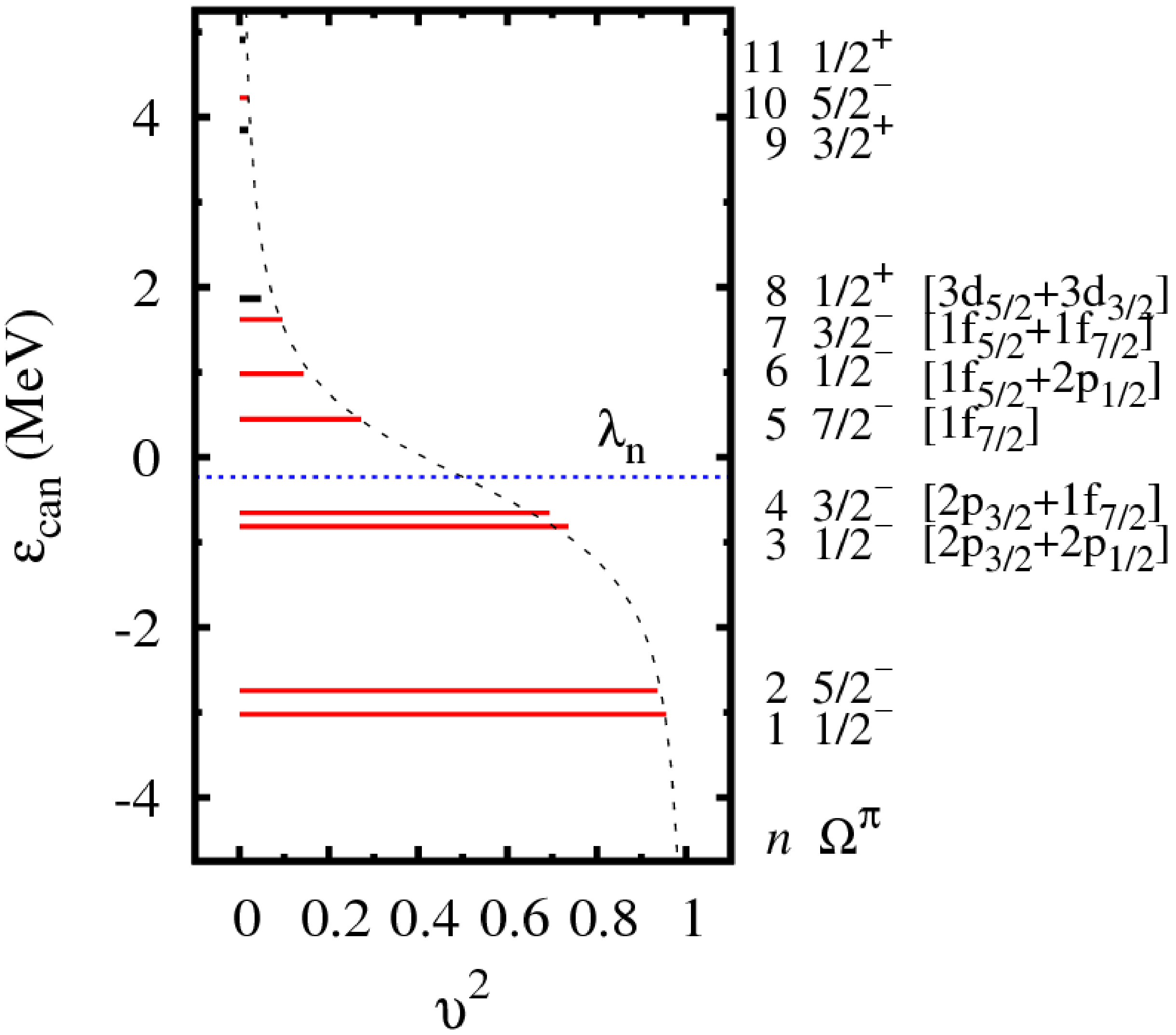
$l = 1, \Lambda = \pm 1$ $\quad |Y_{1\pm1}(\theta,\phi)|^2 \propto \sin^2(\theta)$



$l = 1, \Lambda = 0$ $\quad |Y_{10}(\theta,\phi)|^2 \propto \cos^2(\theta)$



Mechanism of shape decoupling



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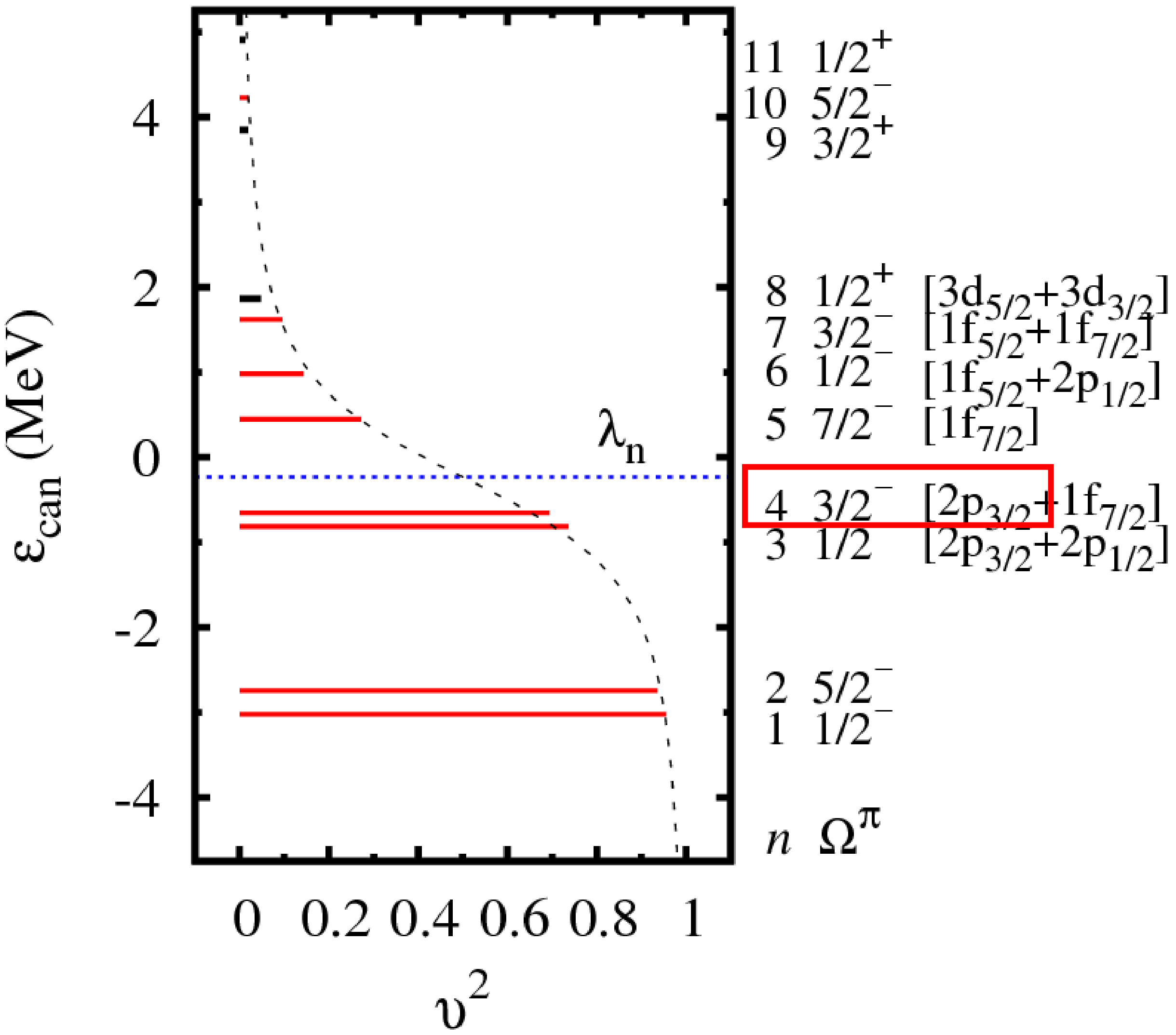
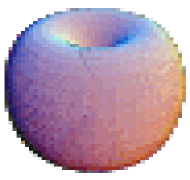
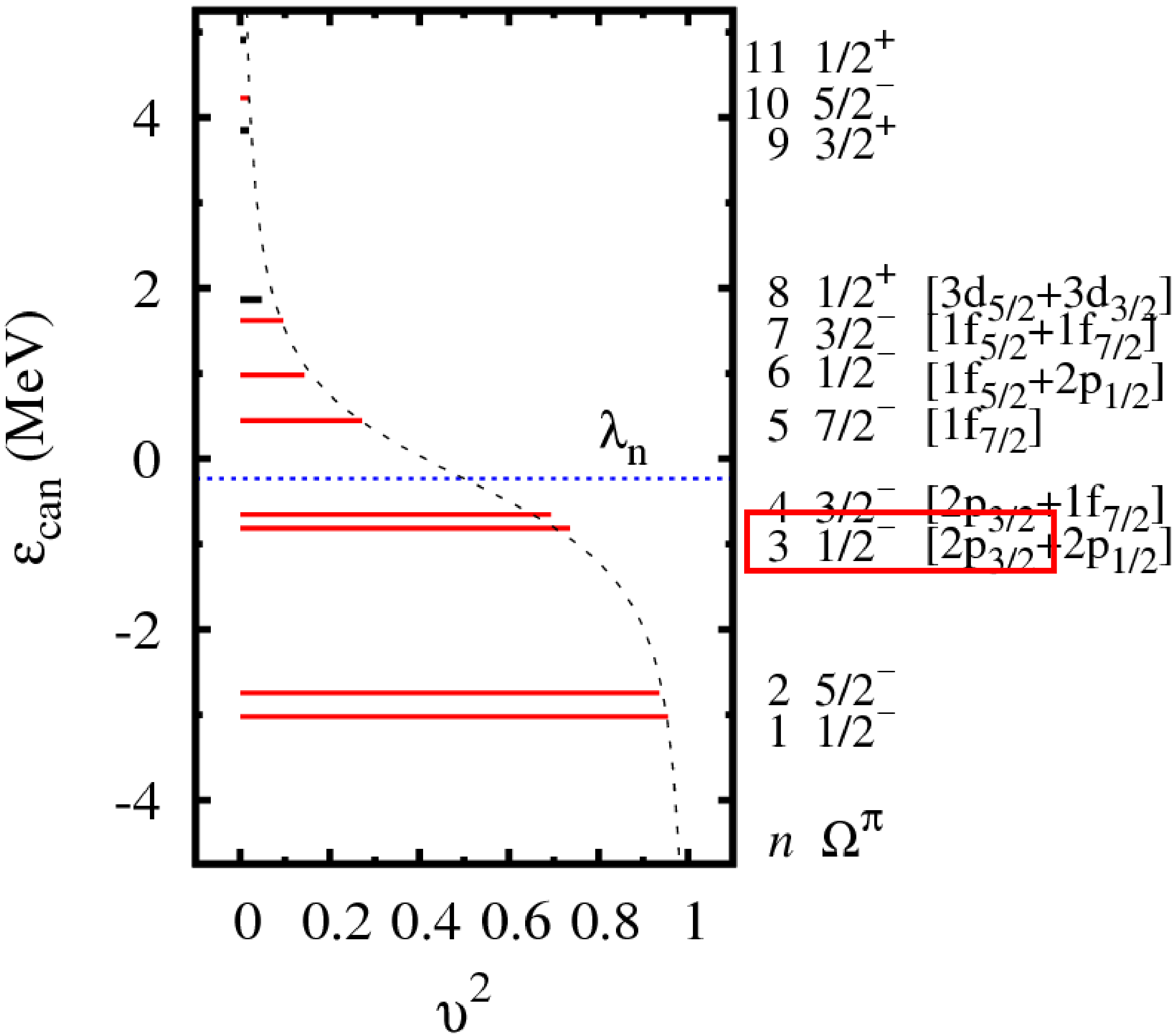


$\Lambda = \pm 1$

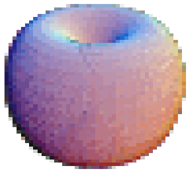


Mechanism of shape decoupling



$\Lambda = \pm 1$

$\Lambda = 0$



^{22}C: Puzzles in S_{2n}, r_m & halo configuration

- Two-neutron separation energy

Refs.	AME2003	AME2012	Gaudefroy et al. 2012 PRL109-202503	AME2016
S_{2n} (MeV)	0.420 ±0.940#	0.110±0.060	–0.14±0.46	0.035±0.020

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- RMS matter radius

Refs.	Tanaka et al. 2010 PRL104-062701	Togano et al. 2016 PLB761-412	Nagahisa&Horiuchi 2018 PRC97-054614	1.2 $A^{1/3}$ fm
r_m (fm)	5.4±0.9	3.44±0.08	3.38±0.10	3.36

^{22}C: Puzzles in S_{2n}, r_m & halo configuration

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S_{2n} (MeV)	0.420 ±0.940#	0.110±0.060	–0.14±0.46	0.035±0.020

- RMS matter radius

Refs.	Tanaka et al. 2010 PRL104-062701	Togano et al. 2016 PLB761-412	Nagahisa&Horiuchi 2018 PRC97-054614	1.2 $A^{1/3}$ fm
r_m (fm)	5.4±0.9	3.44±0.08	3.38±0.10	3.36

- Halo configuration
  - Inert ^{20}C w/ 2n in $2s_{1/2}$ (Horiuchi&Suzuki2006_PRC74-034311, Ershov et al. 2012_PRC86-034331, …)
  - Correlated ^{20}C w/ 2n partly in $2s_{1/2}$ (Suzuki…2016_PLB753-199)
  - Skyrme Hartree-Fock: t_0 adjusted (Inakura…2014_PRC89-064316)
  - RHFB: no halo (Lu…2013_PRC87-034311)

^{22}C w/ ab initio Gamow IMSRG

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Nuclear Theory

Resonances of unbound quantum many-body systems of nuclei

B. S. Hu, Q. Wu, Z. H. Sun, F. R. Xu

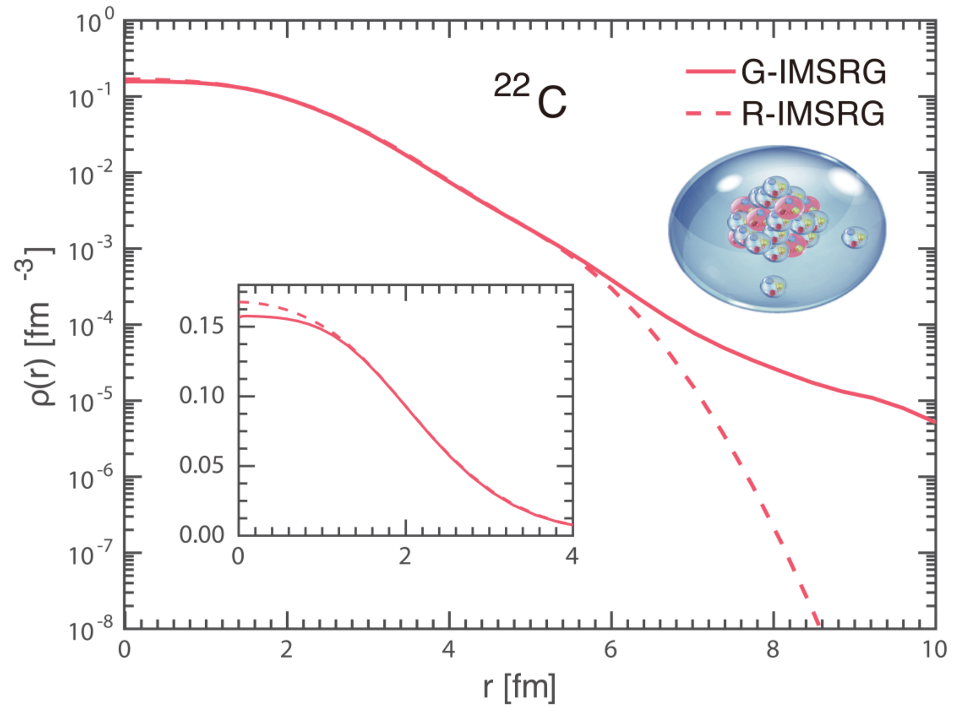
(Submitted on 22 Sep 2018)

Hu_Wu_Sun_Xu2018
arXiv1809.08405

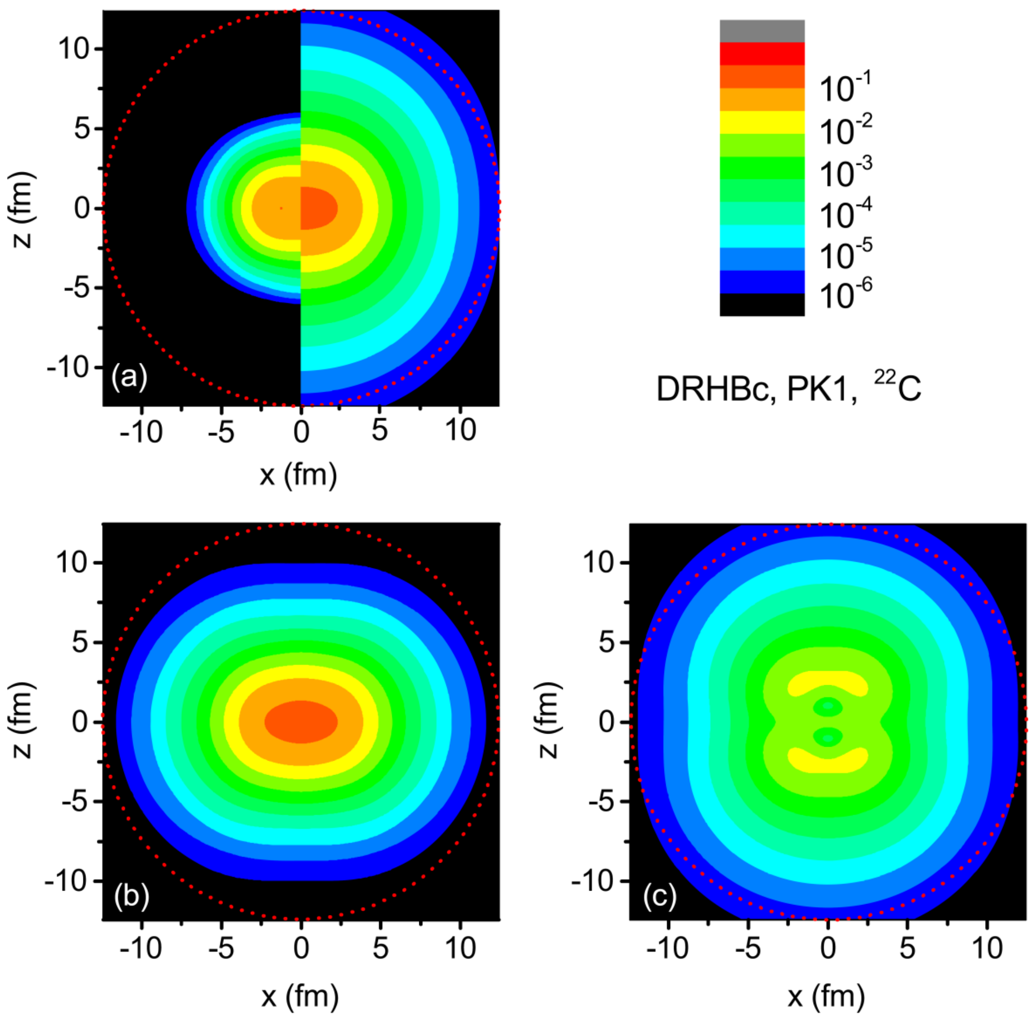
r_m = 2.79 fm w/o continuum
r_m = 3.02 fm w/ continuum

Predictions on excited states (in MeC)

J^π	2_1^+	4_1^+	3_1^+	1_1^+	2_2^+	2_3^+	1_2^+
E_{IMSRG}	1.05	3.26	3.36	3.62	3.93	4.94	5.27
Γ_{IMSRG}	0.000	0.245	0.262	0.135	0.266	0.597	0.604



^{22}C: Halo (?) & shape decoupling

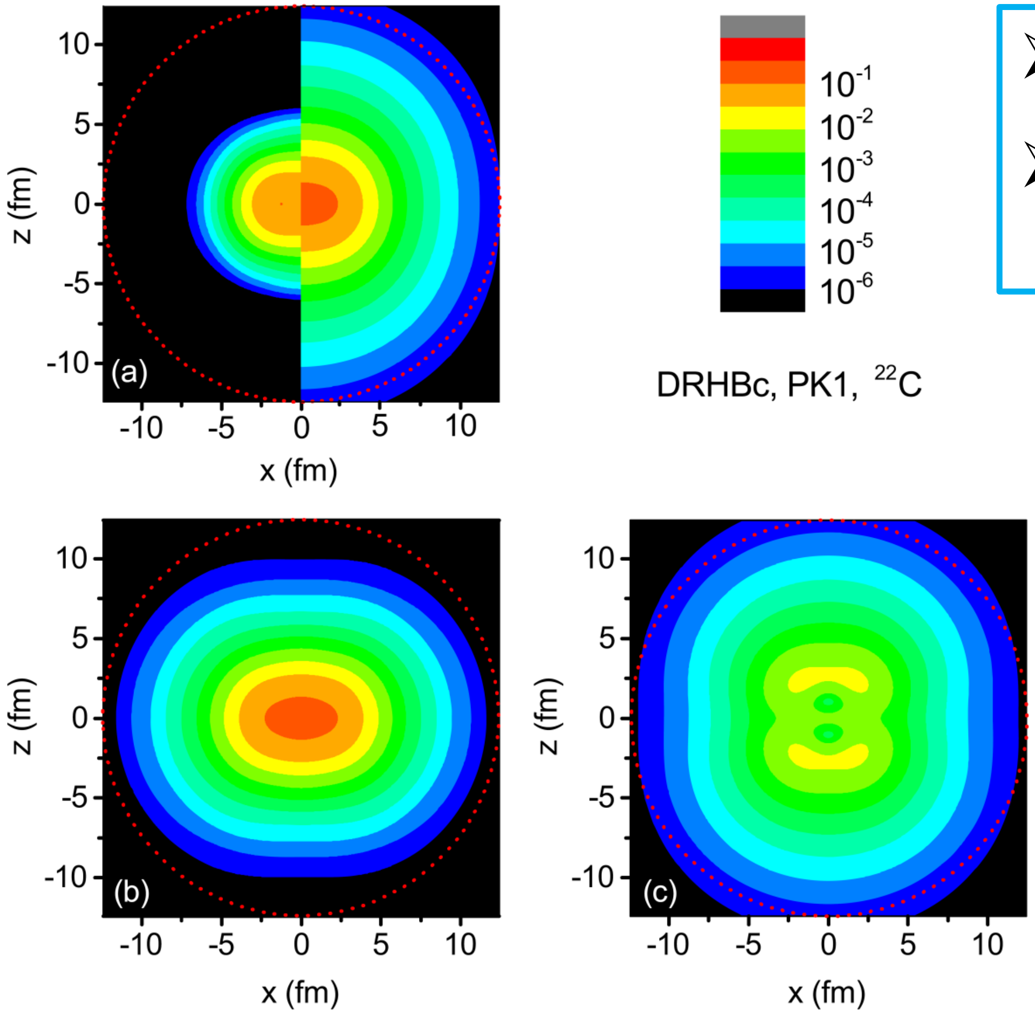


PK1

S_{2n} = 0.43 MeV
r_m = 3.25 fm
β_2 = –0.27

Sun_Zhao_SGZ 2018_PLB785-530

^{22}C: Halo (?) & shape decoupling



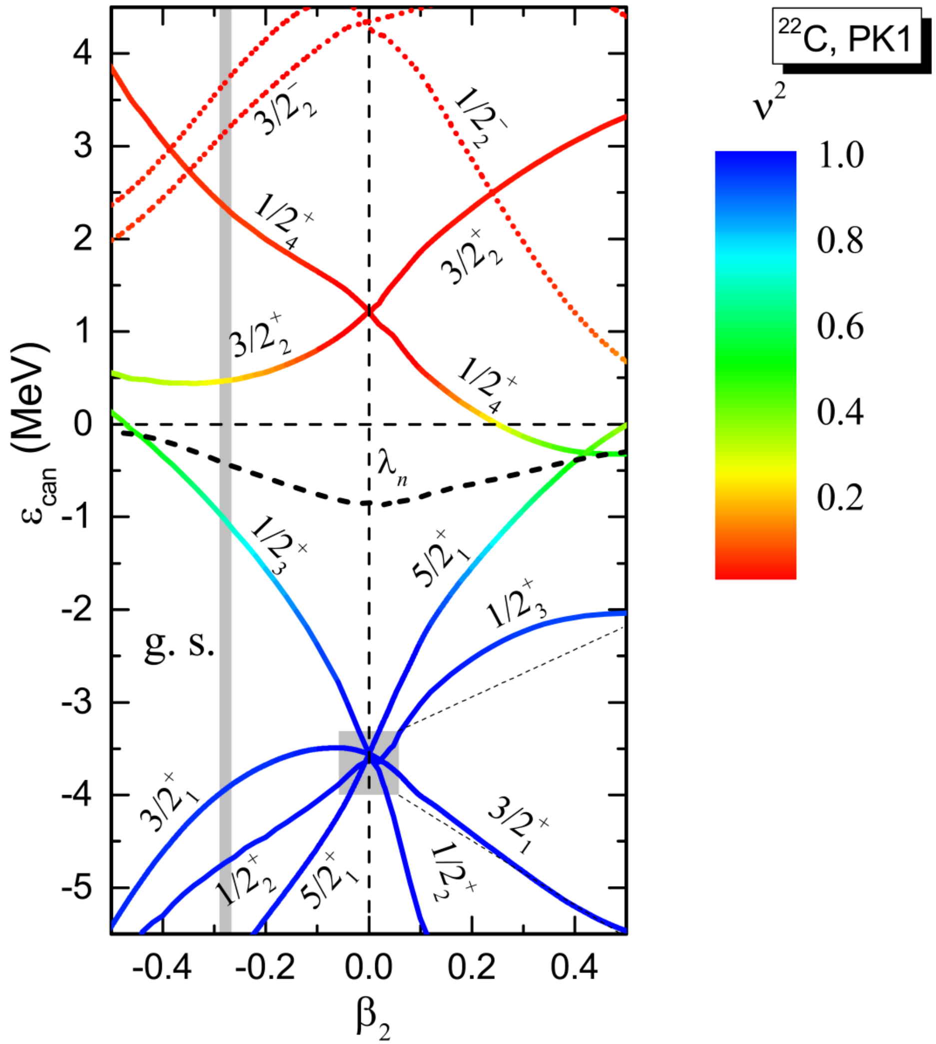
- $2s_{1/2}$: ~25% ⇒ Halo
- Mixture of $(2s_{1/2}, 1d_{5/2})$ ⇒ Prolate halo

PK1

S_{2n} = 0.43 MeV
r_m = 3.25 fm
β_2 = –0.27

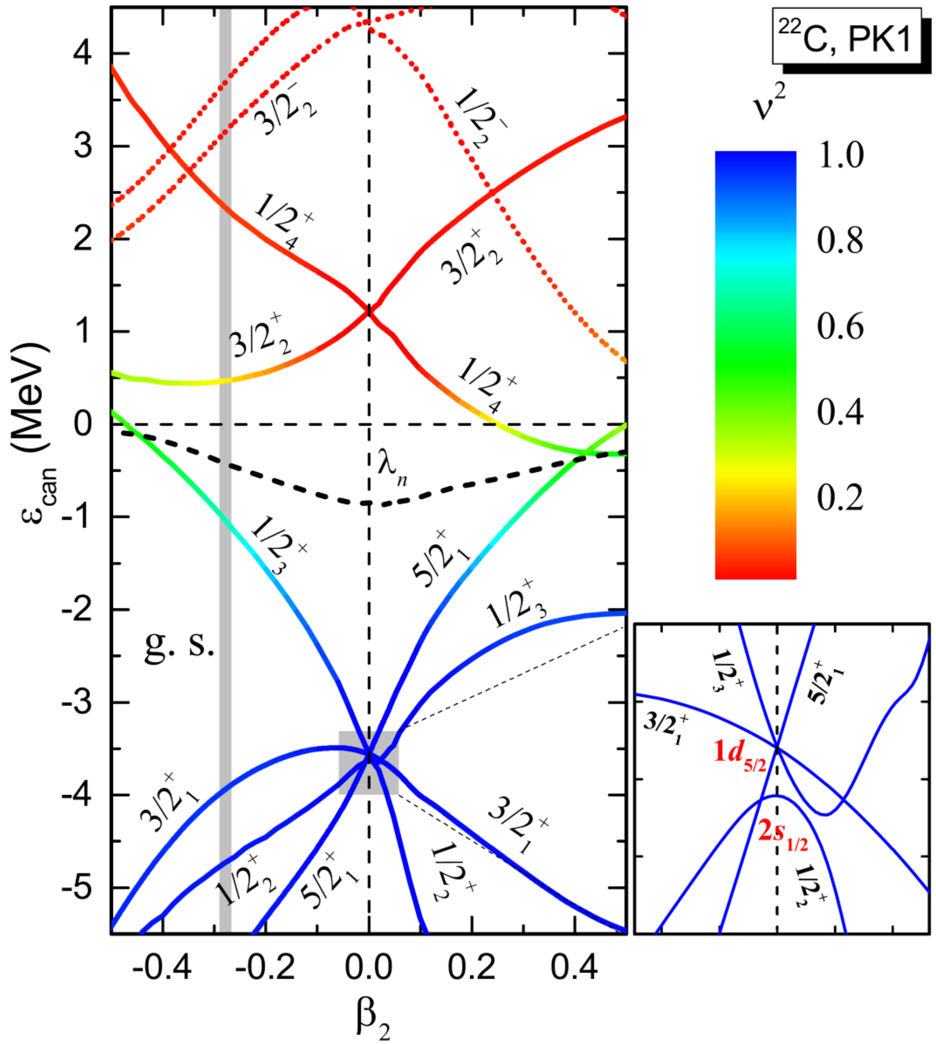
Sun_Zhao_SGZ 2018_PLB785-530

^{22}C: Single neutron levels



Sun_Zhao_SGZ 2018_PLB785-530

^{22}C: Single neutron levels



Sun_Zhao_SGZ 2018_PLB785-530

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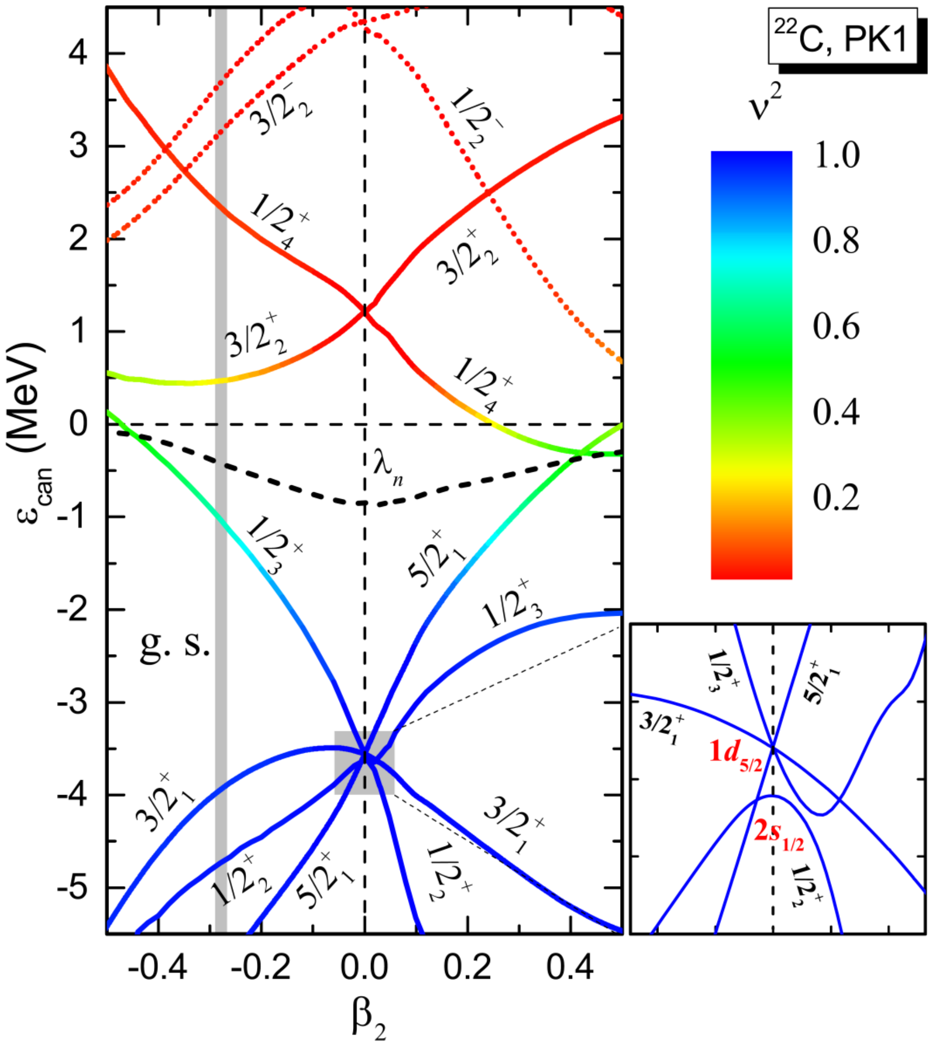
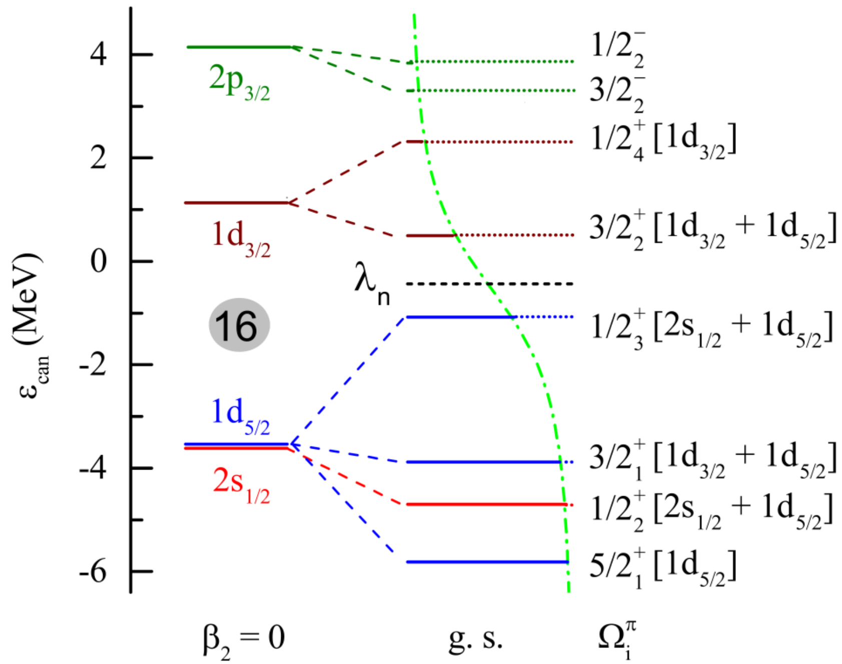
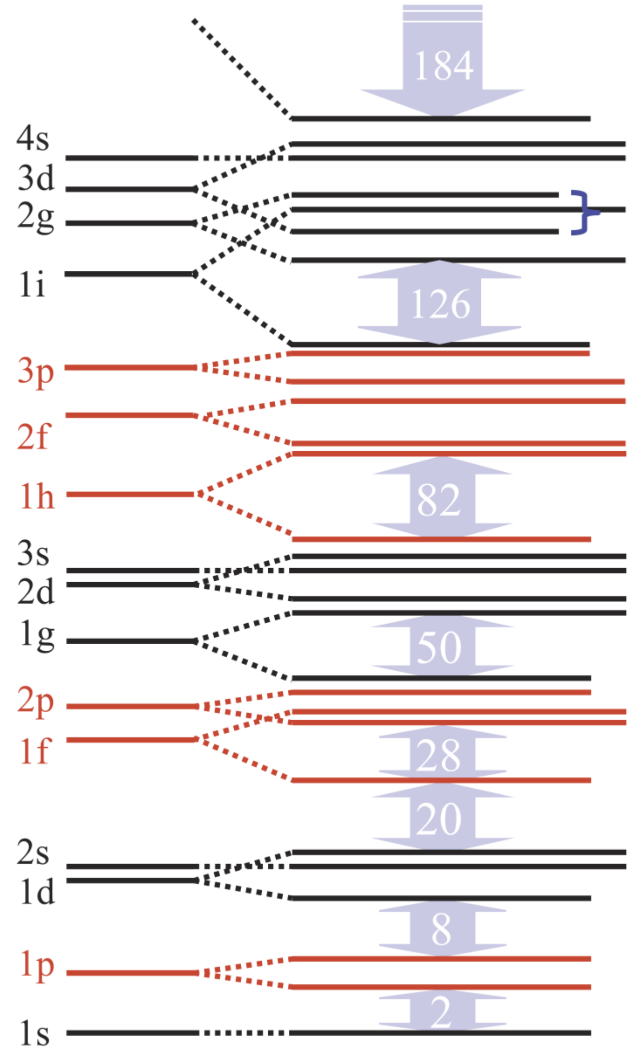


Inversion of ($2s_{1/2}$, $1d_{5/2}$)
No shell closure at N = 16



Sun_Zhao_SGZ 2018_PLB785-530

pseudospin symmetry



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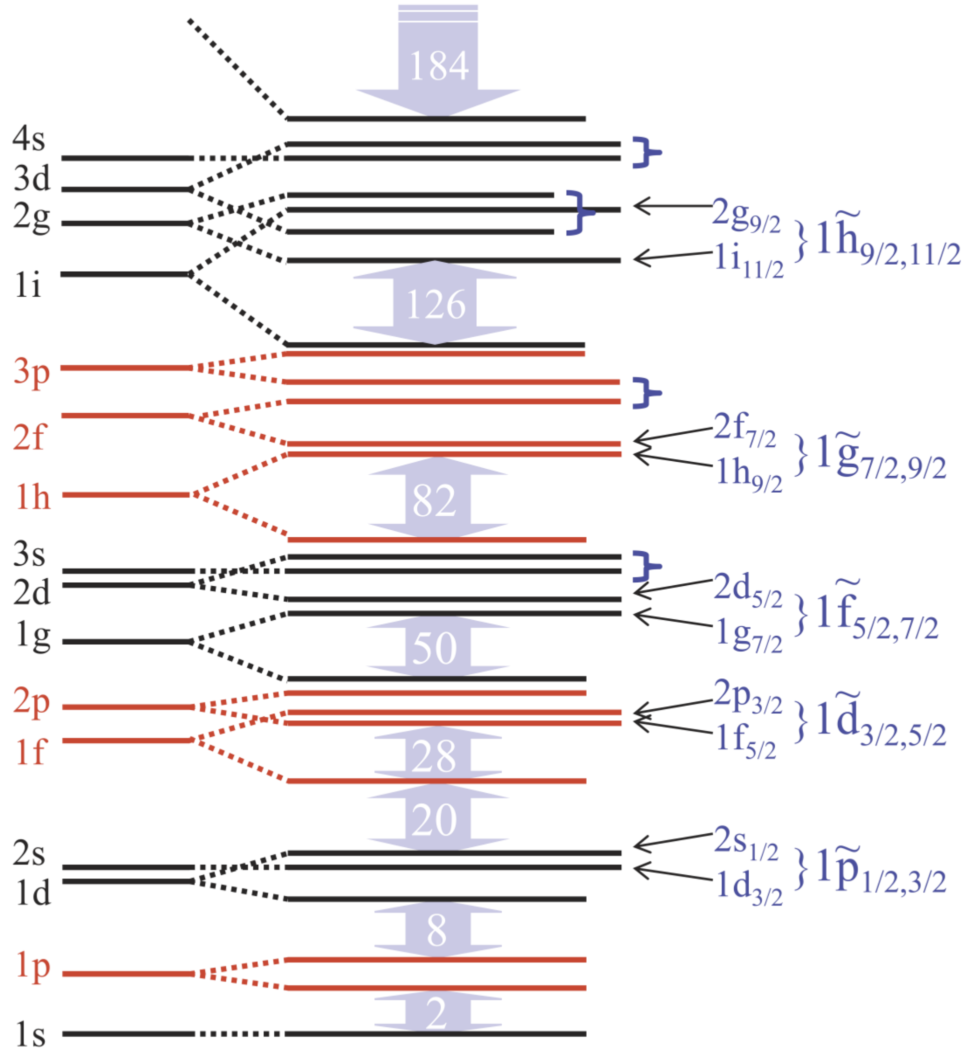


pseudospin symmetry

Arima_Harvey_Shimizu 1969_PLB30-517

Hecht_Adler 1969_NPA137-129

Bohr_Hamamoto_Mottelson
1982_PhysScr26-267

Ginocchio1997_PRL78-436

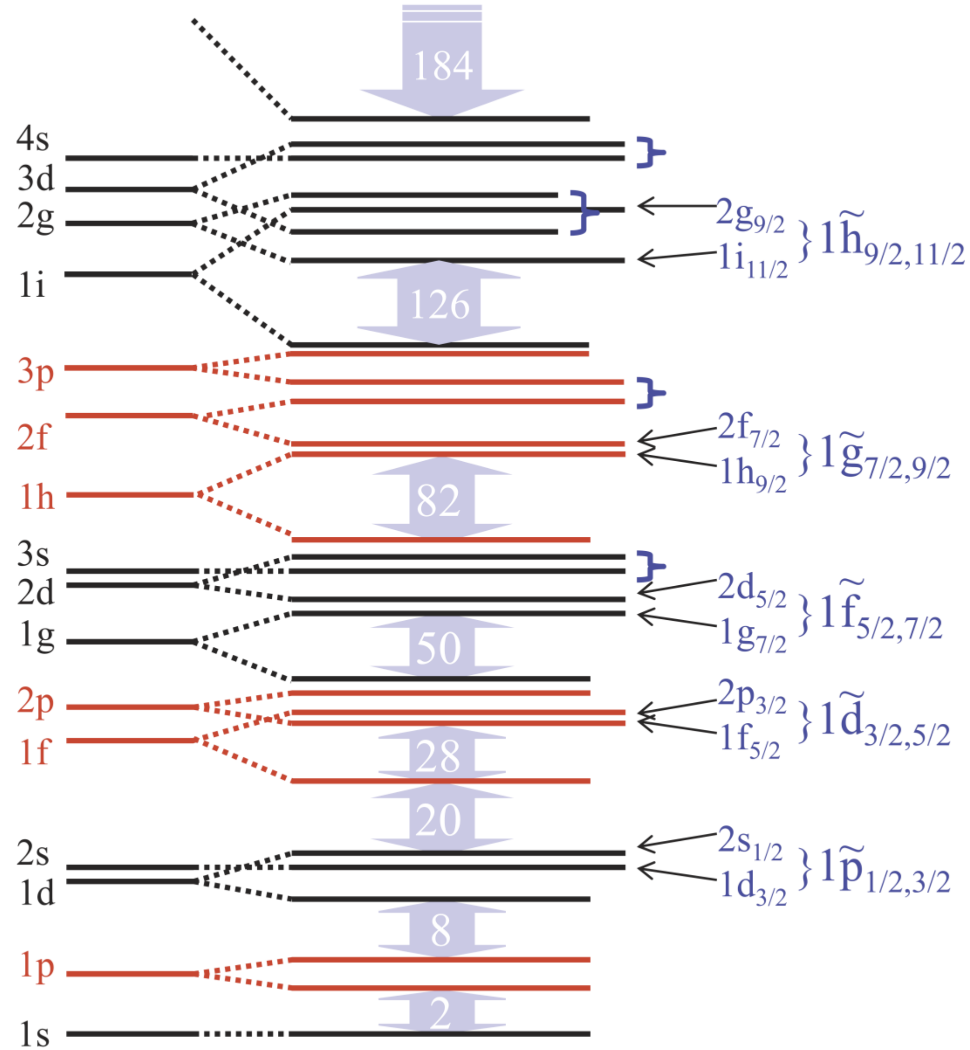
Meng_Sugawara-Tanabe_Yamaji_Ring_Arima
1998_PRC58-R628

SGZ_Meng_Ring2003_PRL91-262501

Lu_Zhao_SGZ2012_PRL109-072501

Li_Shi_Guo_Chen_Liang2016_PRL117-062502

Liang_Meng_SGZ 2015_PhysRep570-1



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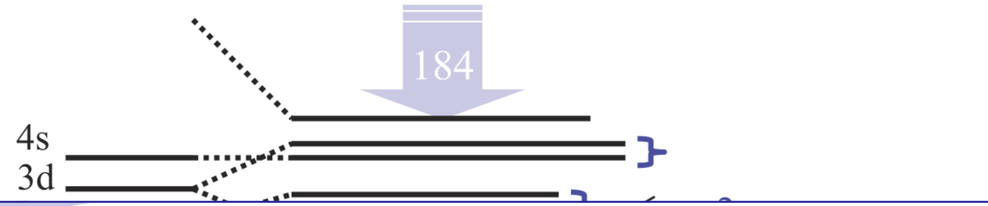

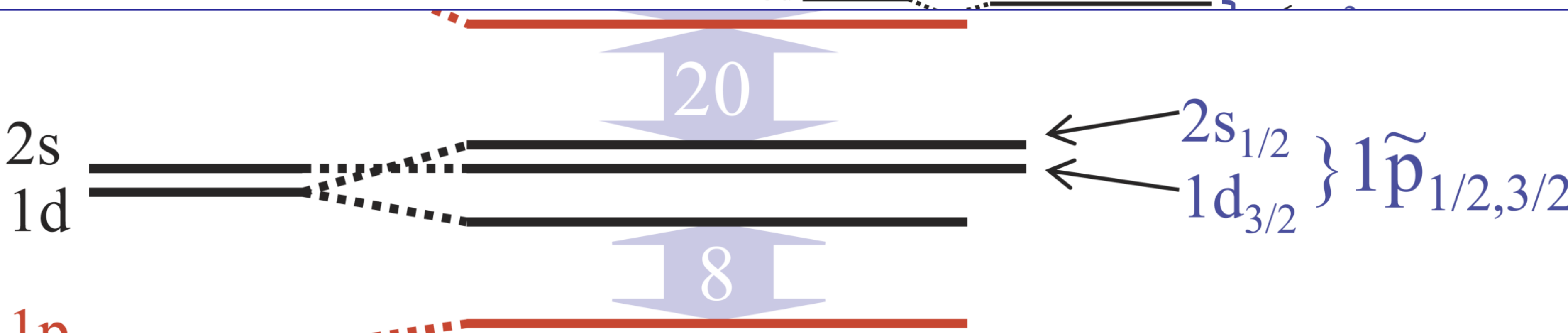

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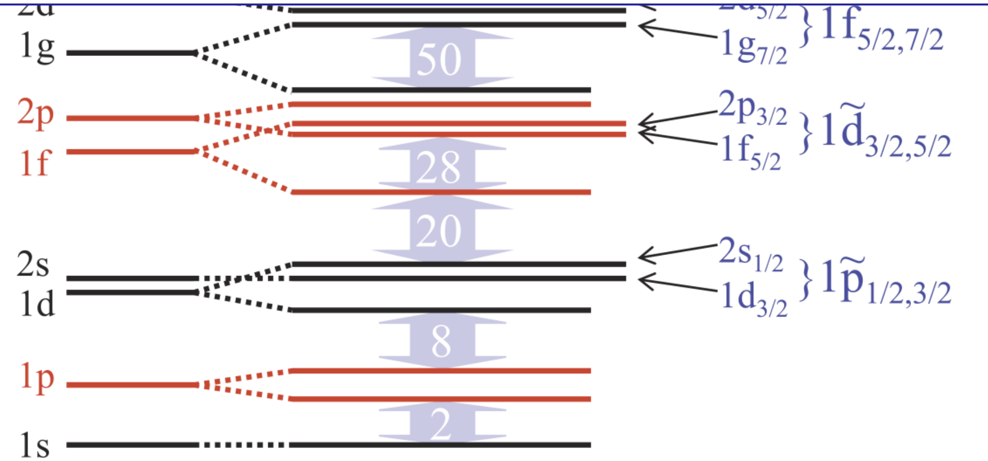
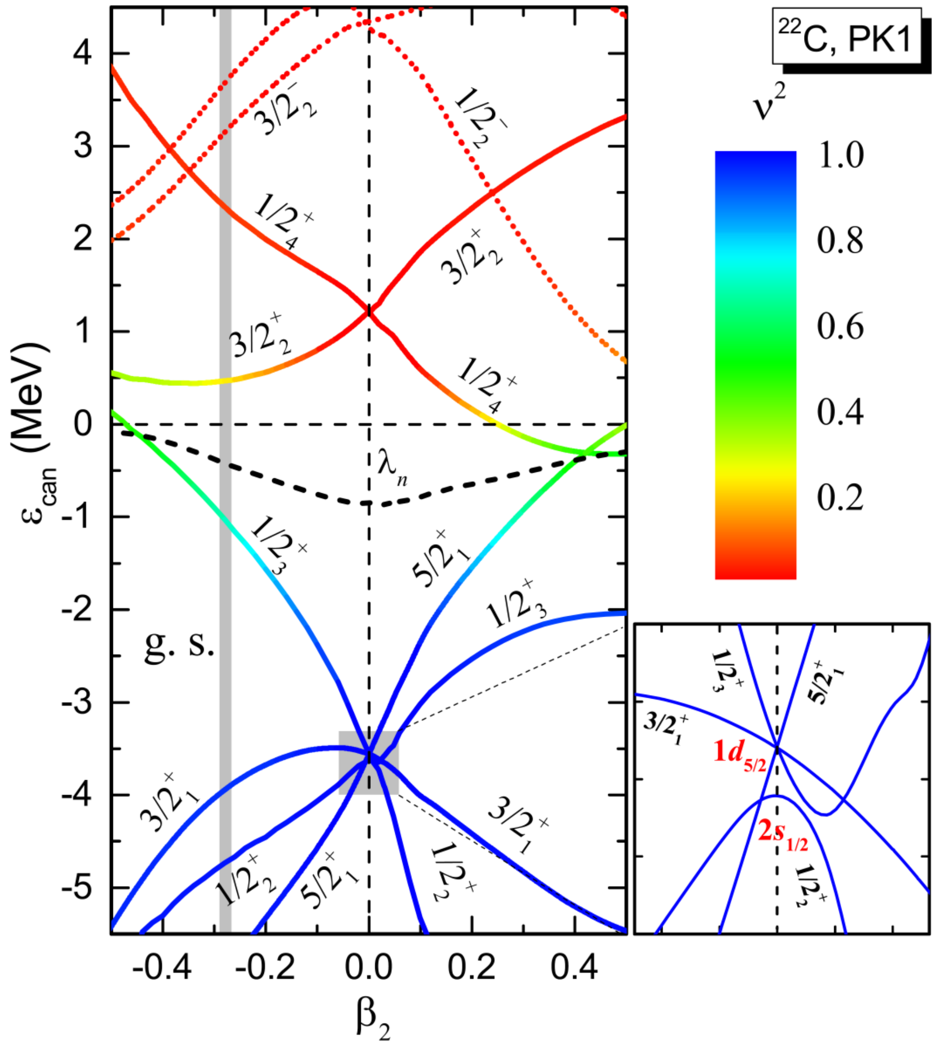


Breaking of pseudospin symmetry?



Inversion of ($2s_{1/2}$, $1d_{5/2}$)
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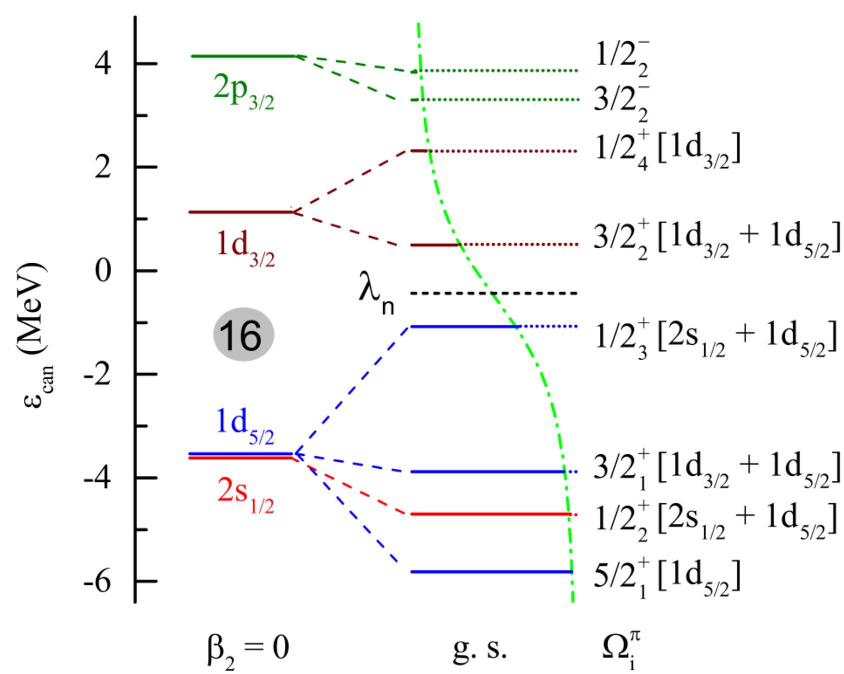

Sun_Zhao_SGZ 2018_PLB785-530

Justification of PSS in Resonant States

PRL **109,** 072501 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Pseudospin Symmetry in Single Particle Resonant States

Bing-Nan Lu (吕炳楠),[1] En-Guang Zhao (赵恩广),[1,2] and Shan-Gui Zhou (周善贵)[1,2,*]

[1]*State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

[2]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*

(Received 23 April 2012; revised manuscript received 2 July 2012; published 16 August 2012)

The pseudospin symmetry (PSS) is a relativistic dynamical symmetry connected with the small component of the Dirac spinor. The origin of PSS in single particle bound states in atomic nuclei has been revealed and studied extensively. By examining the zeros of Jost functions corresponding to the small components of Dirac wave functions and phase shifts of continuum states, we show that the PSS in single particle resonant states in nuclei is conserved when the attractive scalar and repulsive vector potentials have the same magnitude but opposite sign. The exact conservation and the breaking of the PSS are illustrated for single particle resonances in spherical square-well and Woods-Saxon potentials.

DOI: 10.1103/PhysRevLett.109.072501 PACS numbers: 21.10.Pc, 03.65.Nk, 21.10.Tg, 24.10.Jv

Breaking of pseudospin symmetry?

Something new when the pseudospin partners straddle the threshold?

PRL **109,** 072501 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Pseudospin Symmetry in Single Particle Resonant States

Bing-Nan Lu (吕炳楠),[1] En-Guang Zhao (赵恩广),[1,2] and Shan-Gui Zhou (周善贵)[1,2,*]

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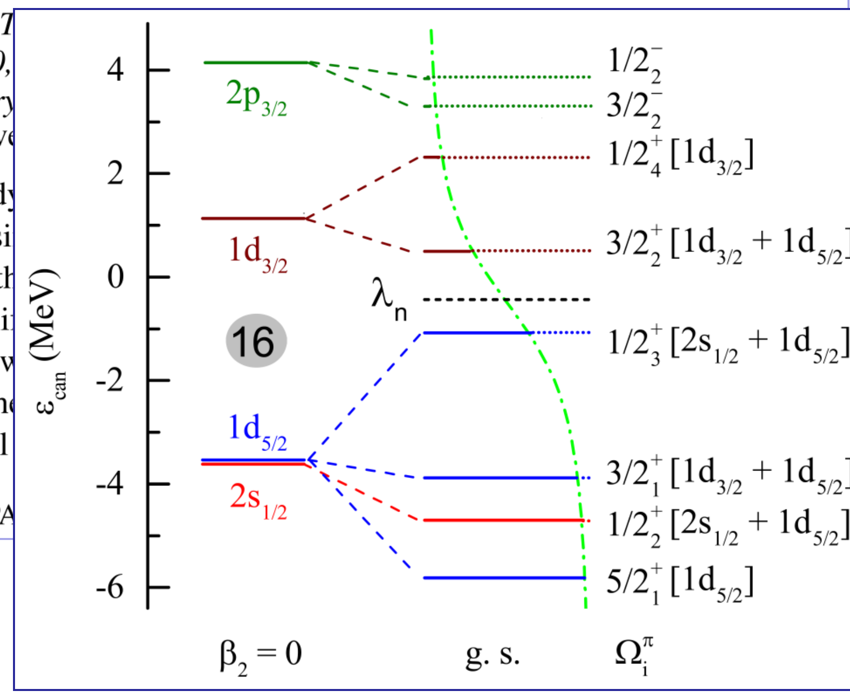
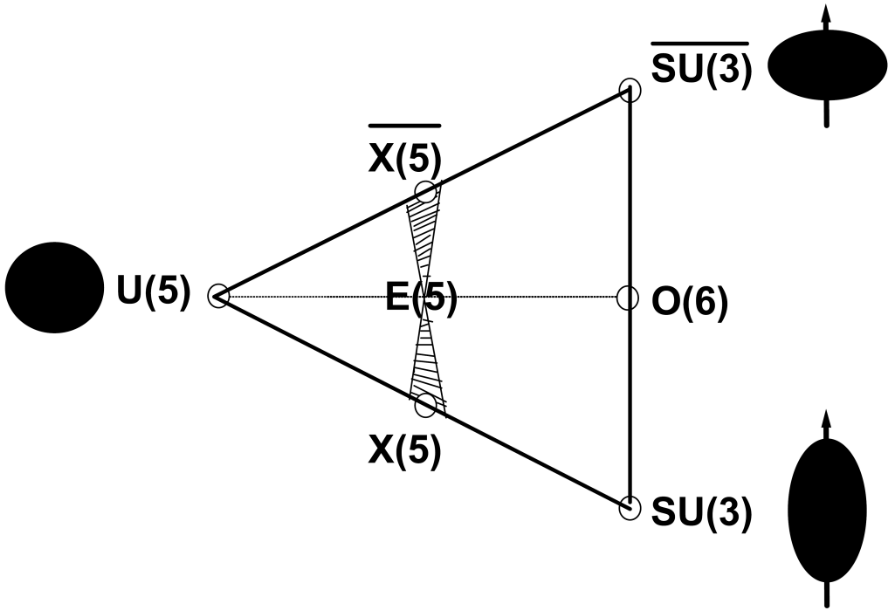
DOI: 10.1103/PhysRevLett.109.072501 PA



Extended Casten triangle

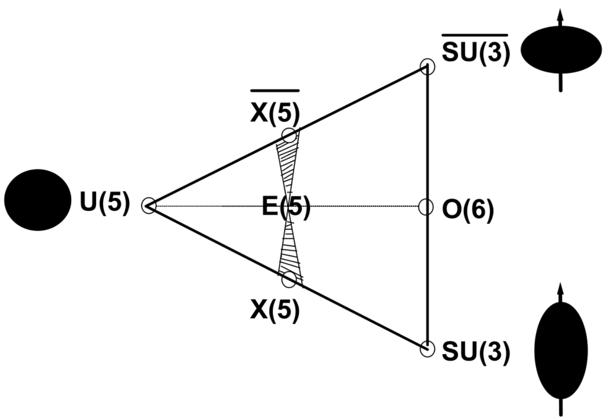


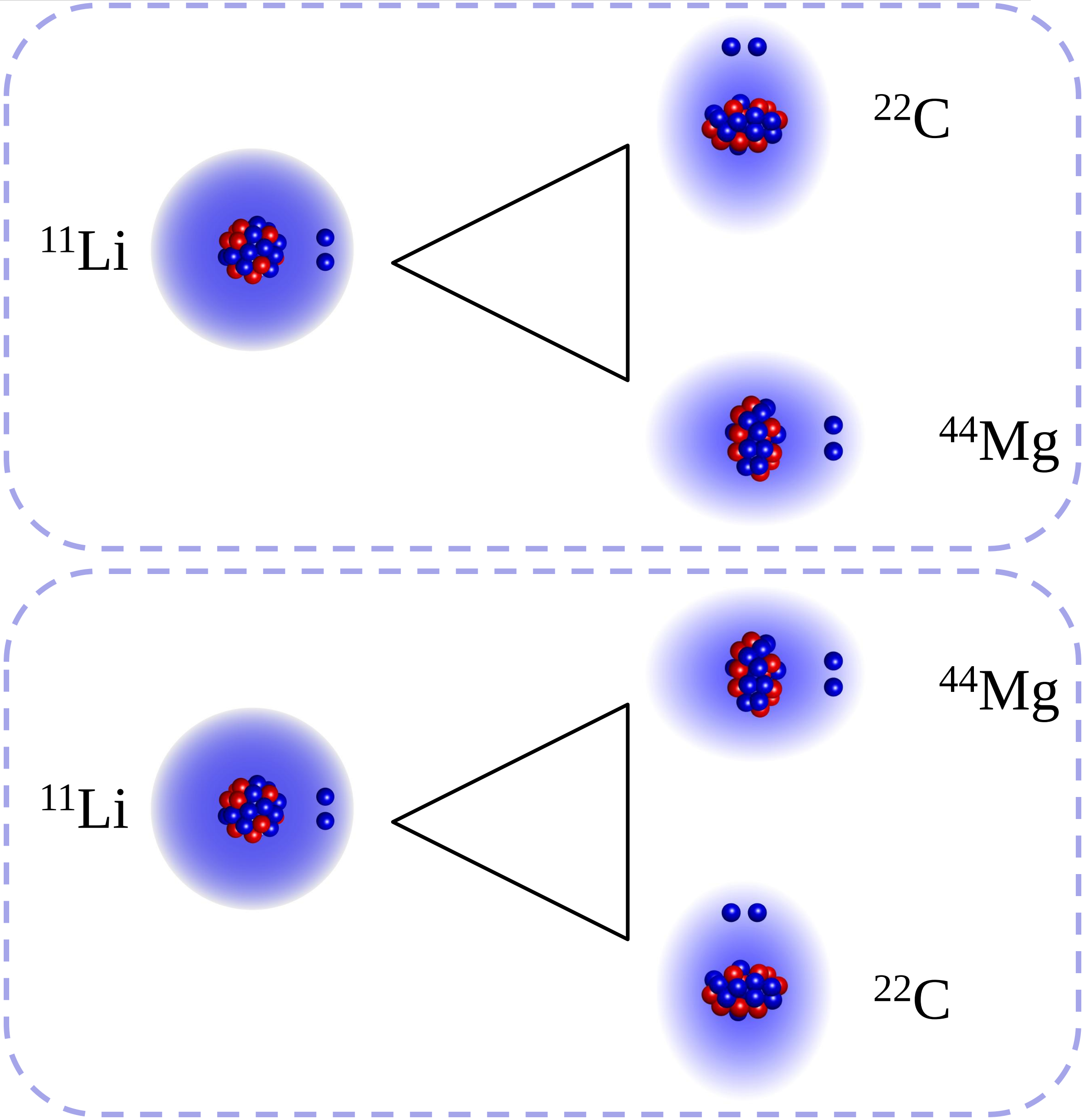
Pan_Wang_Huo_Draayer2006_IJMPE15-1723

Triangle of Borromean nuclei: ^{11}Li, ^{22}C & ^{44}Mg

$^{44}\mathrm{Mg} = {}^{22}\mathrm{C} + {}^{22}\mathrm{C}$

$^{22}\mathrm{C} = {}^{11}\mathrm{Li} + {}^{11}\mathrm{Li}$

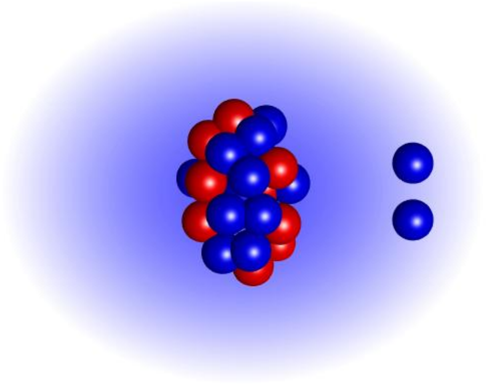




Pan_Wang_Huo_Draayer
2006_IJMPE15-1723

Picture(s): courtesy of
Xin-Hui Wu (吴鑫辉)

How to probe the shape decoupling?



- Larger cross section
- Narrower momentum distribution
  - Bimodal ?

Picture(s): courtesy of Xin-Hui Wu (吴鑫辉)

How to probe the shape decoupling?

- Larger cross section
- Narrower momentum distribution
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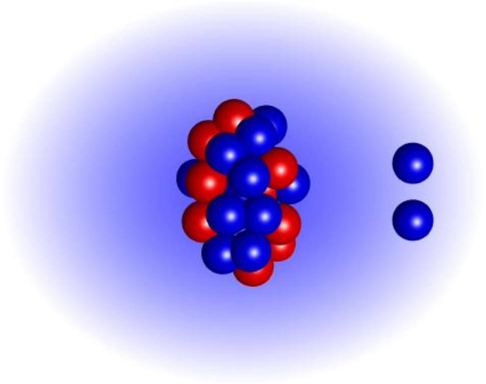
Navin…1997_PRL81-5089

Sakharuk_Zelevinsky1998_PRC61-014609



Picture(s): courtesy of Xin-Hui Wu (吴鑫辉)

How to probe the shape decoupling?

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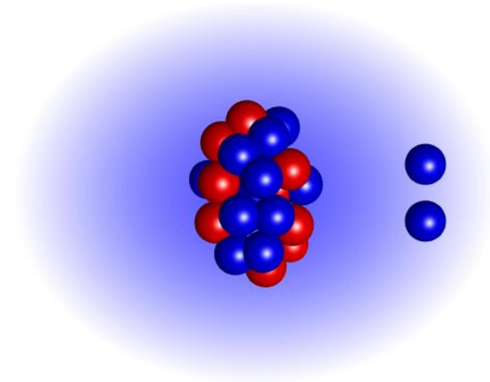
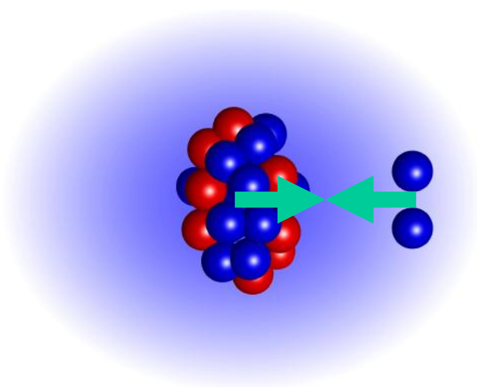
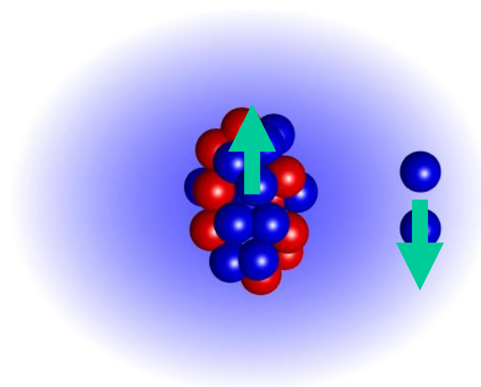
- New dipole modes ?







Picture(s): courtesy of Xin-Hui Wu (吴鑫辉)

How to probe the shape decoupling?

- Larger cross section
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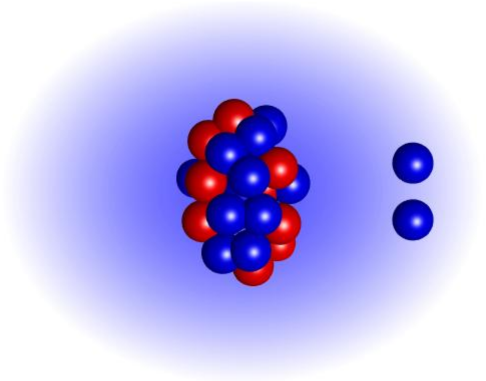
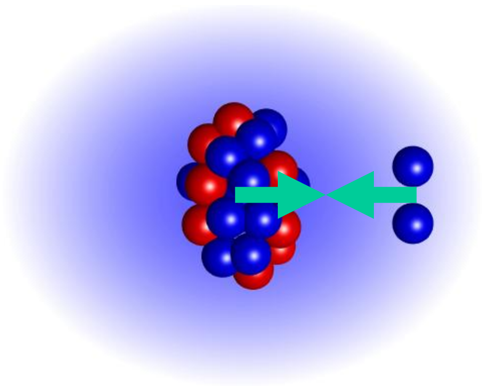
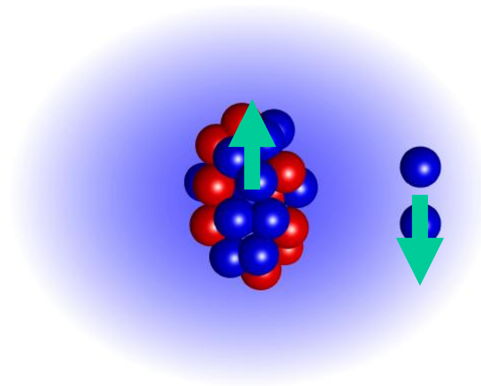
- Rotation ? (X.-X. Sun, DRHBc+Angular Momentum Projection)







Picture(s): courtesy of Xin-Hui Wu (吴鑫辉)

How to probe the shape decoupling?

- Larger cross section
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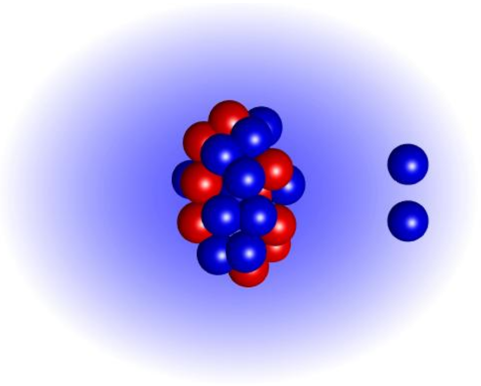
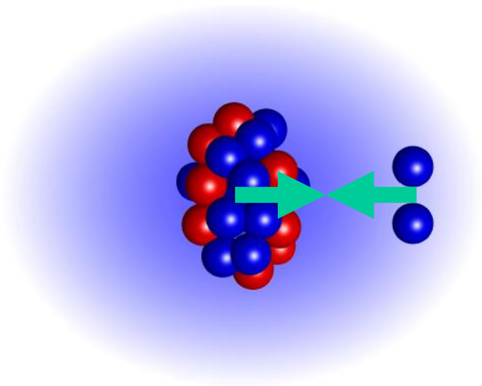
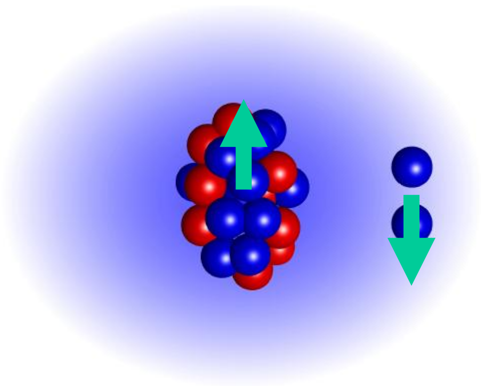
  - ➢Bimodal ?
- New dipole modes ?
- Rotation ? (X.-X. Sun, DRHBc+Angular Momentum Projection)
- Fusion ?







Picture(s): courtesy of Xin-Hui Wu (吴鑫辉)

Summary & perspectives

- Deformed relativistic HB theory in a Woods-Saxon basis
  - Occurrence of a halo in deformed nuclei depending on intrinsic structure of valence orbitals
  - ^{44}Mg: prolate core but oblate halo
  - ^{22}C: oblate core but prolate halo
  - ^{11}Li, ^{22}C & ^{44}Mg: triangle of Borromean nuclei ?
- Breaking of pseudospin symmetry ?
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Thank you !