CRC110 Workshop on Nuclear Dynamics and Threshold Phenomena
Ruhr-Universität Bochum, Apr. 5-7, 2017

Deformation and threshold effects in halo nuclei

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Supported by: NSFC & MOST;
HPC Cluster of SKLTP/ITP-CAS
ScGrid of CNIC-CAS

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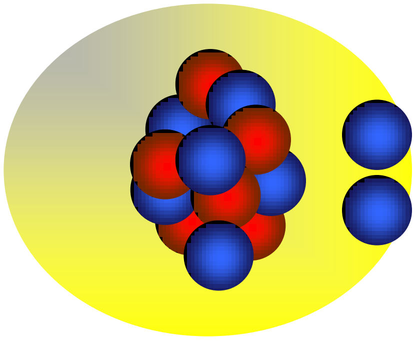
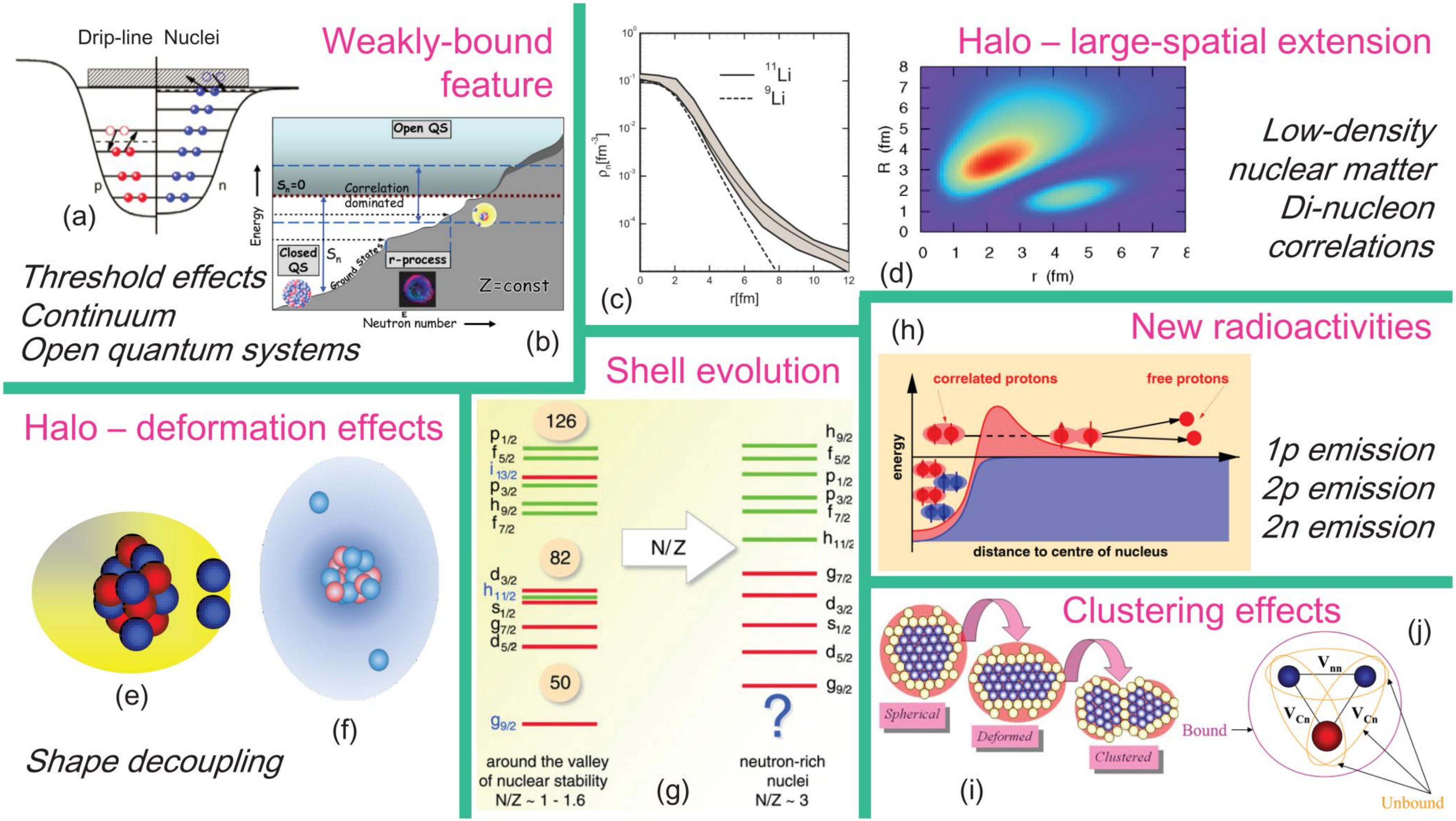
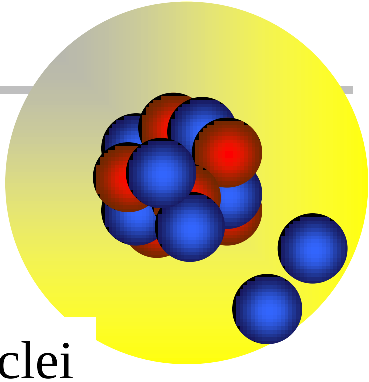


Physics in exotic nuclear structure

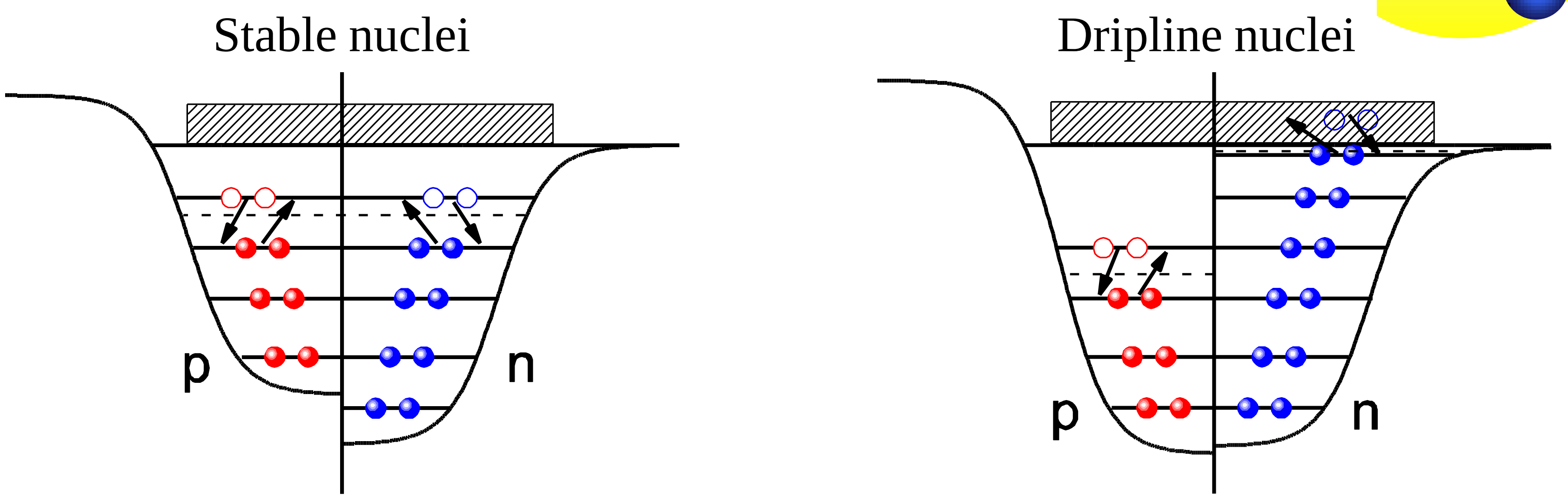


SGZ, PoS (INPC2016) 373

Characteristics of halo nuclei



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



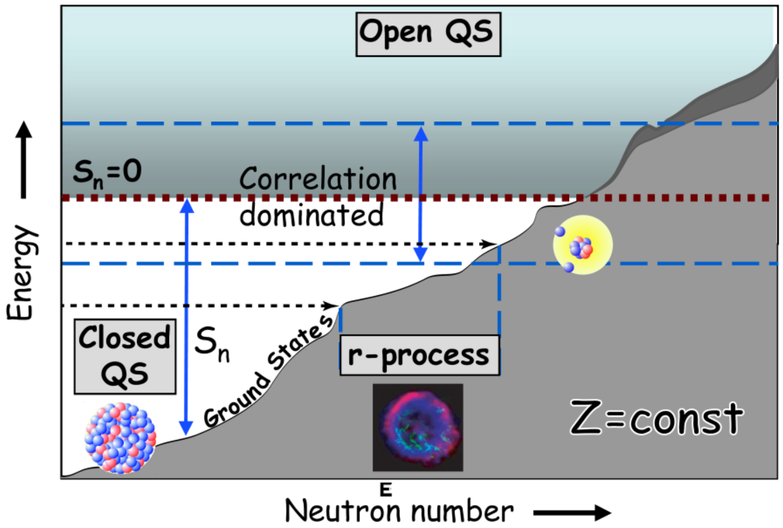
Self-consistent description:

- 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

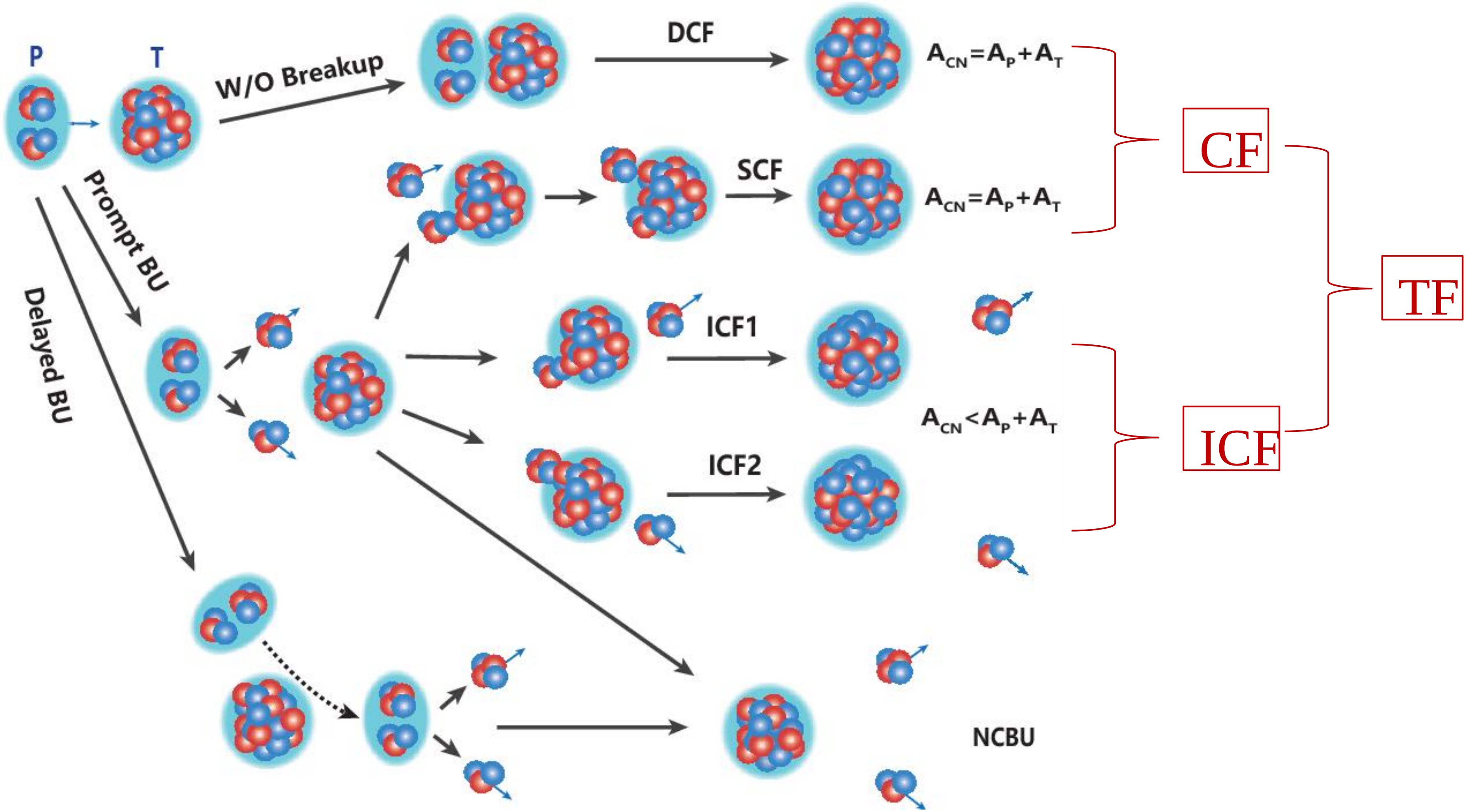
Bulgac1980; nucl-th/9907088
Dobaczewski_Flocard_Treiner1984_NPA422-103

Open quantum systems & threshold effects



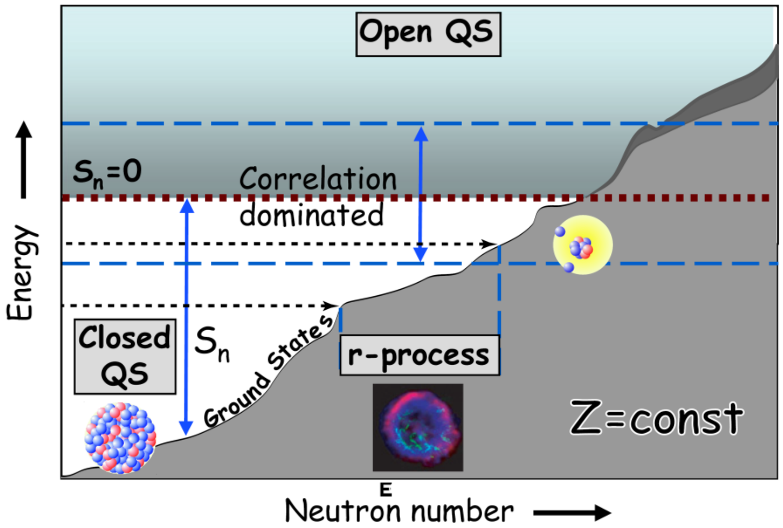
Dobaczewski+2007_PPNP59-432
Michel+2009_JPG36-013101

Breakup effects on fusion of weakly bound projectiles



Courtesy of Bing Wang (王兵)

Open quantum systems & threshold effects



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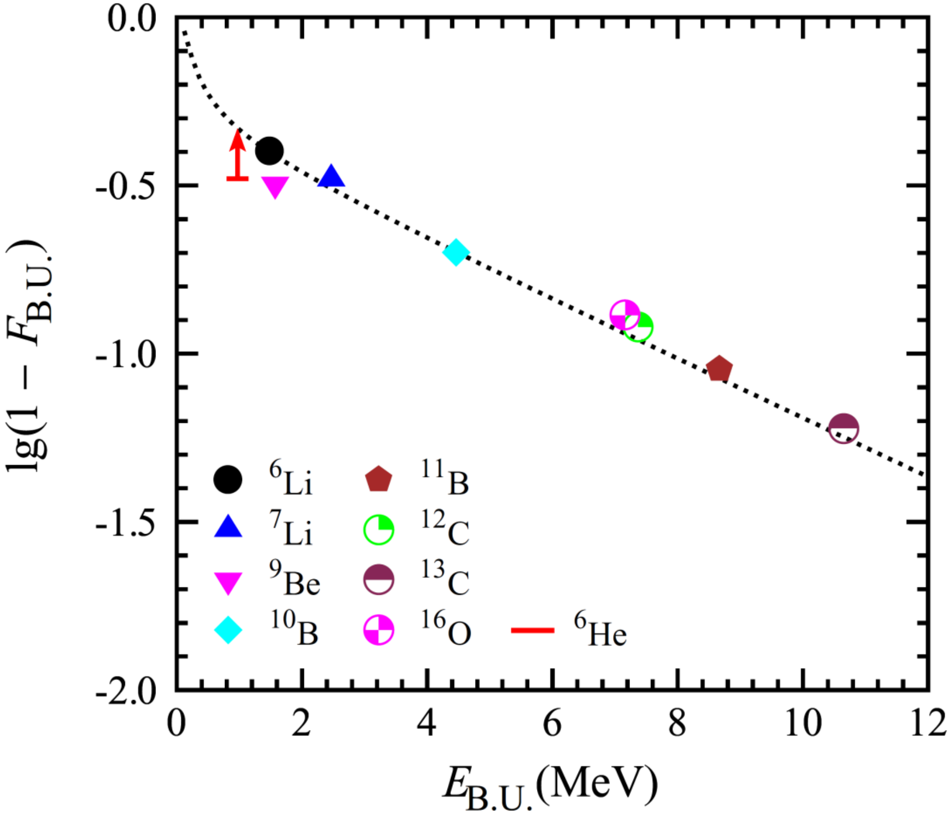
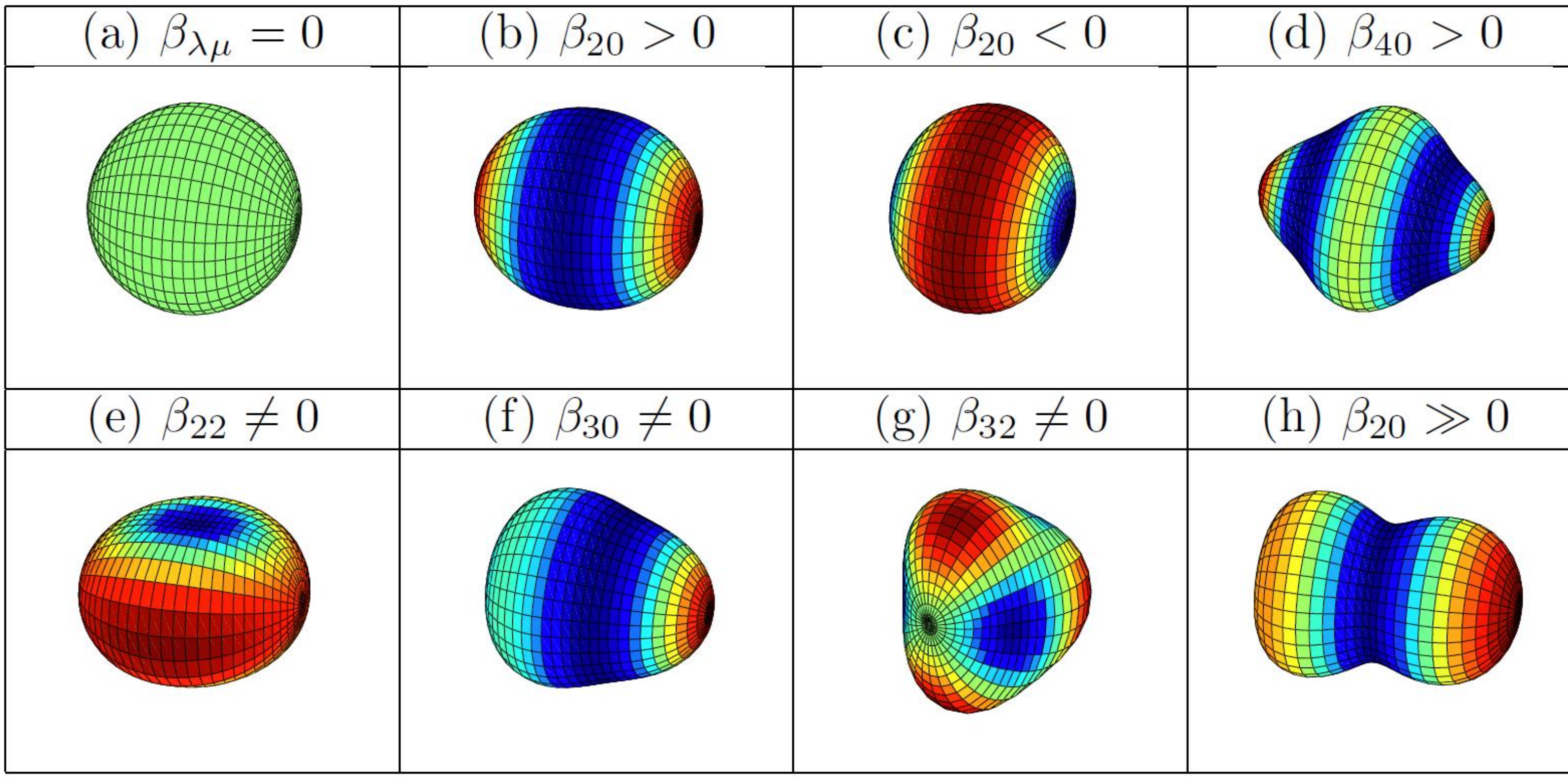


Wang_Zhao_Gomes_Zhao_SGZ2014_PRC90-034612
Wang_Zhao_Diaz-Torres_Zhao_SGZ2016_PRC93-014615

Various shapes of atomic nuclei

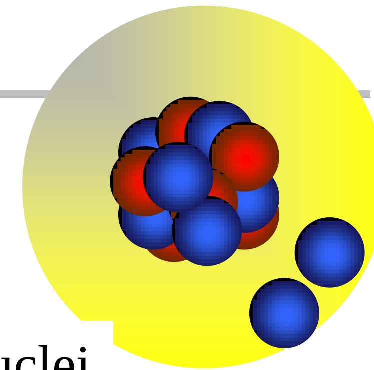
SGZ 2016, Phys. Scr. 91, 063008

$$R(\theta,\varphi) = R_0\left[1+\beta_{00}+\sum_{\lambda=1}^{\infty}\sum_{\mu=-\lambda}^{\lambda}\beta^*_{\lambda\mu}Y_{\lambda\mu}(\theta,\varphi)\right]$$



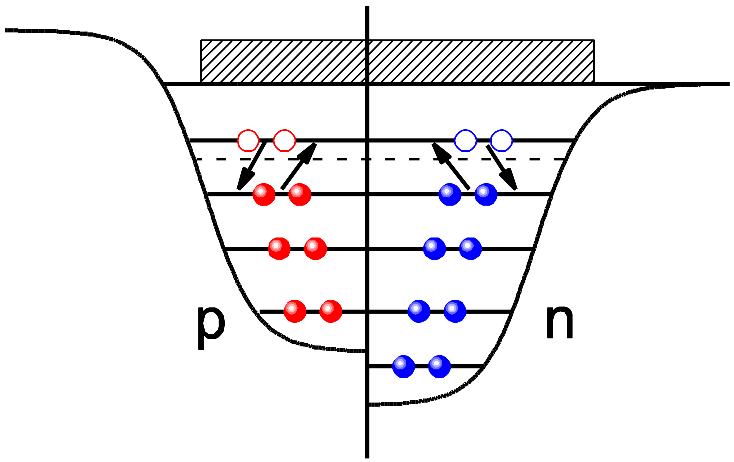
Courtesy of Bing-Nan Lu (吕炳楠)

Characteristics of halo nuclei

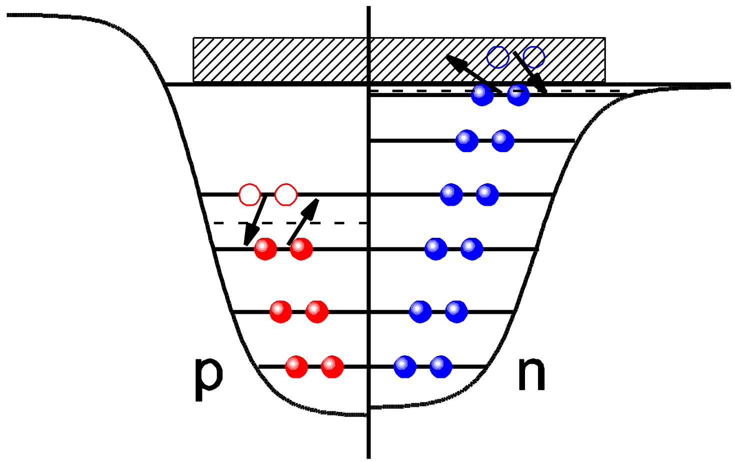


- ☐ Weakly bound; large spatial extension
- ☐ Continuum can not be ignored

Stable nuclei



Dripline nuclei



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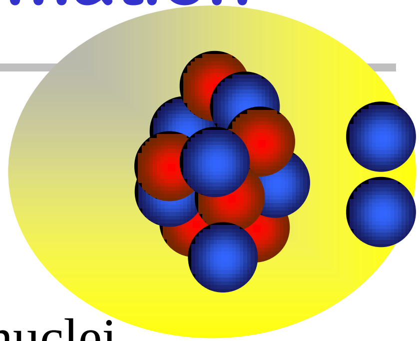
Characteristics of halo nuclei w/ deformation



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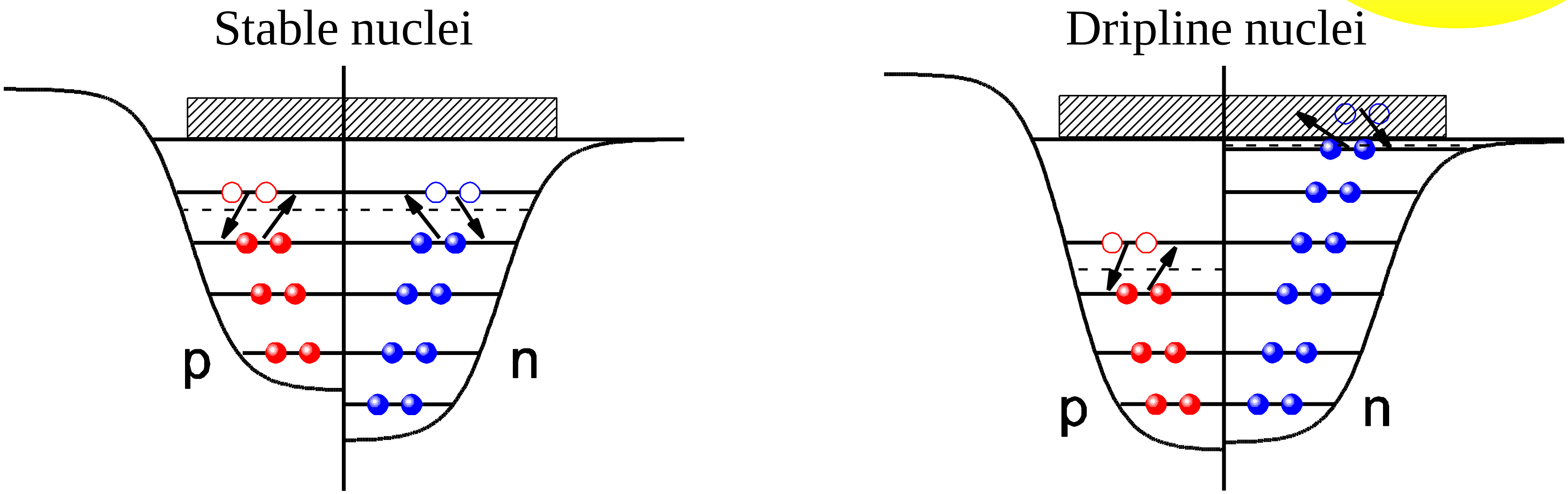

Self-consistent description:

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- Deformation effects
- Couplings among …

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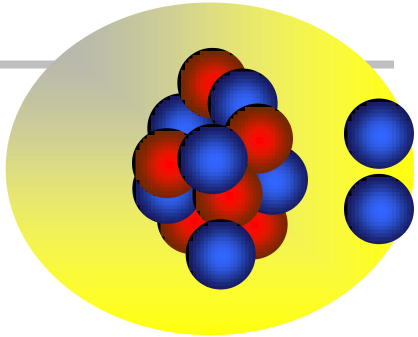
What we aim at



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

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

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

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

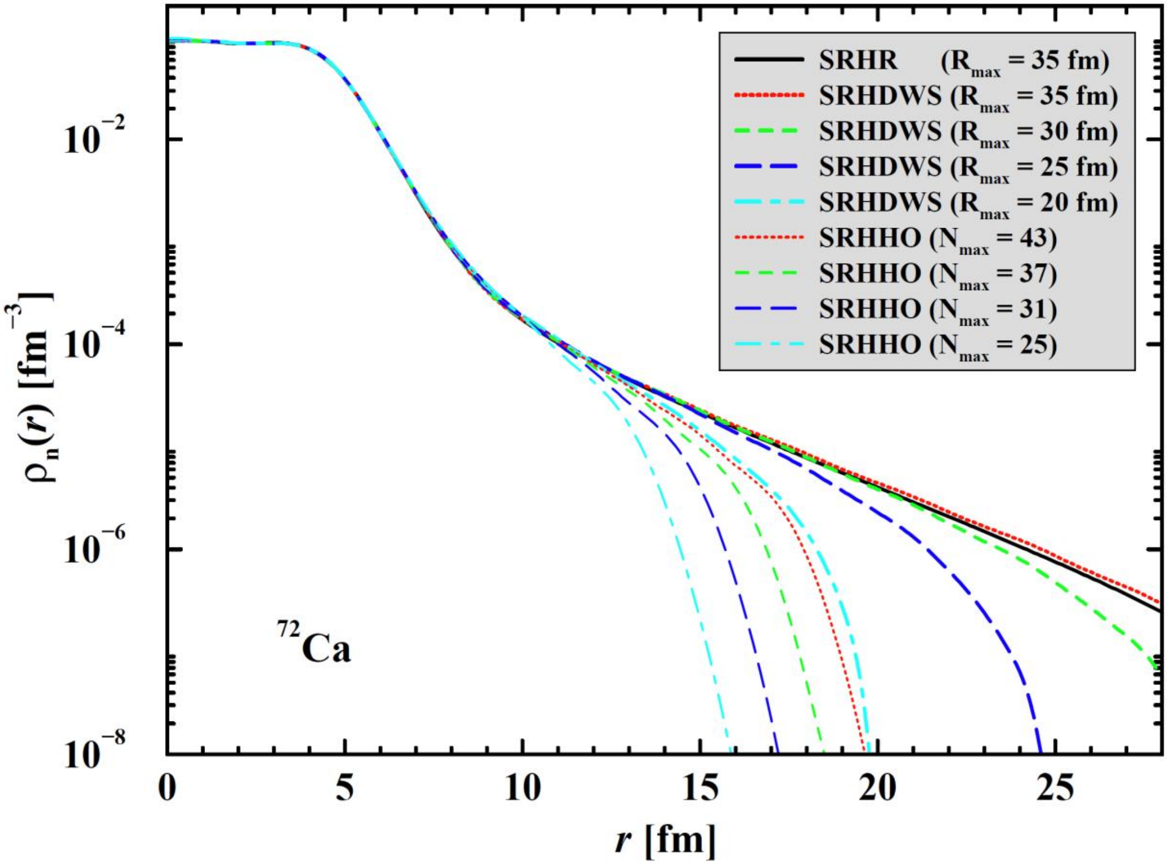
$$\left(-\nabla^2 + m_\rho^2\right)\rho = g_\rho\rho_3$$

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

RMF theories 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

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

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Axially deformed	Rela. Hartree-Bogoliubov		DRHB DWS	√
	SGZ_Meng_Ring 2007_ISPUN Proc. SGZ_Meng_Ring_Zhao 2010_PRC82-011301R SGZ_Meng_Ring_Zhao 2011_JPConfProc312-092067 Li_Meng_Ring_Zhao_SGZ 2012_PRC85-024312 Li_Meng_Ring_Zhao_SGZ 2012_ChinPhysLett29-042101			

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

RMF theories in a Woods-Saxon basis

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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

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

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

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

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

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

Parameter set for ph & pp channels

SGZ_Meng_Ring_Zhao 2010_PRC82-011301R
SGZ_Meng_Ring_Zhao 2011_JPConfProc312-092067
Li_Meng_Ring_Zhao_SGZ 2012_PRC85-024312
Li_Meng_Ring_Zhao_SGZ 2012_ChinPhysLett29-042101

NL3, PK1, ... $R_{\max} = 20$ fm, $\Delta r = 0.1$ fm

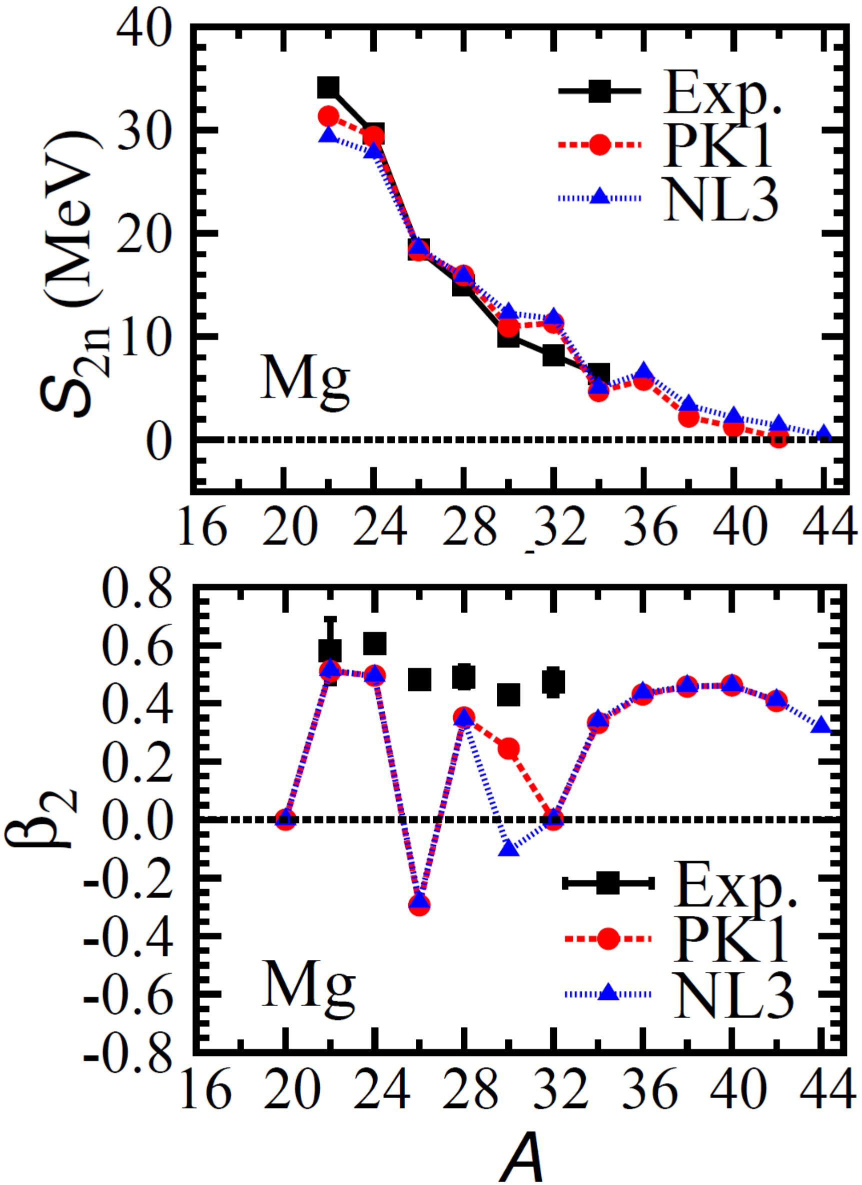
$$V^{\mathrm{pp}}(\boldsymbol{r}_1, \boldsymbol{r}_2) = V_0 \frac{1}{2}(1 - P^{\sigma})\,\delta(\mathbf{r}_1 - \mathbf{r}_2)\left(1 - \frac{\rho(\boldsymbol{r}_1)}{\rho_{\mathrm{sat}}}\right)$$

^{20}Mg: spherical from DRHBWS calculation

Model	Pairing force	Parameters	$E^{\mathrm{p}}_{\mathrm{pair}}$ (MeV)
SRHBHO	Gogny	D1S	−9.2382
RCHB	Surface δ	$V_0 = 374$ MeV fm^3	−9.2387
		$\rho_0 = 0.152$ fm^3	
	Sharp cutoff	$E^{\mathrm{q.p.}}_{\mathrm{cut}} = 60$ MeV	
DRHBWS	Surface δ	$V_0 = 380$ MeV fm^3	−9.2383
		$\rho_0 = 0.152$ fm^3	
	Smooth cutoff	$E^{\mathrm{q.p.}}_{\mathrm{cut}} = 60$ MeV	
		$\Gamma = 5.65$ MeV	

Ground states of Mg isotopes

Li_Meng_Ring_Zhao_SGZ 2012_PRC85-024312

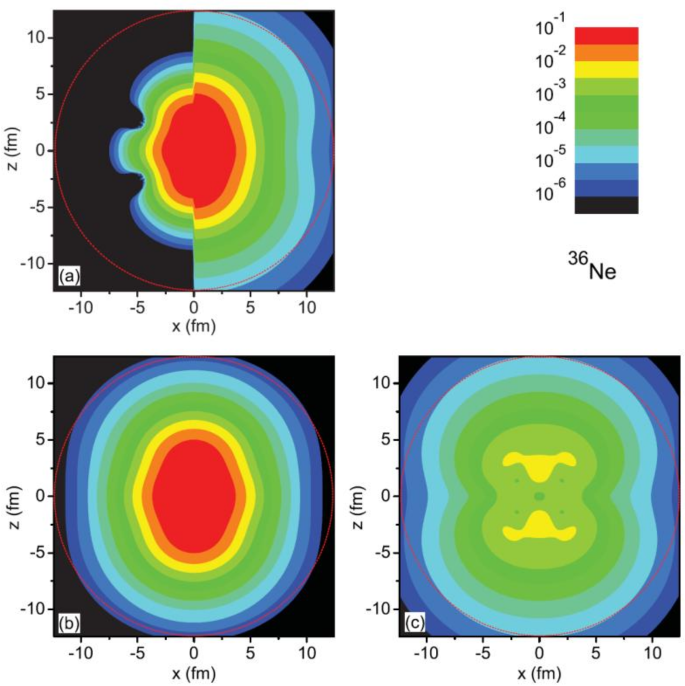


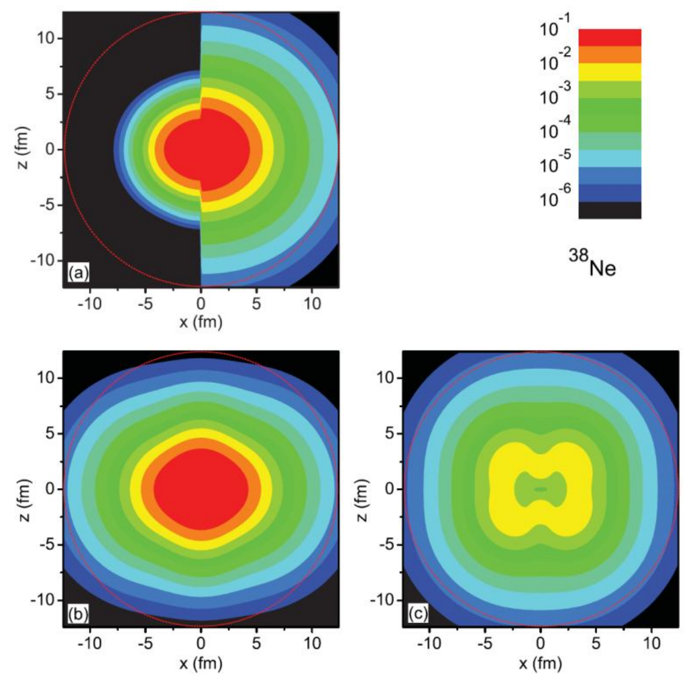
- The calc. reproduce well the experiment
- ^{42}Mg (^{44}Mg) is the last bound deformed nucl. from PK1 (NL3)
- A problem of many mean field models: N = 20 shell quenching can not be obtained
  - ^{32}Mg is deformed according to the expt., but spherical from many MF calc.

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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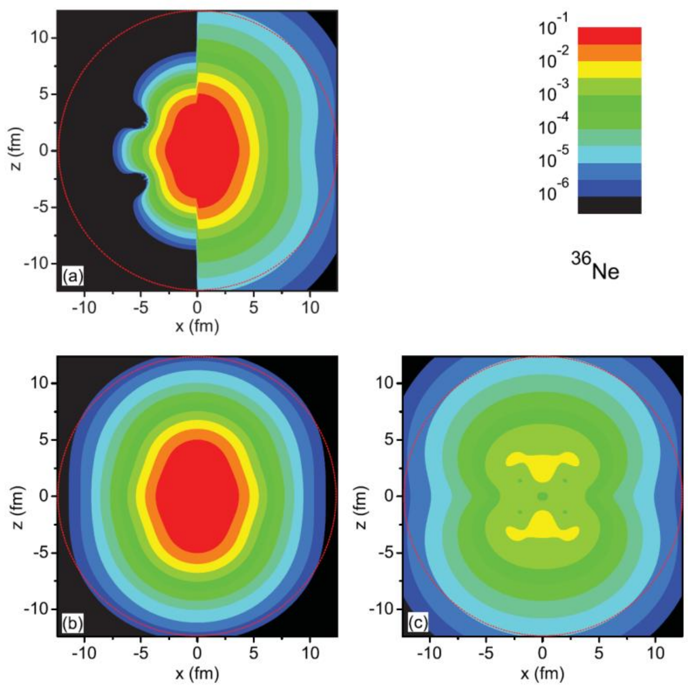
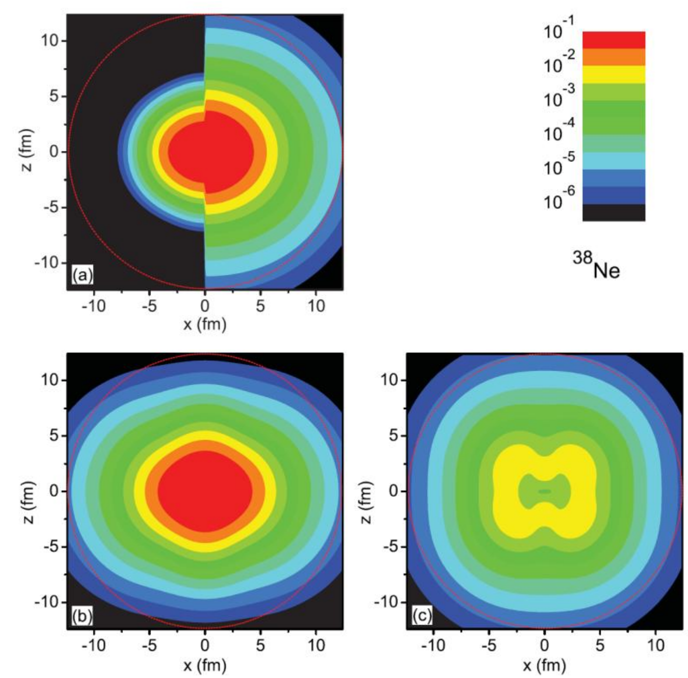
SGZ_Meng_Ring_Zhao 2010 PRC82-011301R

Li_Meng_Ring_Zhao_SGZ 2012 PRC85-024312

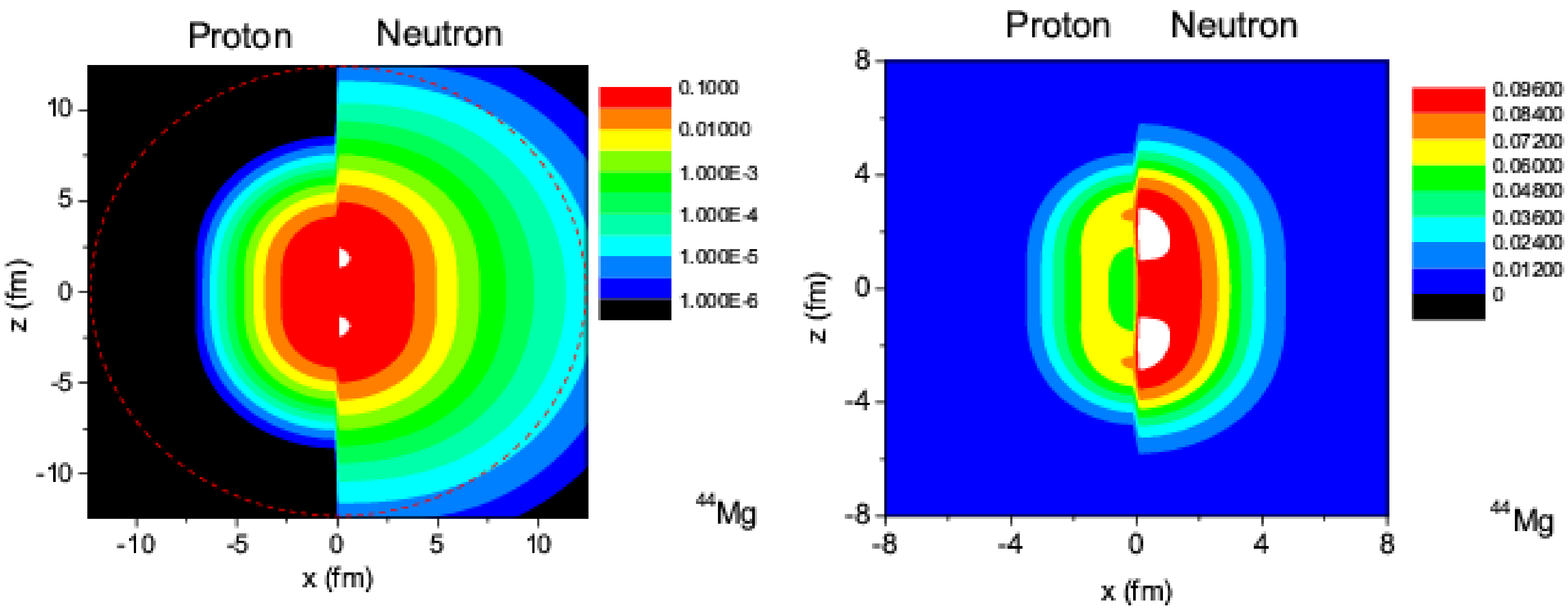
Pei_Zhang_Xu2013PRC87-051302R





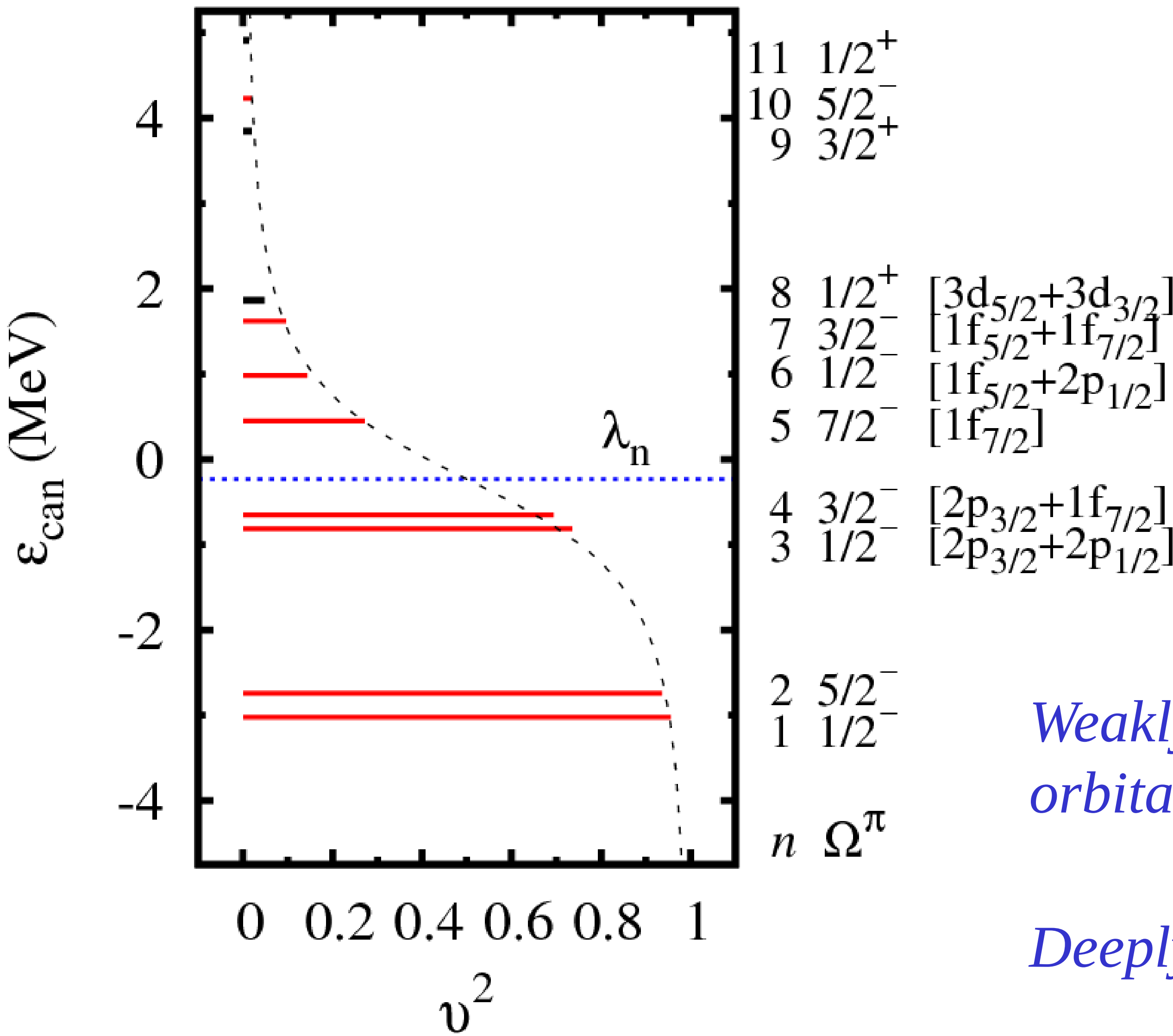
^{44}Mg: Density distributions

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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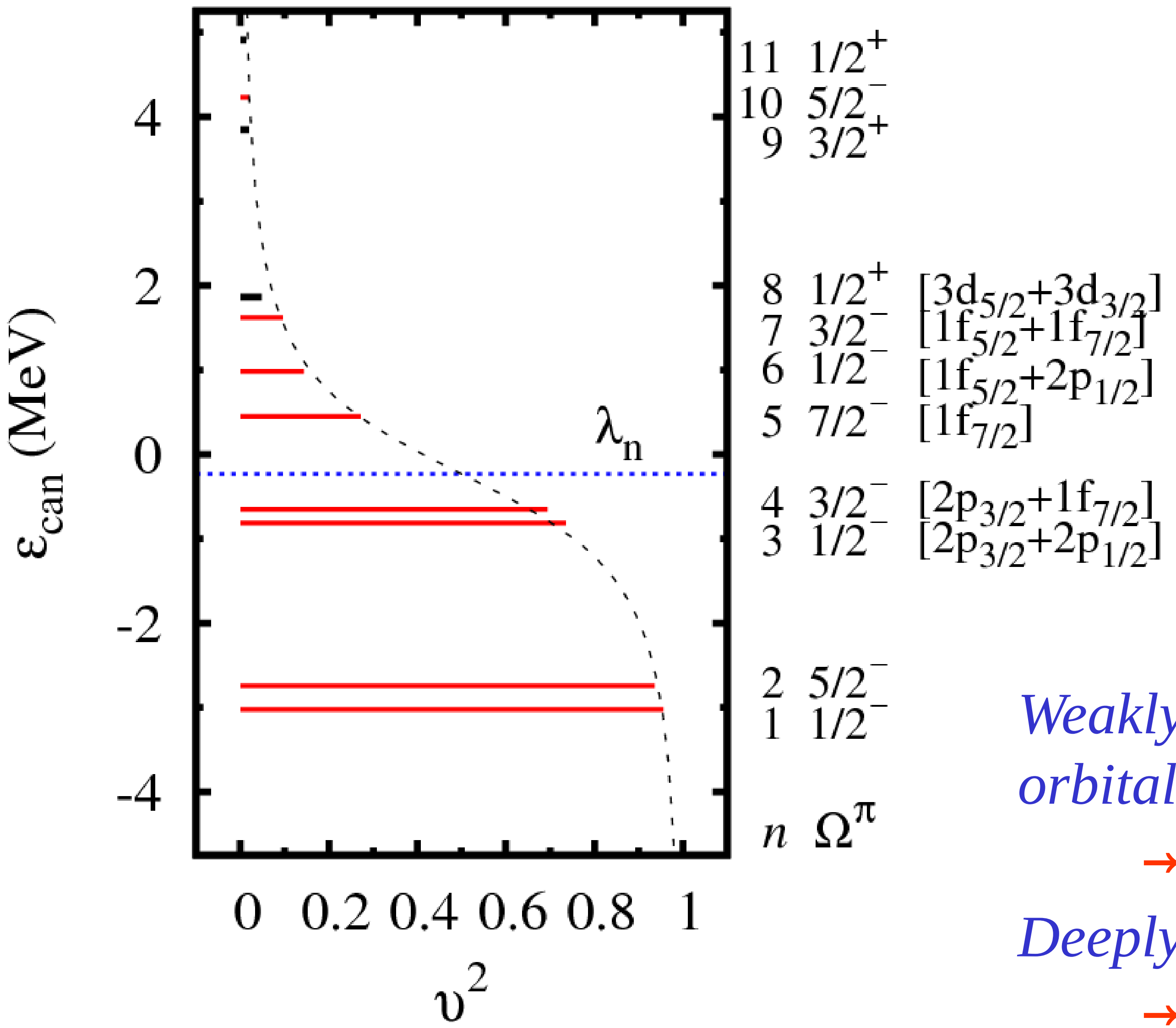


Weakly bound & continuum orbitals

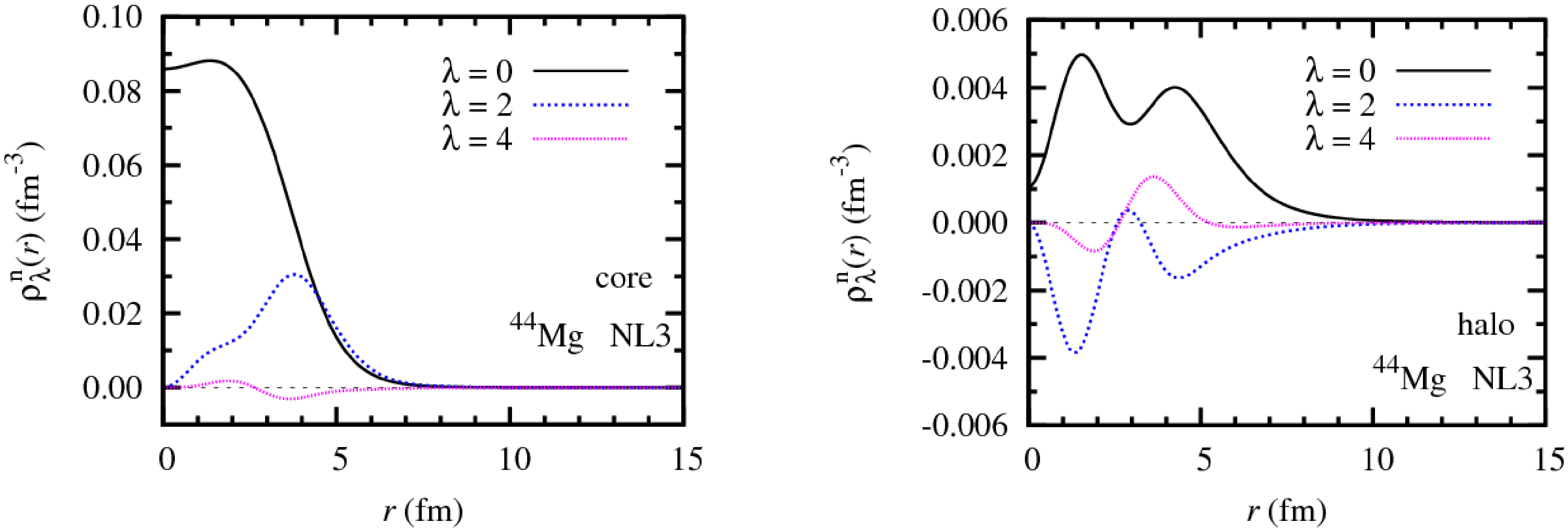
→ halo

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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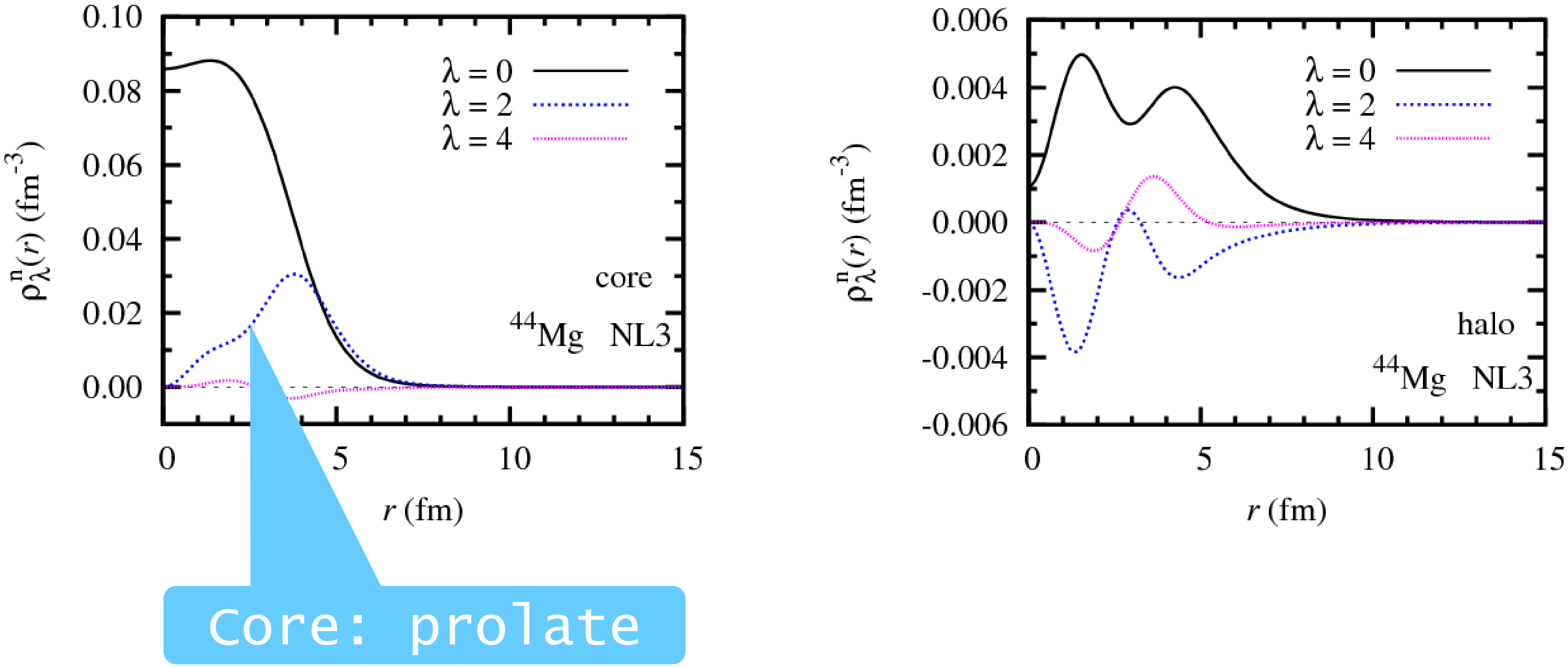

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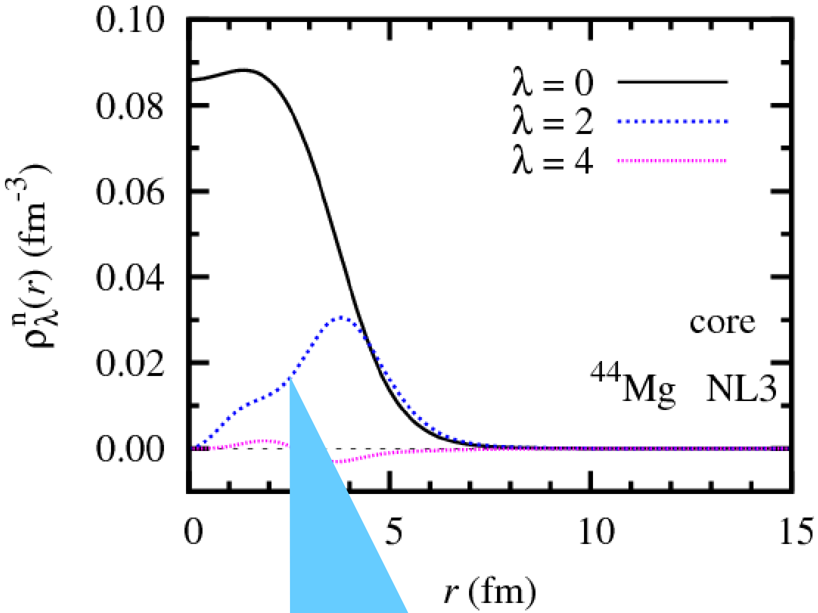
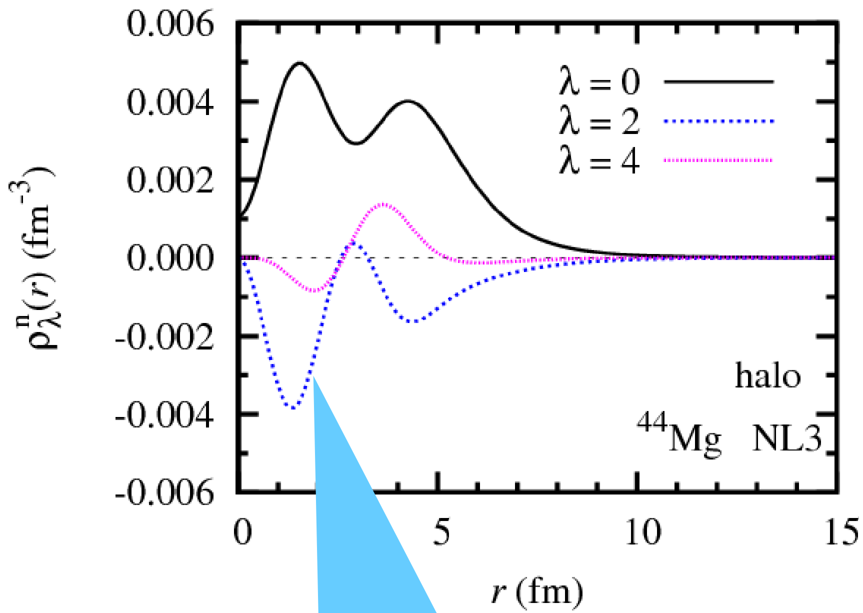
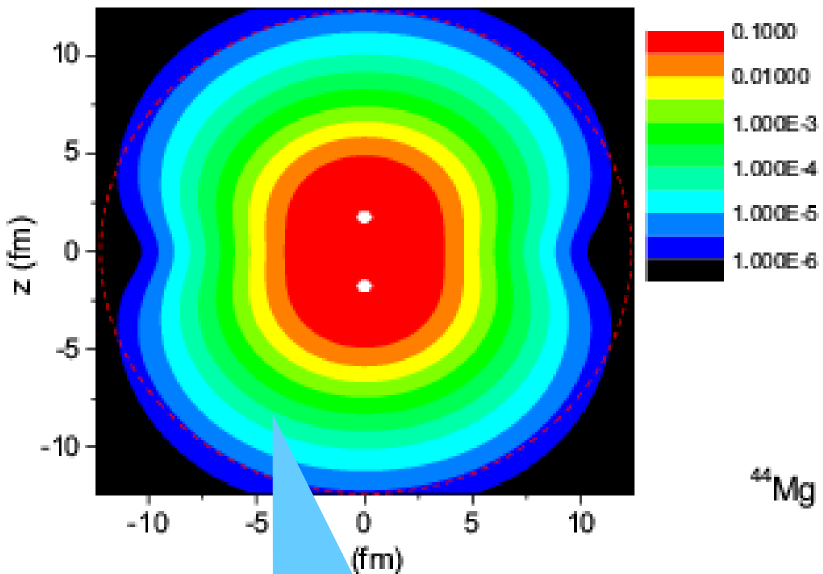


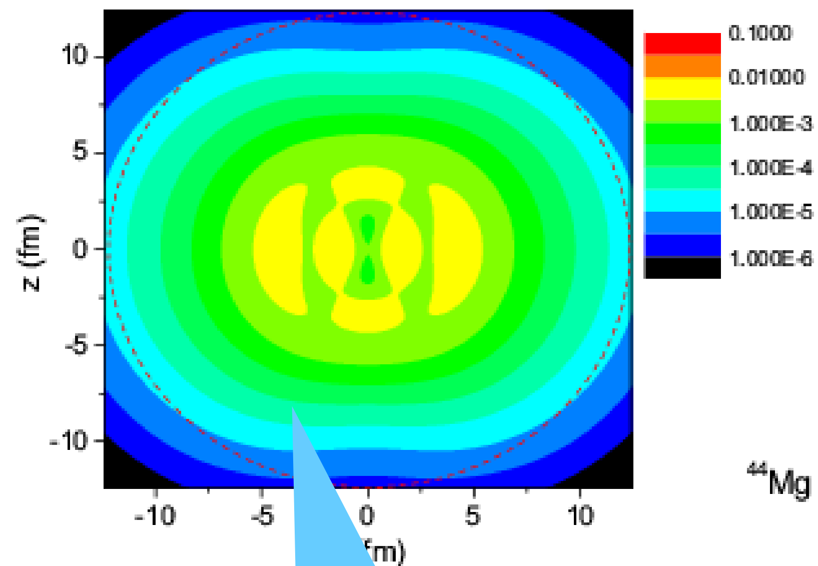
Core: prolate



halo: oblate

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



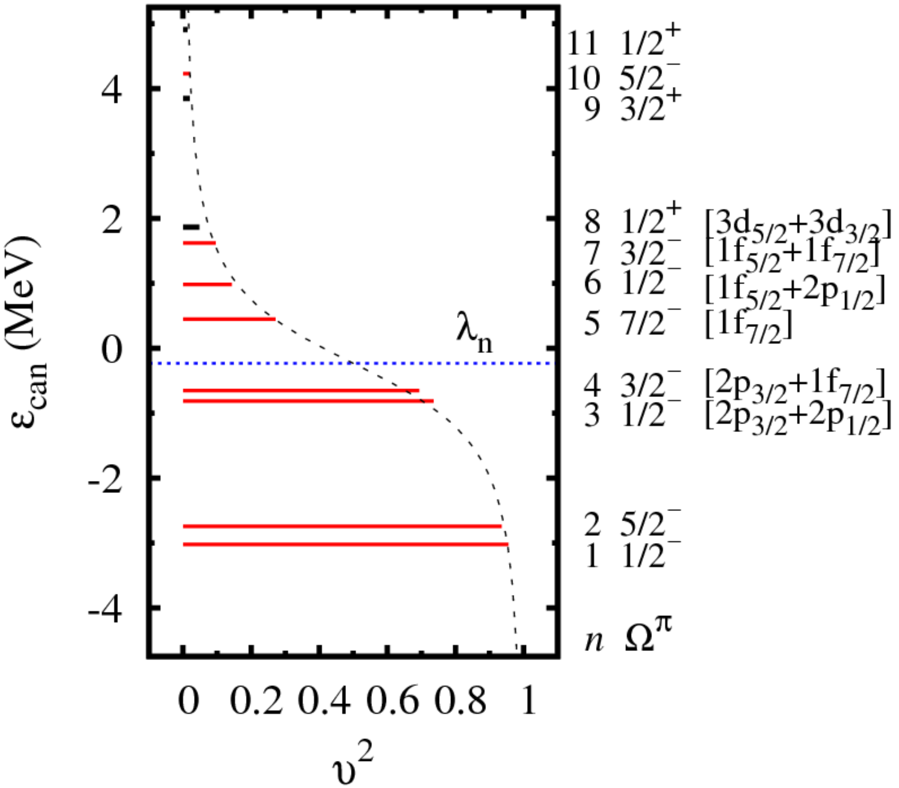


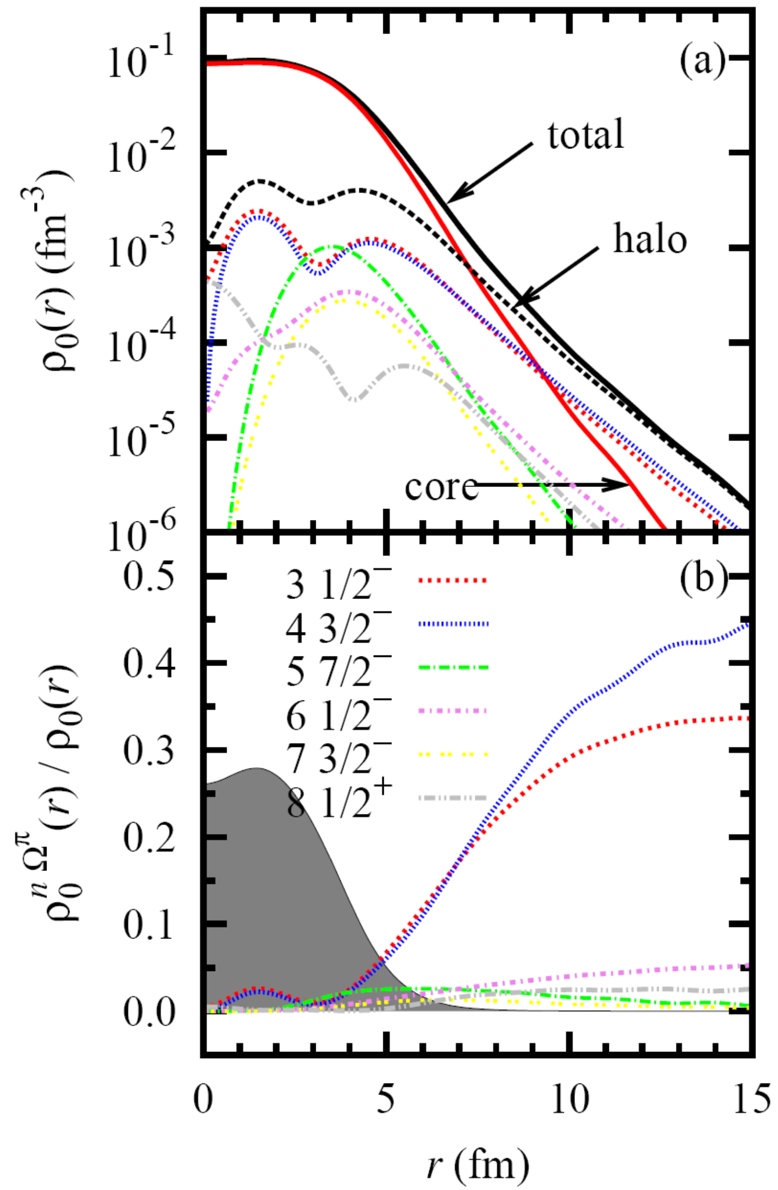
Core: prolate

halo: oblate

^{44}Mg: Decomposition of neutron density distribution

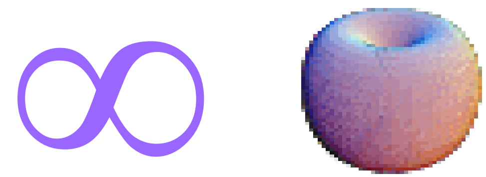
- The 3rd & 4th states contribute to tail part of neutron density distribution
- Main component: $2p_{3/2}$
- $R_{\rm core} = 3.72$ fm, $R_{\rm halo} = 5.86$ fm



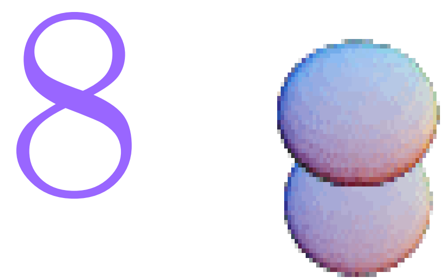


Shape of low-Λ single particle orbital

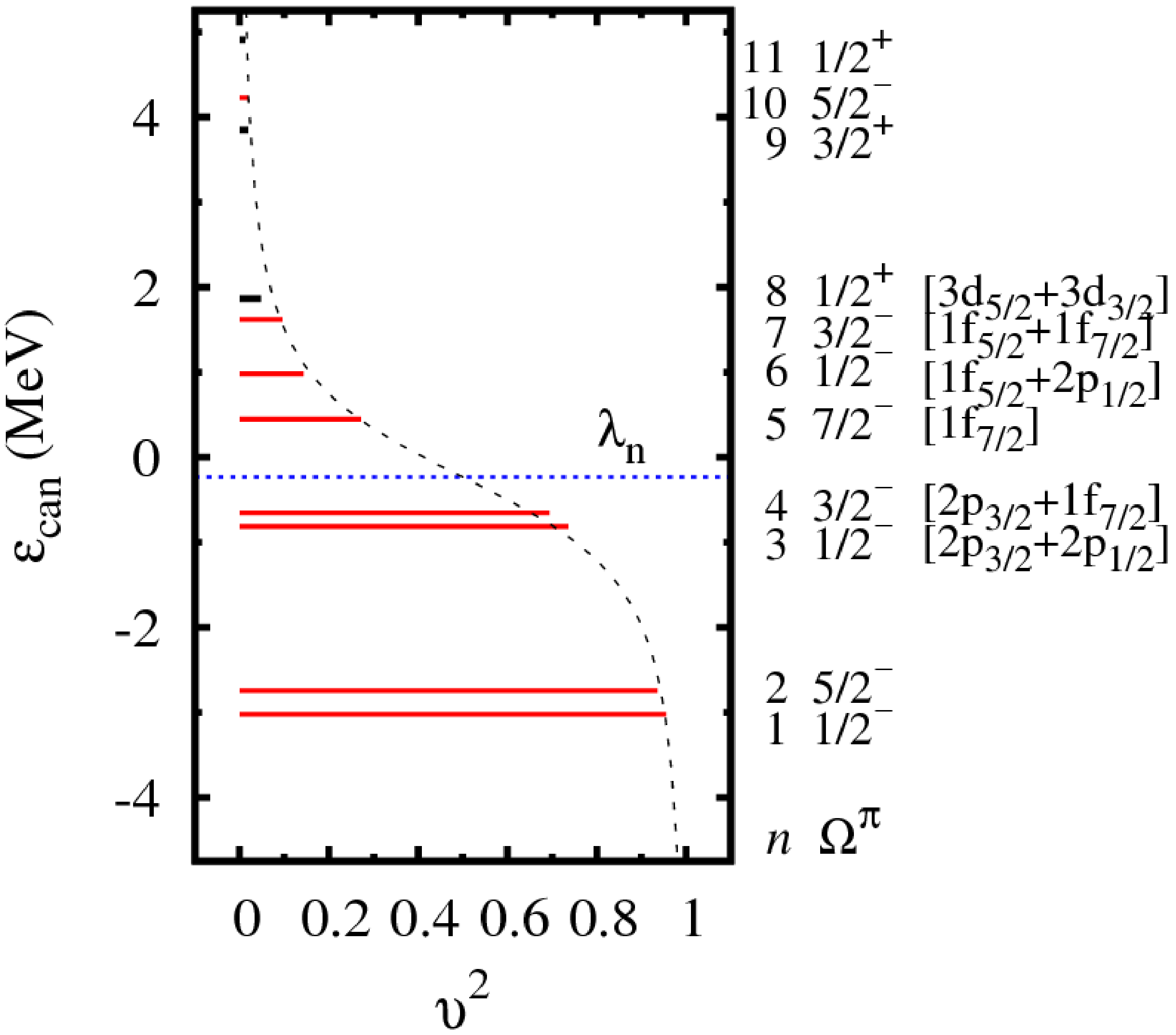
$l = 1, \Lambda = \pm 1 \quad |Y_{1\pm1}(\theta, \phi)|^2 \propto \sin^2(\theta)$



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



Mechanism of shape decoupling



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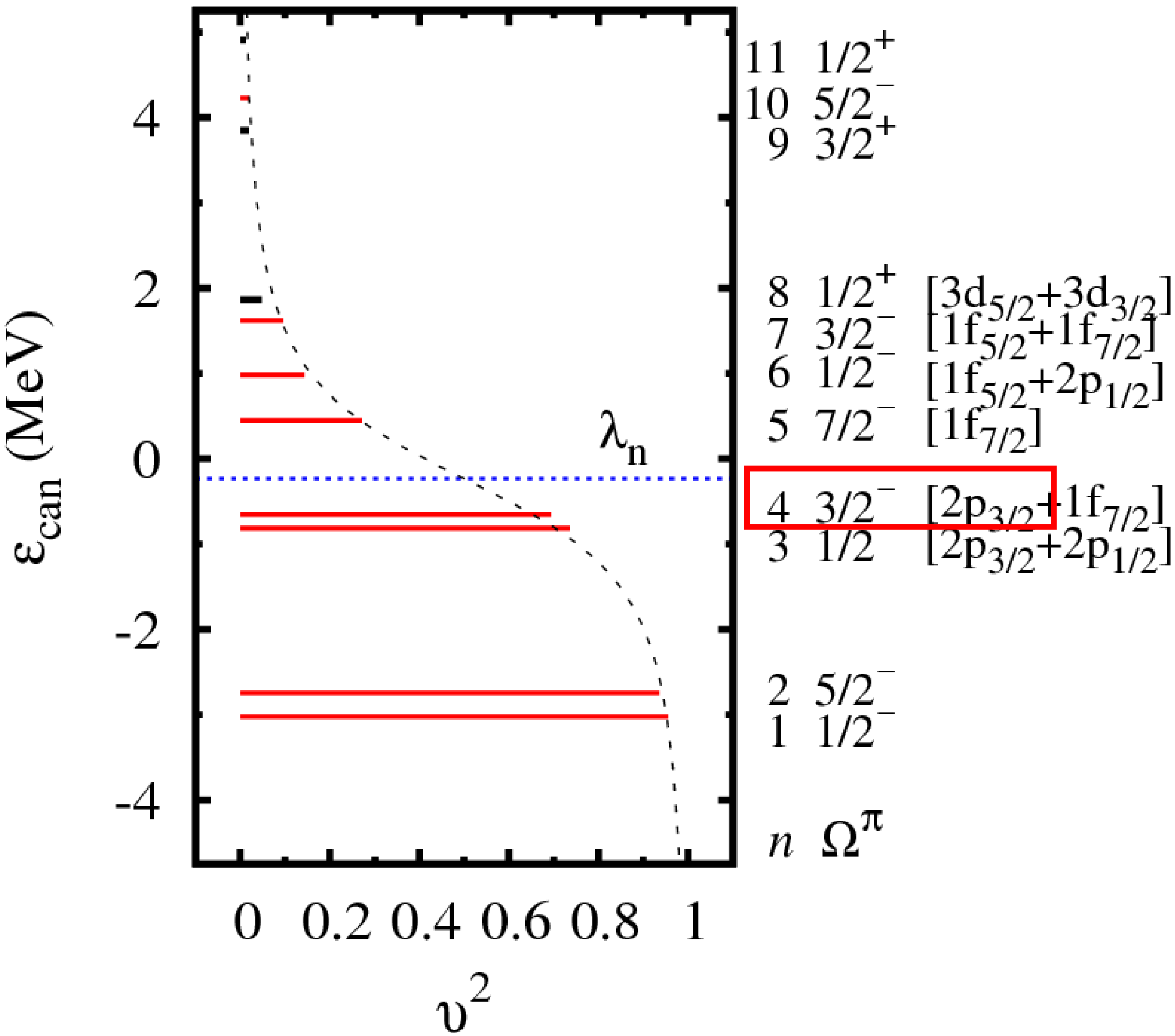
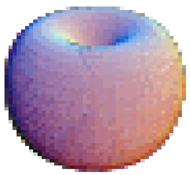
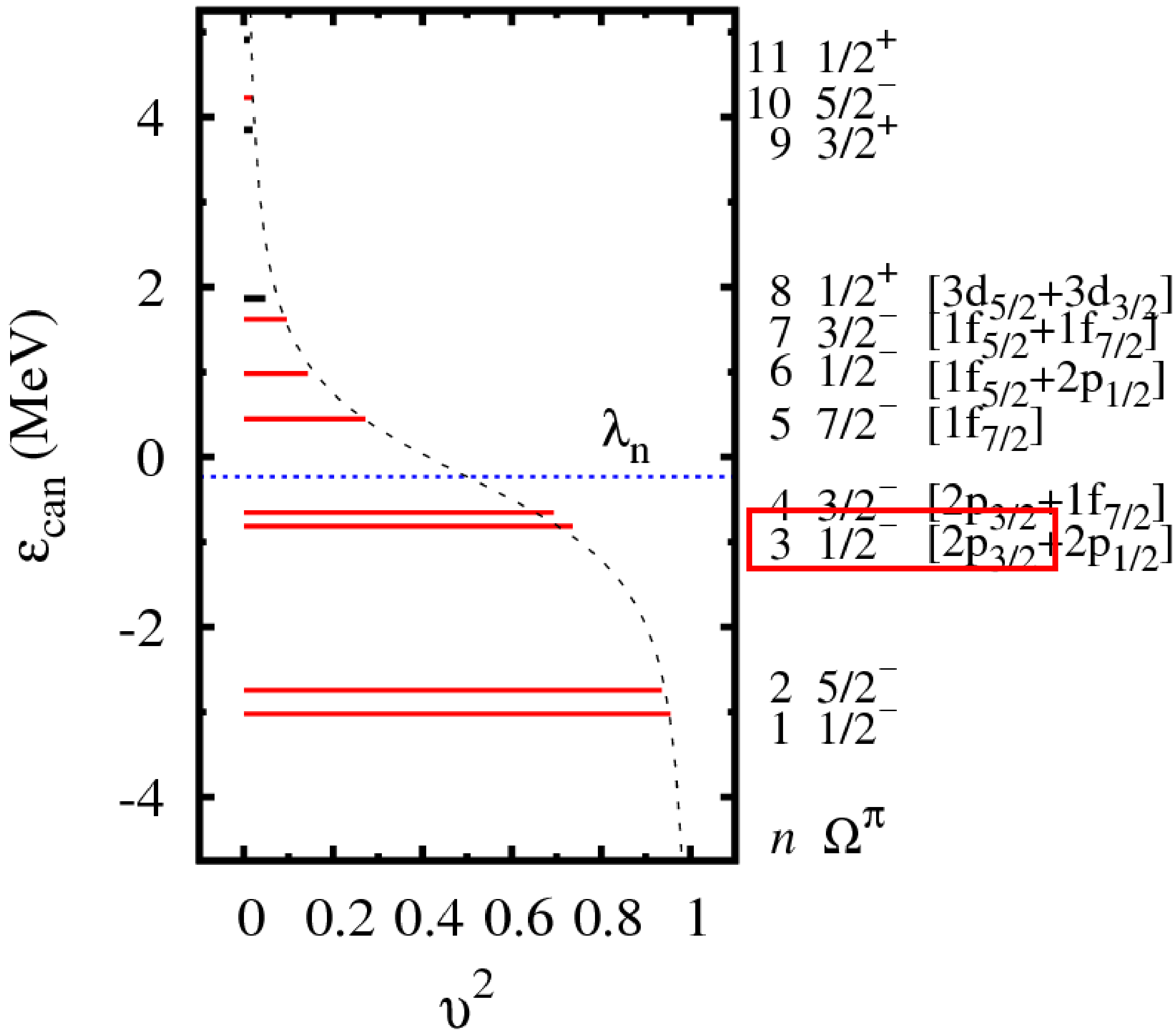


$\Lambda = \pm 1$

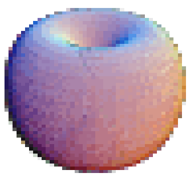


Mechanism of shape decoupling



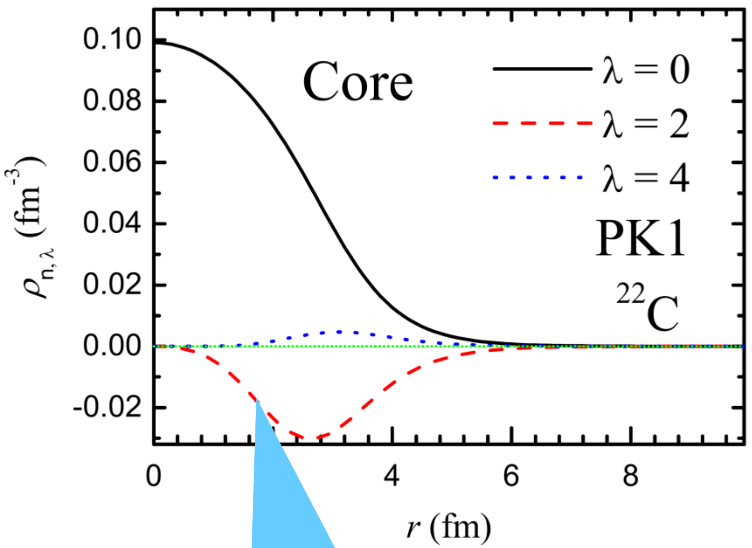
$\Lambda = \pm 1$

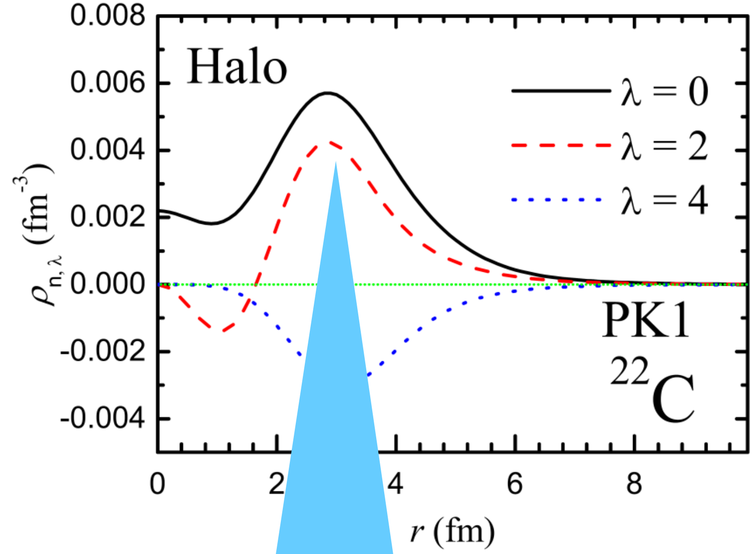
$\Lambda = 0$



^{22}C: Density of core & halo---shape decoupling

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





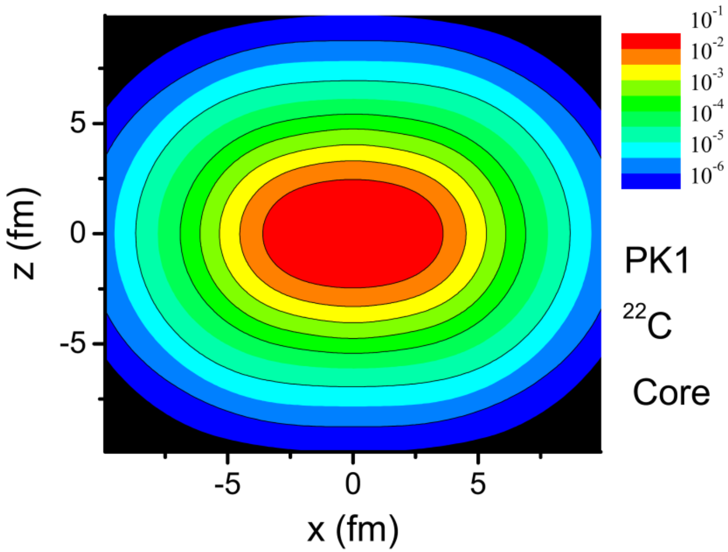
Core: oblate

halo: prolate

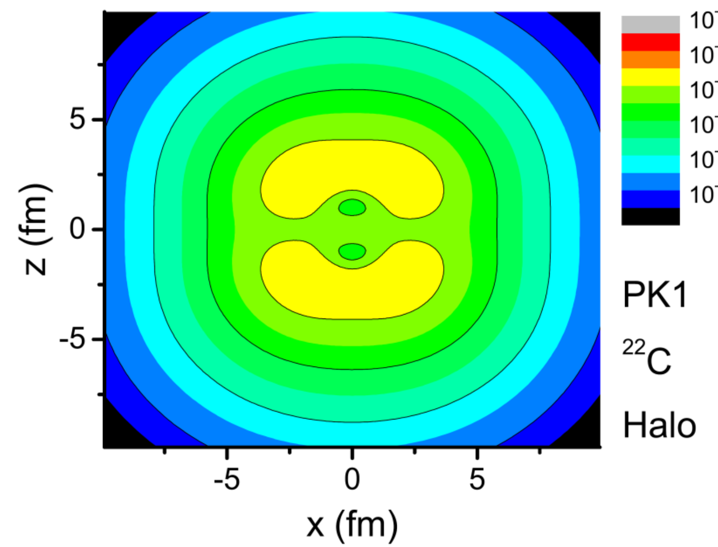
Xiang-Xiang Sun et al., in preparation

^{22}C: Density of core & halo---shape decoupling

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



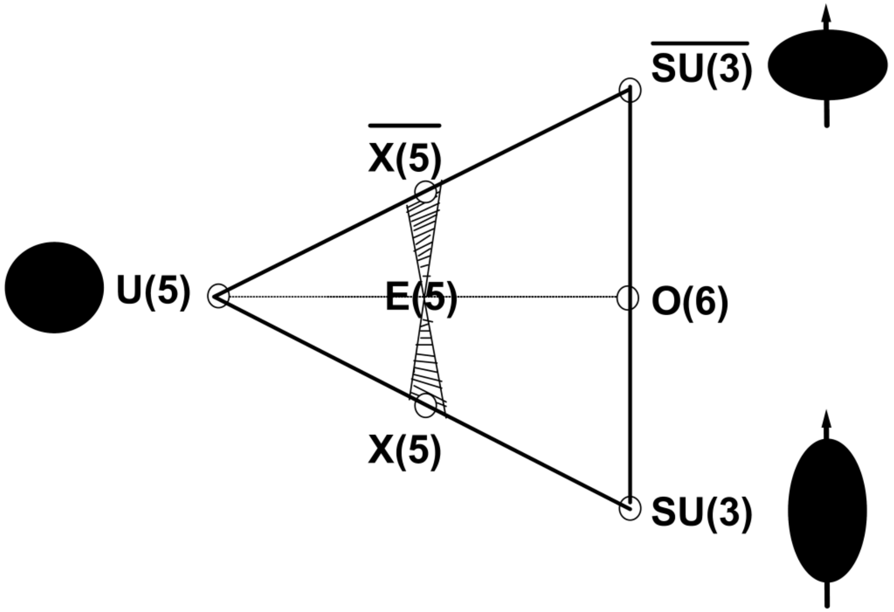
Core: oblate



halo: prolate

Xiang-Xiang Sun et al., in preparation

Extended Casten triangle

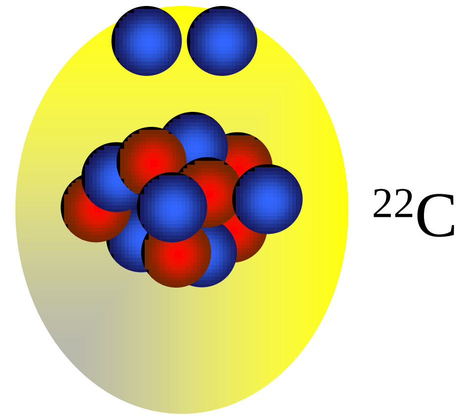


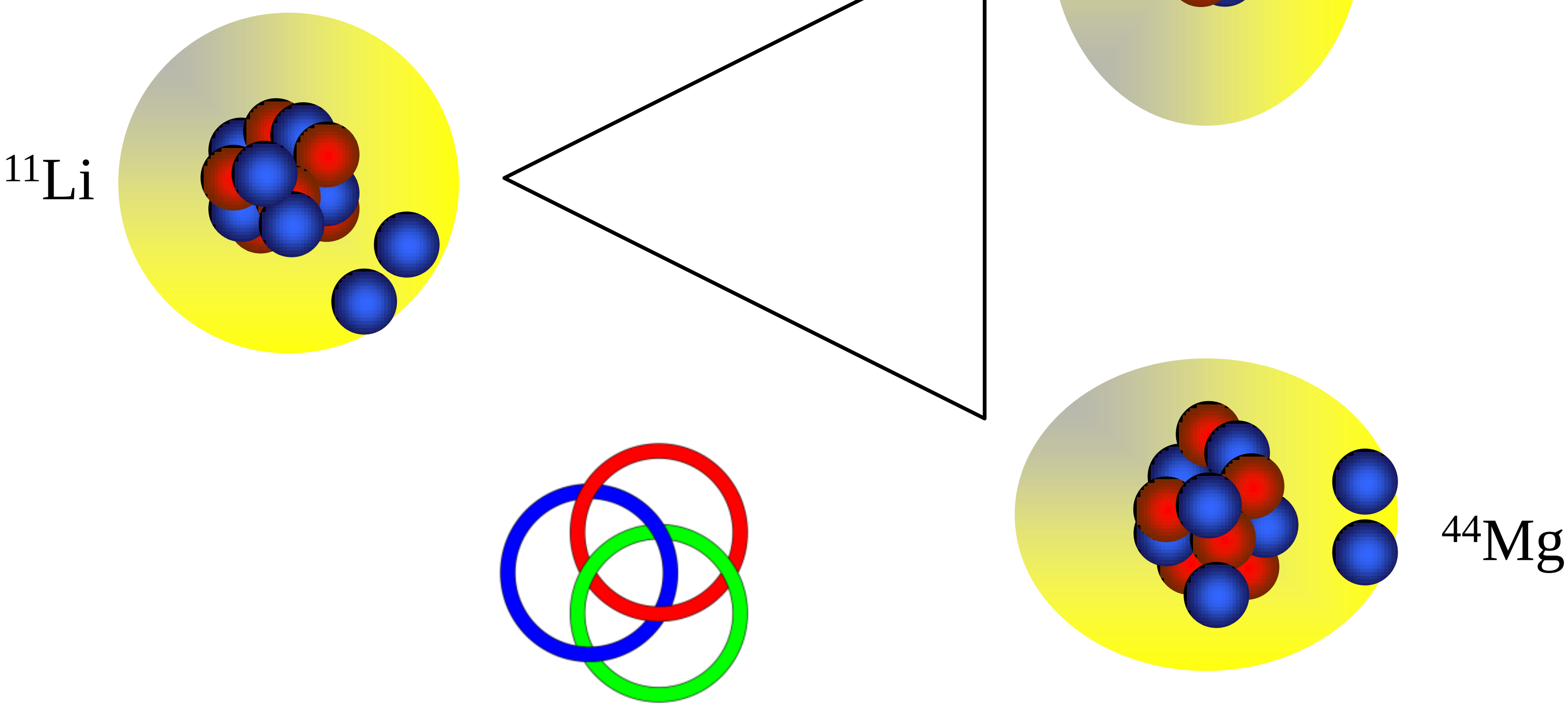
Pan_Wang_Huo_Draayer2006_IJMPE15-1723

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

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

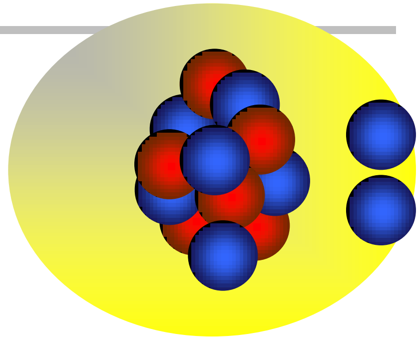
$^{22}C = {}^{11}Li + {}^{11}Li$





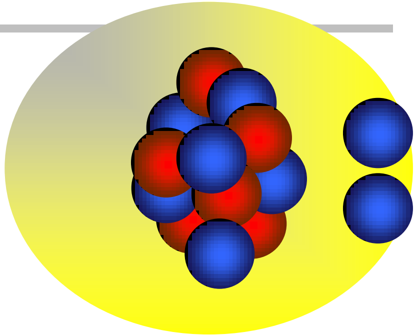
Borromean Ring

How to probe the shape decoupling?



- Larger cross section
- Narrower momentum distribution
  - Double-hump ?

How to probe the shape decoupling?



- Larger cross section
- Narrower momentum distribution
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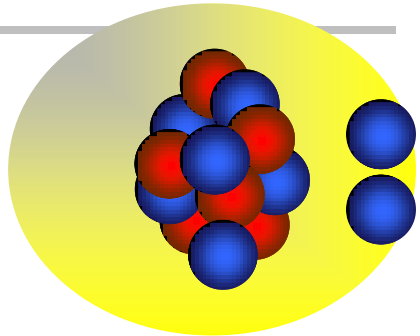
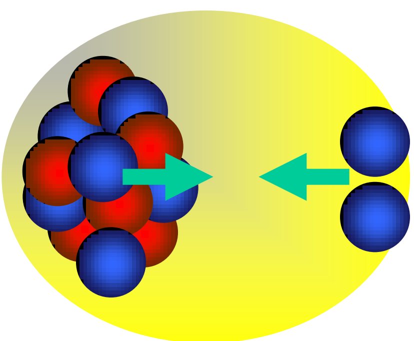
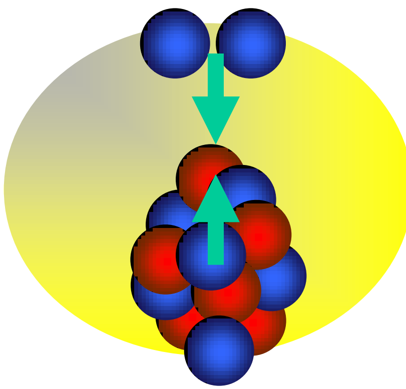
How to probe the shape decoupling?

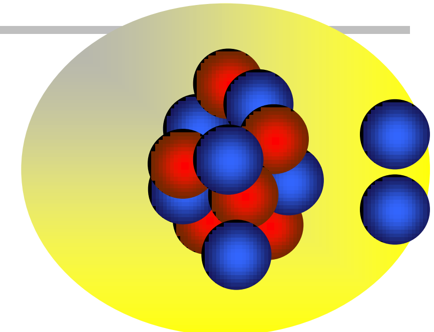


- Larger cross section
- Narrower momentum distribution
  - Double-hump ?
- New dipole modes ?

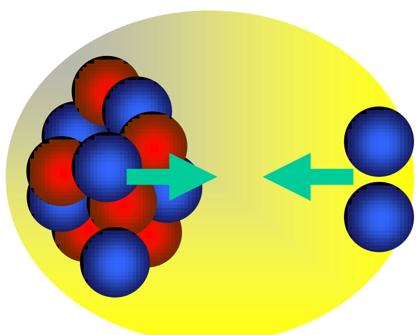


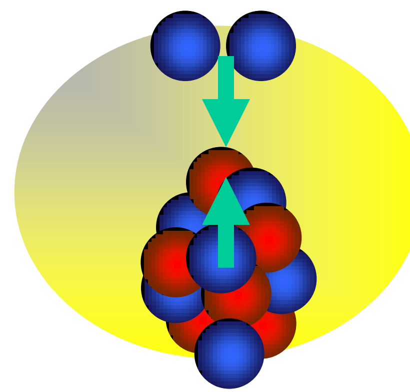


How to probe the shape decoupling?

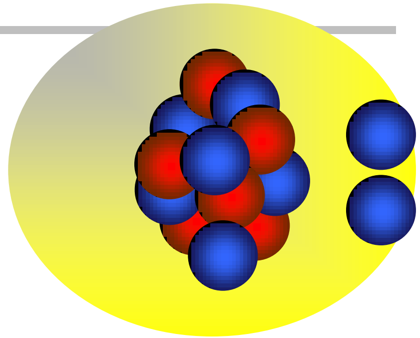


- Larger cross section
- Narrower momentum distribution
  - ➢Double-hump ?
- New dipole modes ?
- Rotation ?

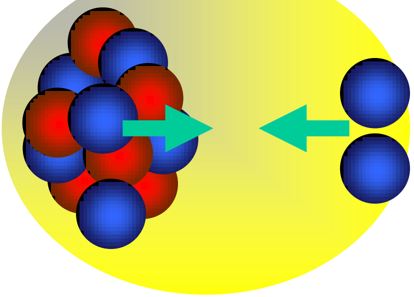


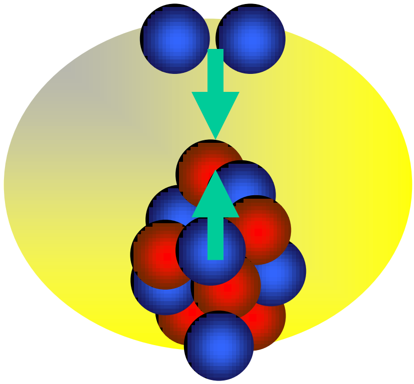


How to probe the shape decoupling?



- Larger cross section
- Narrower momentum distribution
    - Double-hump ?
- New dipole modes ?
- Rotation ?
- Fusion ?





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
  - Prolate deformed core w/ oblate halo: ^{44}Mg
  - Oblate deformed core w/ prolate halo: ^{22}C
  - Triangle of Borromean nuclei: ^{11}Li, ^{22}C & ^{44}Mg
- How to probe shape decoupling ?

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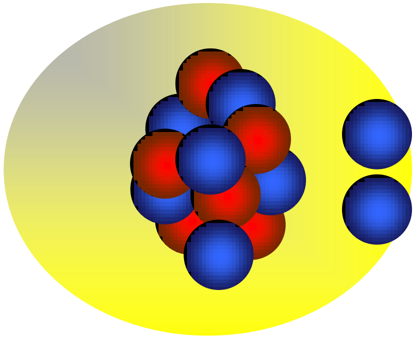
P. Ring (TU Munich & PKU), Xiang-Xiang Sun (ITP)
Jie Zhao (ITP), En-Guang Zhao (ITP)



Thanks

谢谢

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