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Neutron Halo in Deformed Nuclei

李璐璐
Li, Lulu

北京大学 物理学院
School of Physics, Peking University

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Collaborators: Jie Meng (PKU)
Peter Ring (TUM)
En-guang Zhao (ITP, CAS)
Shan-gui Zhou (ITP, CAS)

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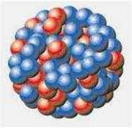
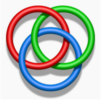
Introduction

Properties of halo nuclei:

- Large spatial distribution. Like ^{11}Li. Tanihata PRL1985



- Halo nucleons may polarize the core.
  - Charge radius of ^{9}Li is 2.217 fm, and 2.467 fm for ^{11}Li. Sanchez et al. PRL2006
  - Charge radius of ^{4}He is 1.676 fm, 2.068 fm for ^{6}He, and 1.929 fm for ^{8}He. Mueller et al. PRL2001
- Oscillation of the weakly bound halo nucleons against the core — pygmy dipole resonance。 Adrich et al. PRL2005
- Non-linear and cluster effects. Borromean nuclei ^{11}Li, ^{6}He. Zhukov et al. PRep1993



- What about the shape of halo nuclei?

Halo in deformed nuclei?

- ^{11}Be
  - The spin-parity of the ground state and first exciting state are $\frac{1}{2}^+$ and $\frac{1}{2}^-$.
    $\Rightarrow$ The parity-inversion phenomenon may caused by deformation. Li et al. PRC1996, Misu et al. NPA1997, Pei et al. NPA2006
- ^{14}Be
  - Halo structure is obtained with spherical RMF model. Ren, et al. PLB1995
  - A kinematical complete measurement of the fragments suggests a large $(2s_{\frac{1}{2}})^2$ admixture and $(1d_{\frac{5}{2}})^2$ in ^{14}Be.
    $\Rightarrow$ Deformation. Labiche et al. PRL2001
- ^{31}Ne
  - The major components of wave function might be $^{30}\mathrm{Ne}(0_1^+) \otimes 2p_{3/2}(C^2S = 0.12)$, $^{30}\mathrm{Ne}(2_1^+) \otimes 2p_{3/2}(C^2S = 0.27)$, $^{30}\mathrm{Ne}(2_1^+) \otimes 2f_{7/2}(C^2S = 0.25)$.
    $\Rightarrow$ "...as such, suggests that it will be strongly deformed." Nakamura et al. PRL2009
- Three body model:
  "Our results suggest that it is unlikely to find (two neutron) halo nuclei on the dripline of deformed nuclei" Nunes NPA2005

Halo in deformed nuclei? Deformed halo?

With energy density functional theory,

- Halo structure is obtained for ^{11}Li, by taking into account the continuum. Meng and Ring PRL1996
- Giant neutron halo was predicted. Meng and Ring PRL1998

- Halo in deformed nuclei? Deformed halo?
  ⇒ Deformed energy density functional theory needed.
- Pairing effect and the contribution of continuum
  ⇒ Bogouliubov transformation used.
- Traditional Harmonic Oscillator basis is not suitable for halo nuclei.
  ⇒ RHB equation should be solved in coordinate space or equivalent basis, like Woods-Saxon basis.

A self consistent deformed Relativistic Hartree-Bogoliubov theory in WS basis is established. S.G. Zhou, J. Meng, P. Ring, E.G. Zhao, Phys. Rev. C 82, 011301R (2010)

Present work: the halo phenomena in Mg isotopes is studied with developed theory.

Deformed relativistic hartree-bogoliubov theory

RHB Equation

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

Dirac hamiltonian

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

Scalar and vector density read

$$\begin{aligned} S(r) &= g_\sigma \sigma(r) \\ V(r) &= g_\omega \omega^0(r) + g_\rho \tau_3 \rho^0(r) + e\frac{1-\tau_3}{2}A^0(r) \end{aligned}$$

Equations of corresponding meson and photon feilds

$$\begin{aligned} (-\Delta + m_\sigma^2)\sigma(r) &= -g_\sigma \rho_s(r) & \rho_s(r) &= \bar{\psi}\psi \\ (-\Delta + m_\omega^2)\omega^0(r) &= g_\omega \rho_v(r) & \rho_v(r) &= \psi^\dagger\psi \\ (-\Delta + m_\rho^2)\rho^0(r) &= g_\rho \rho_3(r) & \rho_3(r) &= \psi^\dagger\tau_3\psi \\ -\Delta A^0(r) &= e\rho_p(r) & \rho_c(r) &= \psi^\dagger\frac{1-\tau_3}{2}\psi \end{aligned}$$

Deformed relativistic hartree-bogoliubov theory

Coefficients of RHB equation are expanded with Dirac Woods-Saxon basis

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

Spherical Dirac spinor
$\{\varphi_{i\kappa m}(\mathbf{r}\sigma p);\ i = 0,\ 1,\ 2,\ \cdots, \kappa = \pm 1,\ \pm 2,\ \cdots,\ m = \pm\frac{1}{2},\ \pm\frac{3}{2},\ \cdots, \pm(|\kappa| - \frac{1}{2})\}$,

$$\varphi_{i\kappa m}(\mathbf{r}\sigma p) = \frac{1}{r} \begin{pmatrix} iG_{i\kappa}(r)\phi_{\kappa m}(\Omega\sigma) \\ -F_{i\kappa}(r)\phi_{-\kappa m}(\Omega\sigma) \end{pmatrix},$$

where

$$\begin{aligned} \phi_{\kappa m}(\Omega\sigma) &= \sum_{m_l m_s} \langle l m_l s m_s | j m \rangle Y_{l m_l}(\Omega) \chi_{m_s}(\sigma), \\ \phi_{-\kappa m}(\Omega\sigma) &= \sum_{m_l m_s} \langle \tilde{l} m_l s m_s | j m \rangle Y_{\tilde{l} m_l}(\Omega) \chi_{m_s}(\sigma), \end{aligned}$$

and $\Omega = (\theta, \phi)$,

$$\kappa = \pm(j + 1/2) \textit{ for } j = l \mp 1/2,\ j = |\kappa| - \frac{1}{2},\ l = j + \mathrm{sign}(\kappa)/2,\ \tilde{l} = j - \mathrm{sign}(\kappa)/2$$

Numerical details

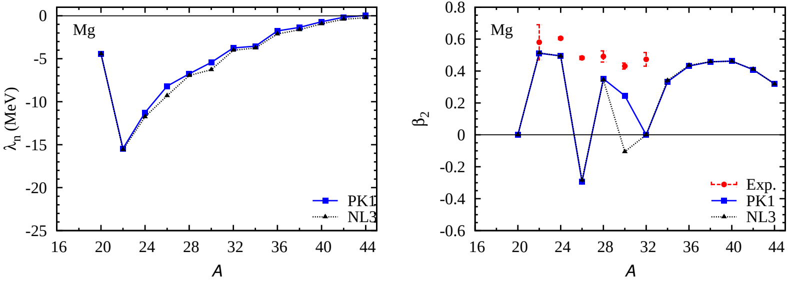
- Box size $R = 20$ fm and step size $dr = 0.1$ fm are used for solving DWS basis.
- Energy cut off is chosen to be $E_{\rm cut} = 100$ MeV.
- Density dependent delta force is used for pairing, and smooth cut off is used.

$$s(E_k) = \frac{1}{2}\left(1 - \frac{E_k - E_{\rm cut}^{\rm q.p.}}{\sqrt{(E_k - E_{\rm cut}^{\rm q.p.})^2 + (\Gamma_{\rm cut}^{\rm q.p.})^2}}\right)$$

Parameters of pairing interaction is chosen by fitting the proton pairing energy of spherical ^{20}Mg given by Gogny D1S.

Model	Pairing force	Parameters	$E^{\rm p}_{\rm pair}$ (MeV)
SRHBHO	Gogny	D1S	-9.2382
RCHB	Surface δ with sharp cutoff	$V_0 = 374$ MeV fm^3 $\rho_{\rm sat} = 0.152$ fm^{-3} $E_{\rm cut}^{\rm q.p.} = 60$ MeV	-9.2387
DRHBWS	Surface δ with smooth cutoff	$V_0 = 380$ MeV fm^3 $\rho_0 = 0.152$ fm^{-3} $E_{\rm cut}^{\rm q.p.} = 60$ MeV $\Gamma_{\rm cut}^{\rm q.p.} = 5.65$ MeV	-9.2382

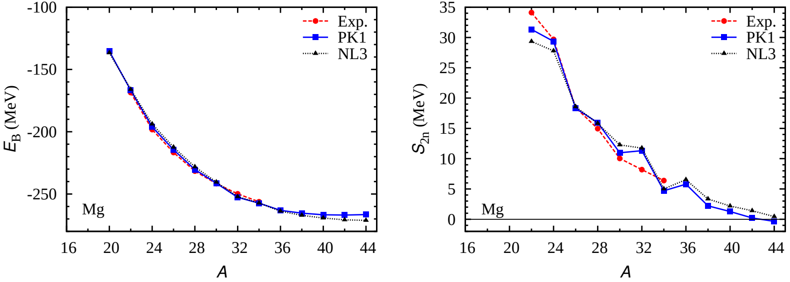
Mg isotopes



- ^{42}Mg is the drip line nucleus (PK1).
- ^{32}Mg is spherical for both parameter sets.

S. Raman, et al., Atom. Data Nucl. Data Tab. 78, 1 (2001)

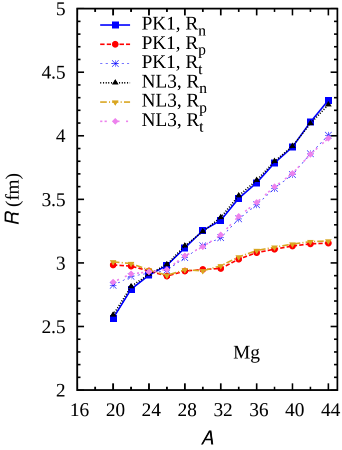
Mg isotopes



- Reasonable two neutron separation energy obtained.
- Strong shell effect of $N = 20$ is observed with mean field theory.

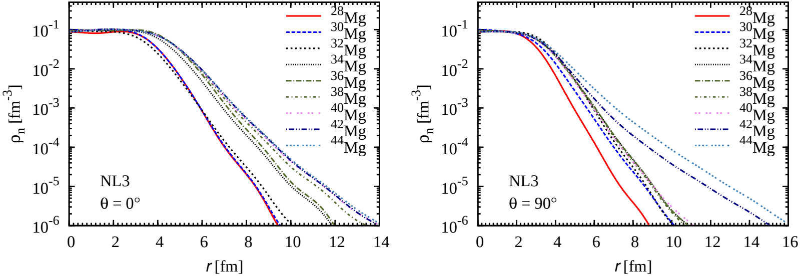
G. Audi, et al., Nucl. Phys. A 729 (2003)
L.S. Geng, Ph.D Thesis (2005)

Mg isotopes (radii)



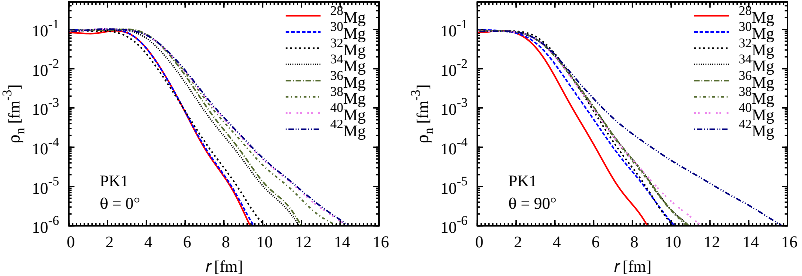
- Slope of neutron radii changes slightly at ^{32}Mg $\Rightarrow$ Shell effect with mean field theory.
- Slope of neutron radii changes slightly at ^{40}Mg $\Rightarrow$?

Mg isotopes (neutron density profiles)



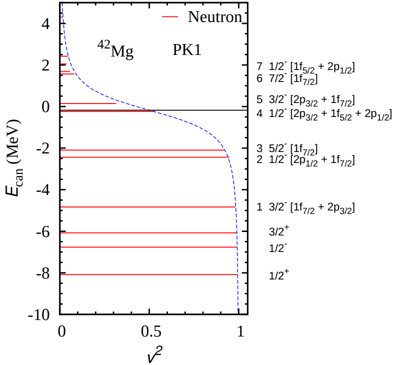
- In the direction of z axis, neutron density profile of Mg isotopes changes smoothly.
- In the direction of x axis, neutron density of ^{42}Mg extend far away from the center . $\Rightarrow$ Oblate halo

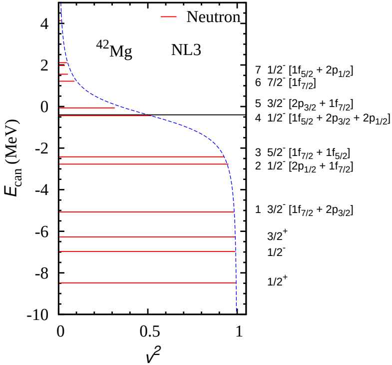
Mg isotopes (neutron density profiles)



- In the direction of z axis, neutron density profile of Mg isotopes changes smoothly.
- In the direction of x axis, neutron density of ^{42}Mg extend far away from the center . ⇒ Oblate halo

^{42}Mg: single particle levels

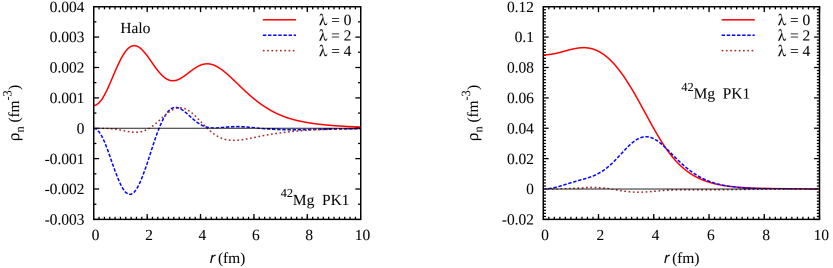




- Weakly bound and continuum orbitals → Halo
- Deeply bound orbitals → Core

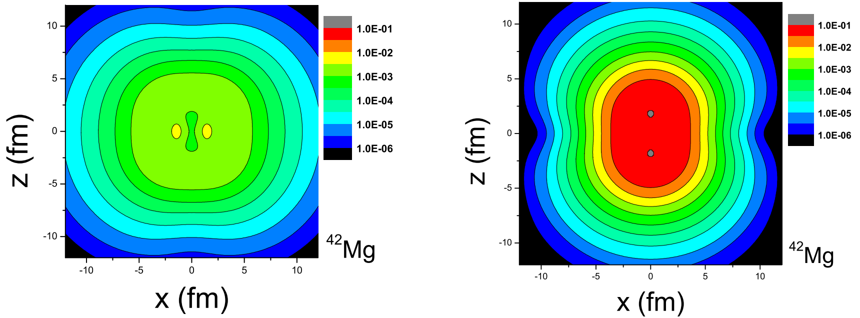
^{42}Mg: density profile

$$\rho(\mathbf{r}) = \sum_{\lambda} \rho_\lambda(r) P_\lambda(\cos\theta), \qquad \lambda = 0, 2, 4 \ldots$$



- Shape decoupling between core and halo.
  - Oblate halo
  - Prolate core

^{42}Mg: density profile of halo and core



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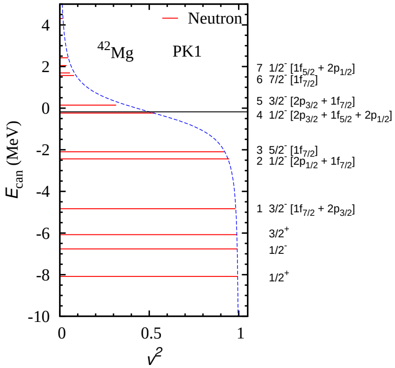
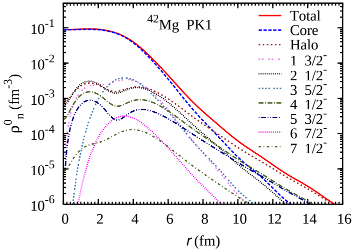
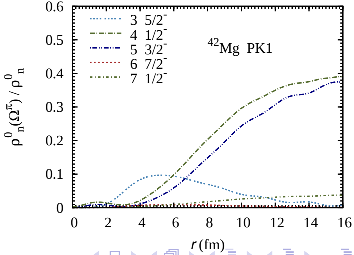
^{42}Mg: single particle levels

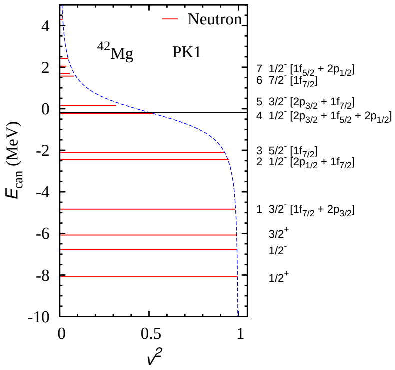


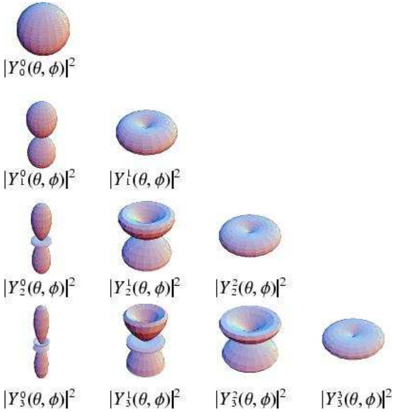




- Level 4, 5 give most contributions of the halo.

^{42}Mg: shape of the halo





- Level 4
  - $2p_{3/2}$: gives 37% of the contribution, in which $\Lambda = 0$ component domains;
  - $1f_{5/2}$: gives 32% of the contribution, in which $\Lambda = 1$ component domains;
  - $2p_{1/2}$: gives 21% of the contribution, in which $\Lambda = 1$ component domains.
- Level 5
  - $2p_{3/2}$: gives 79% of the contribution, only has the component of $\Lambda = 1$.

Summary

Summary

- It is focused on halo phenomena in deformed nuclei (Mg isotopes).
- Halo may occur, depending on intrinsic properties of orbitals around the Fermi level.
- There might be shape decoupling between core and halo (^{42,44}Mg).

Perspective

- How about the halo in odd-A nuclei?
- What about the contribution of Fock term to halo phenomena?
    - The effect of π meson,
    - The effect of tensor force,
    - ...