Int. Conf. on Simplicity, Symmetry & Beauty of Atomic Nuclei
Sep 26-28, 2018, Shanghai

Deformed nuclear halos

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Collaborators: Lulu Li (ITP, PKU, IAPCM), Jie Meng (PKU),
P. Ring (TU Munich & PKU), Xiang-Xiang Sun (ITP)
Jie Zhao (ITP), En-Guang Zhao (ITP)

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

Happy birthday, Professor Arima!

Congratulations also from Prof. En-Guang Zhao (赵恩广)

Prof. Arima's visit of ITP/CAS in 1998

What I learned from Prof. Arima (continued)

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/ 学术及文化活动

【北航大讲堂预告】有马朗人教授将莅校做“自然、文化和科学中的对称性”专题讲座

打印

Symmetries in Arts, Culture and Nature

Akito Arima

What I learned from Prof. Arima (continued)

有马先生：北航大讲堂
2010年4月28日

Summary of this part

1 European paintings and buildings do not break Bilateral Symmetry

2 Chinese buildings keep bilateral symmetry but Chinese paintings break it

3 Japanese buildings and paintings often break bilateral symmetry

A Question ; Why?

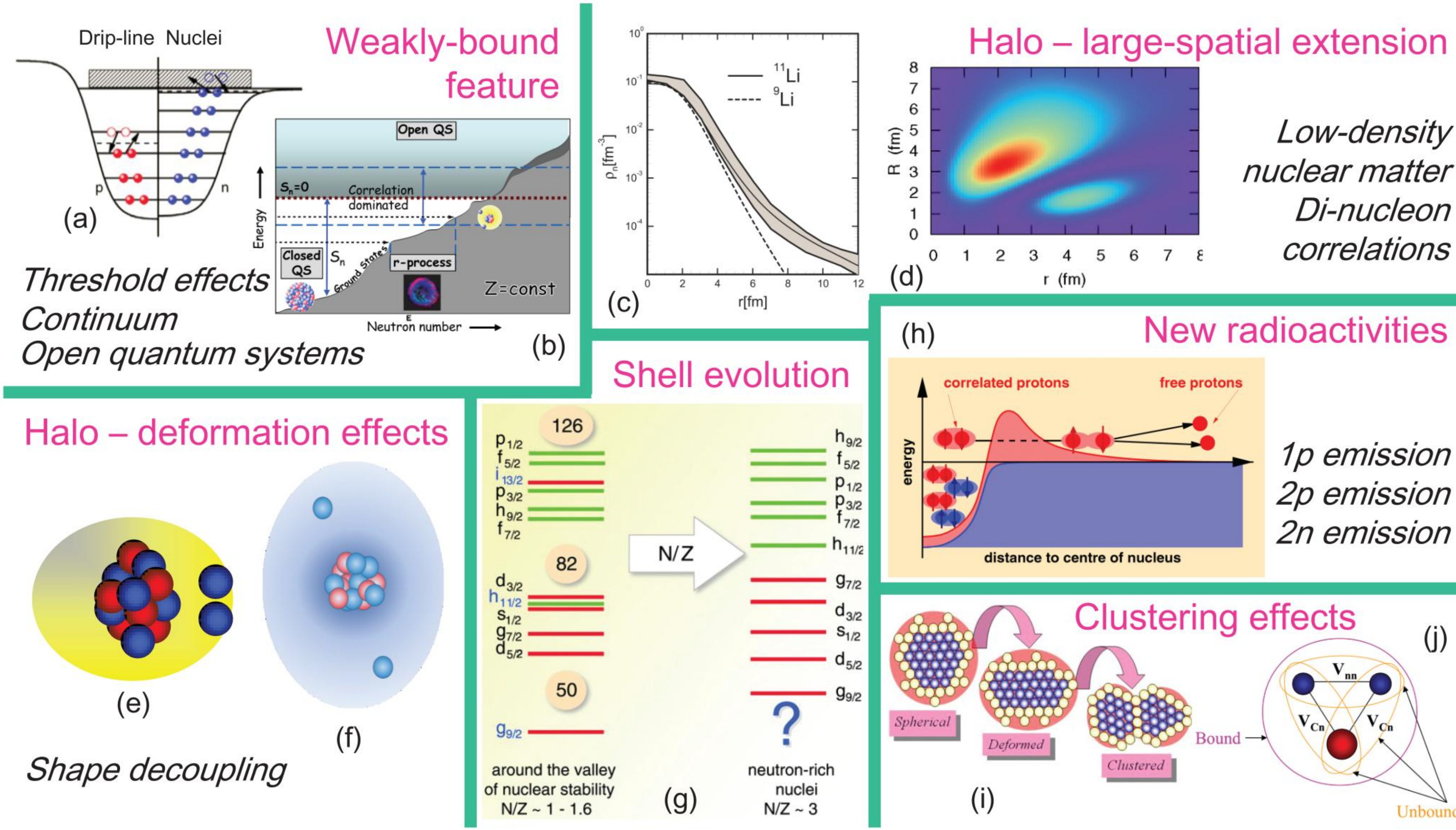
One answer is because culture is affected by the climate such as monsoon in Asia, dry air in the Middle East and African desert land and moderate climate in Europe.

One more question. Can such differences affect our thoughts such as physics?

Contents

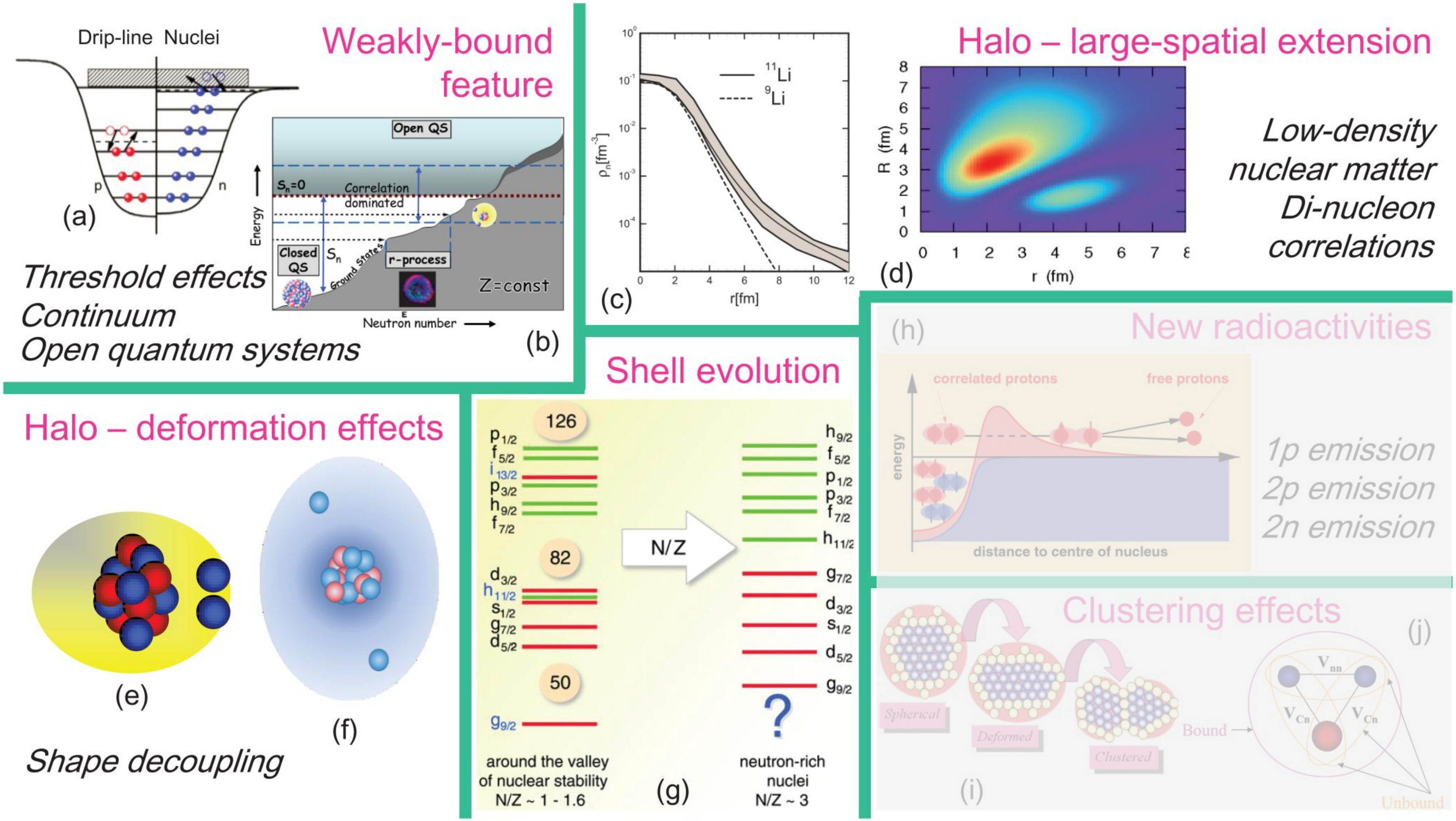
- Introduction
- Deformed RHB model in continuum (Woods-Saxon basis)
- Shape decoupling in deformed halo nuclei
  - ^{44}Mg: prolate core but oblate halo
  - ^{22}C: oblate core but prolate halo
  - ^{11}Li, ^{22}C & ^{44}Mg: triangle of Borromean nuclei
- How to probe shape decoupling in deformed halo nuclei?
- Summary & perspectives

Physics in exotic nuclear structure



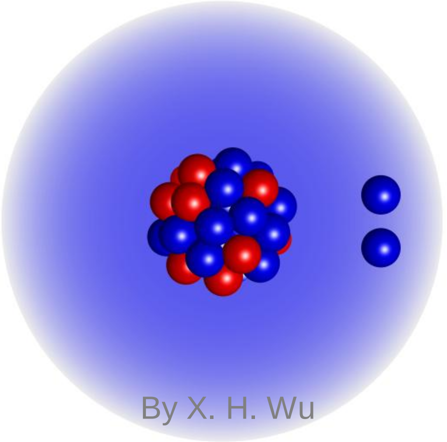
SGZ, PoS (INPC2016) 373

Physics in exotic nuclear structure

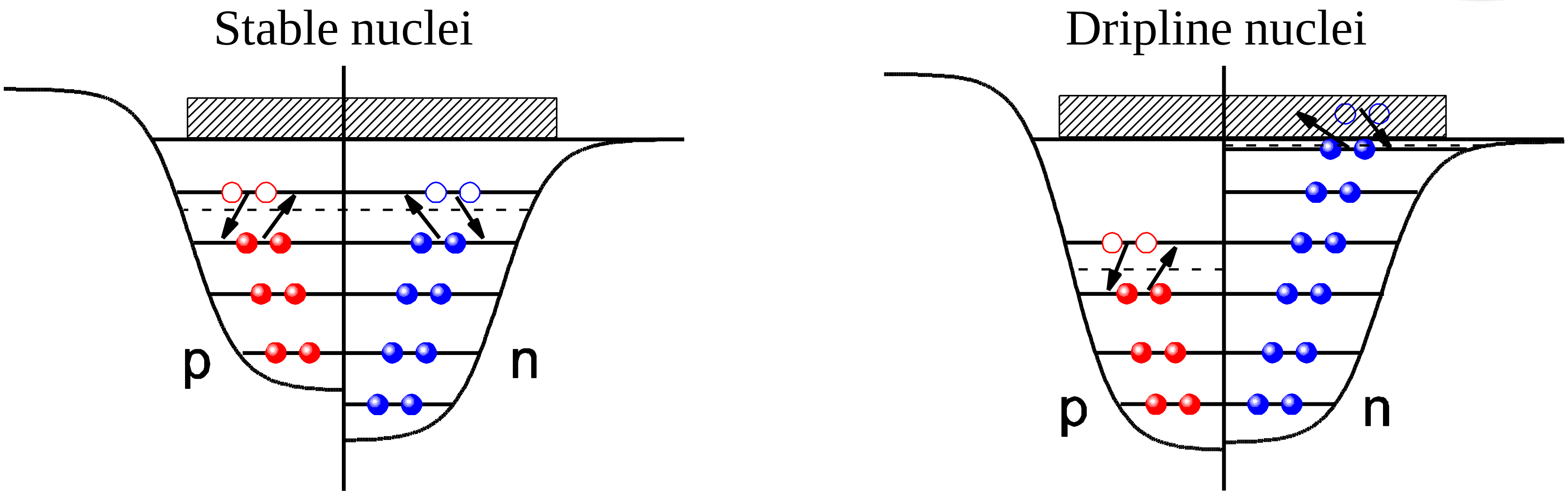


SGZ, PoS (INPC2016) 373

Characteristics of halo nuclei



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



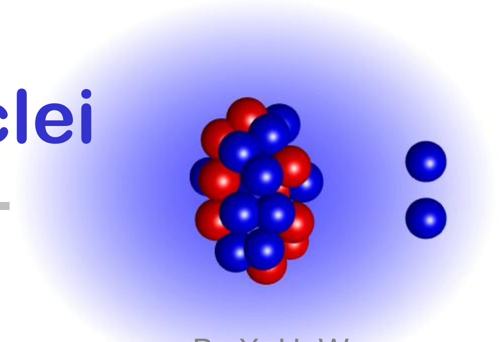
Self-consistent description:

- 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

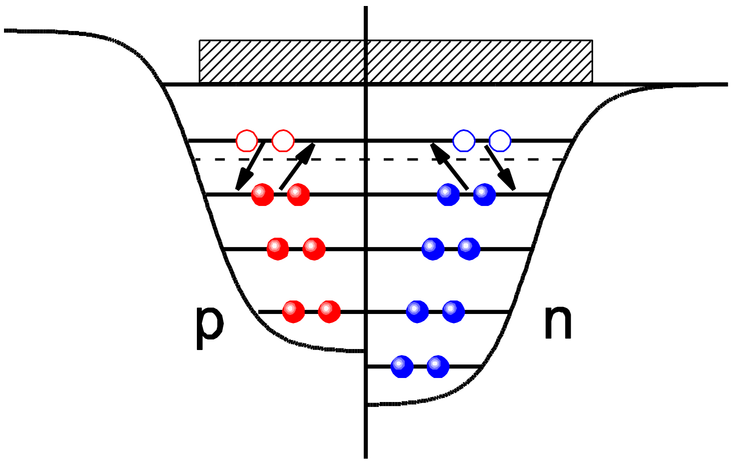
Characteristics of deformed halo nuclei



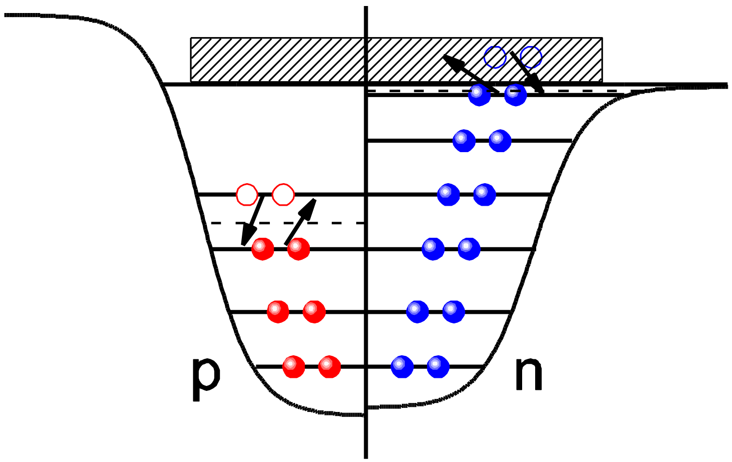
By X. H. Wu

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

Stable nuclei



Dripline nuclei



Self-consistent description:

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

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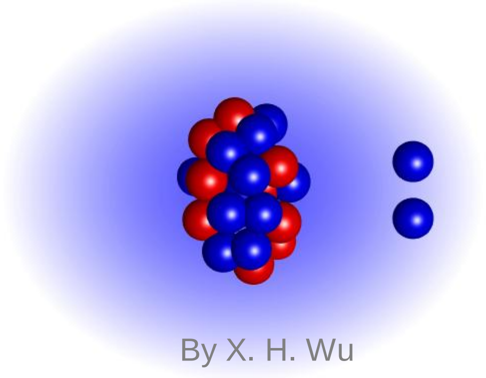
What we aim at



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

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

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

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

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

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

Deformed RHB theory in continuum

Kucharek_Ring1991_ZPA339-23

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

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

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

Woods-Saxon basis

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

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

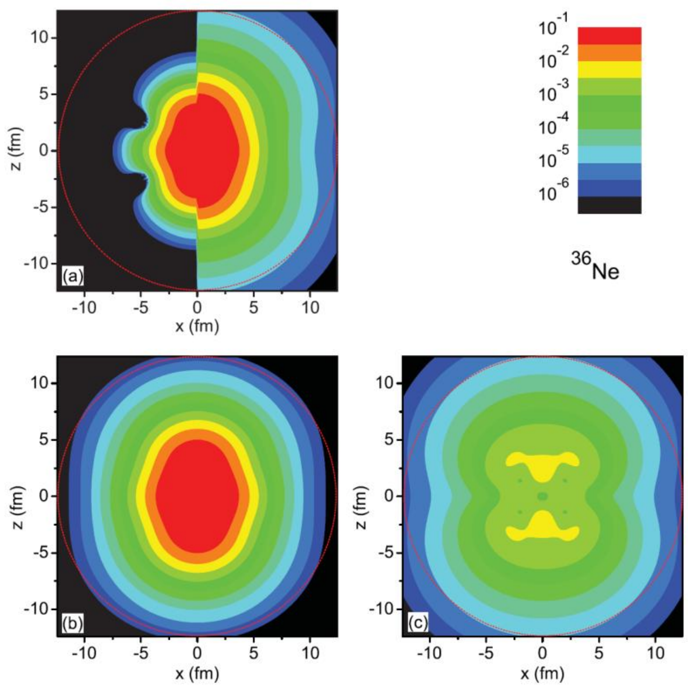
$$\mathcal{U} = \left(u^{(m)}_{k,(i\kappa)} \right), \quad \mathcal{V} = \left(v^{(m)}_{k,(\widetilde{i\kappa})} \right)$$

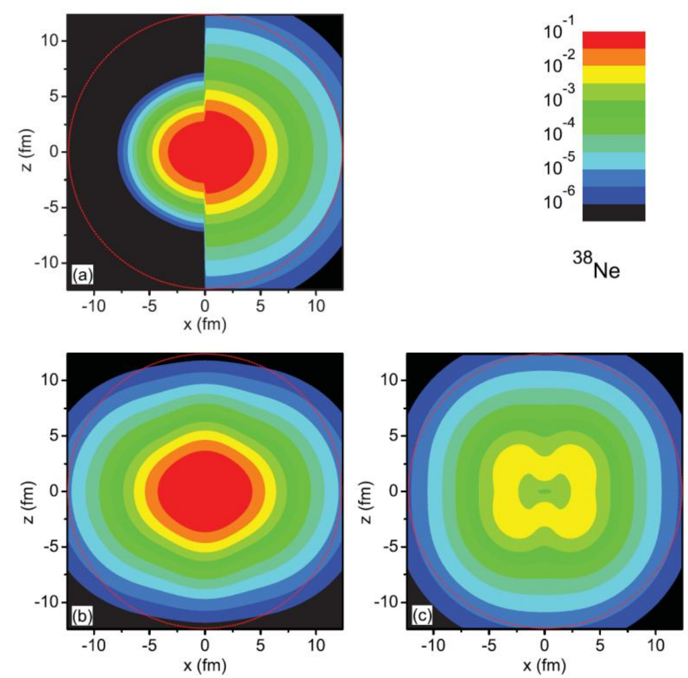
SGZ_Meng_Ring 2007_ISPUN Proc.
SGZ_Meng_Ring_Zhao 2010_PRC82-011301R
SGZ_Meng_Ring_Zhao 2011_JPConfProc312-092067
Li_Meng_Ring_Zhao_SGZ 2012_PRC85-024312
Li_Meng_Ring_Zhao_SGZ 2012_ChinPhysLett29-042101

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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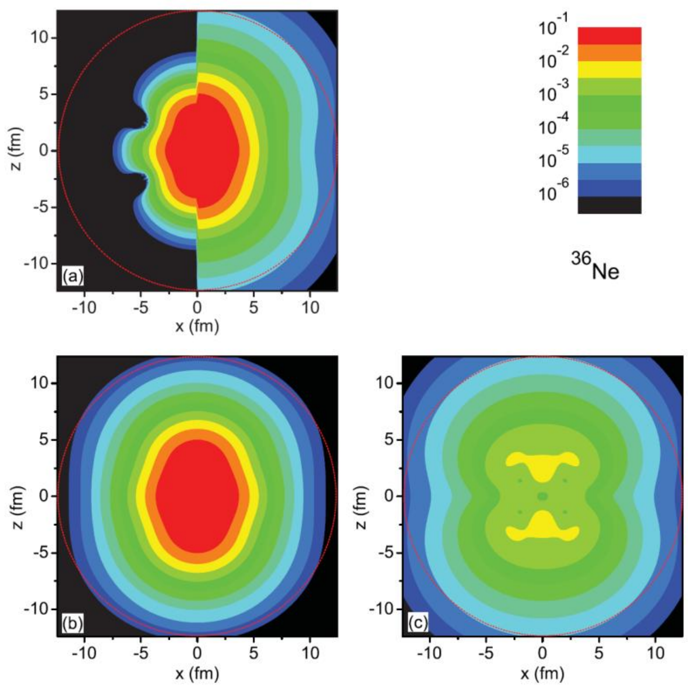
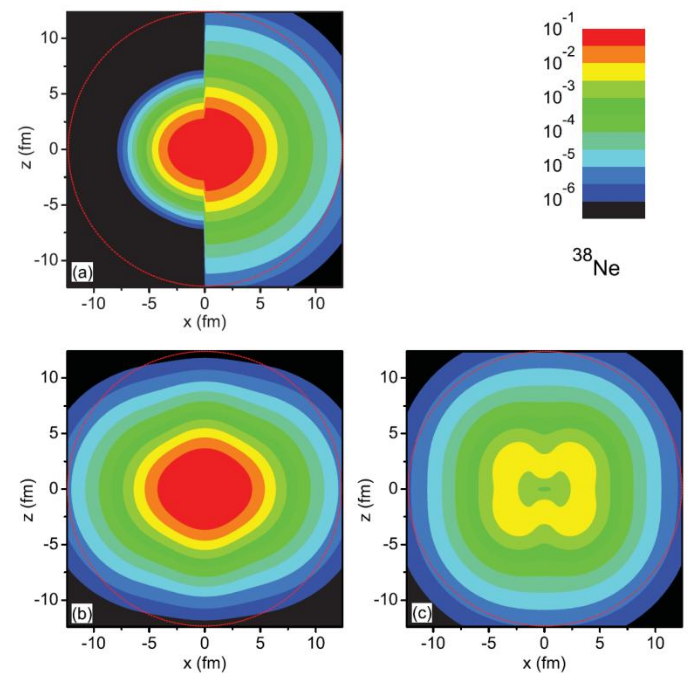
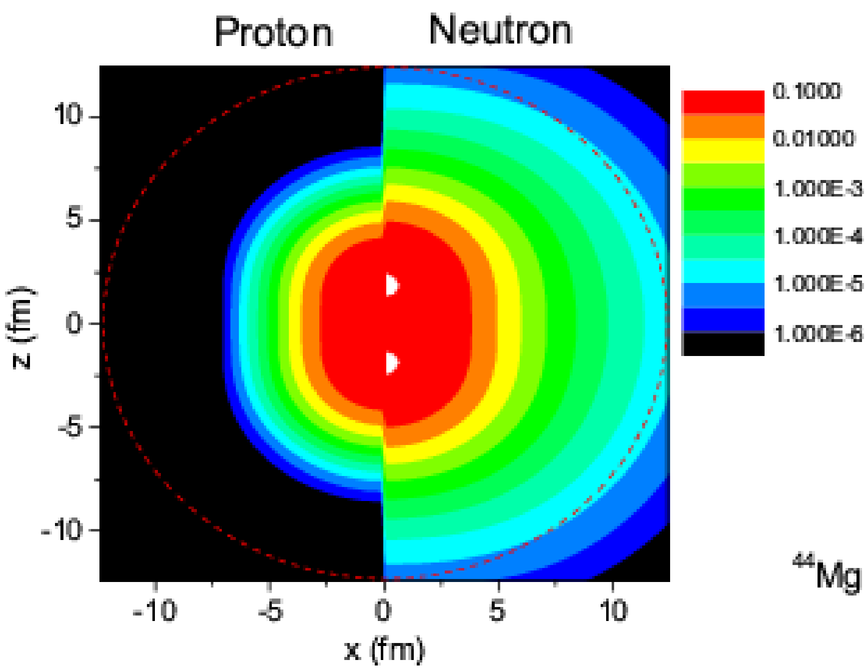
SGZ_Meng_Ring_Zhao 2010 PRC82-011301R
Li_Meng_Ring_Zhao_SGZ 2012 PRC85-024312
Pei_Zhang_Xu2013PRC87-051302R
Nakada_Takayama2018_PRC98-011301R

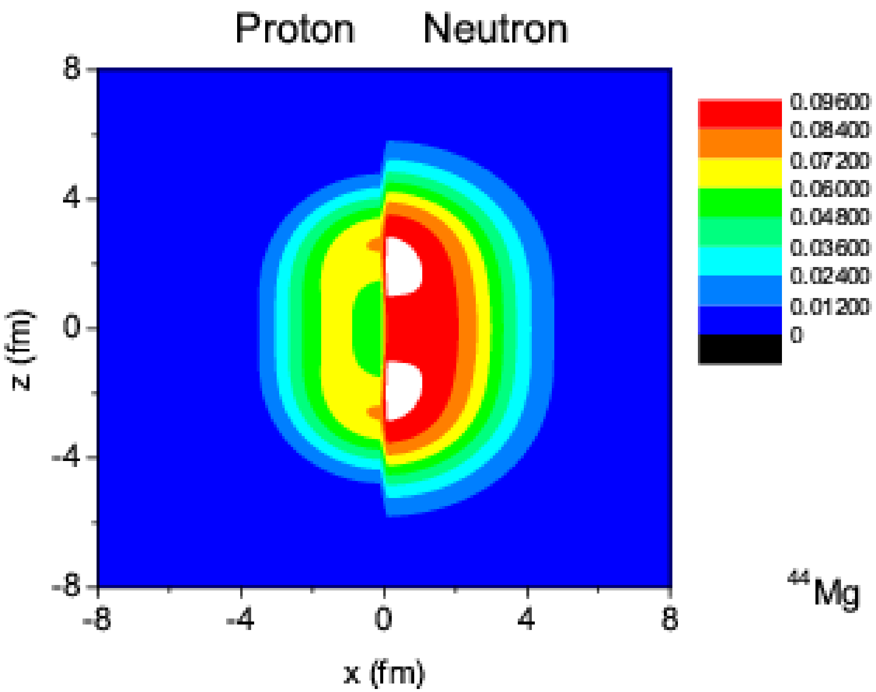




^{44}Mg: Density distributions

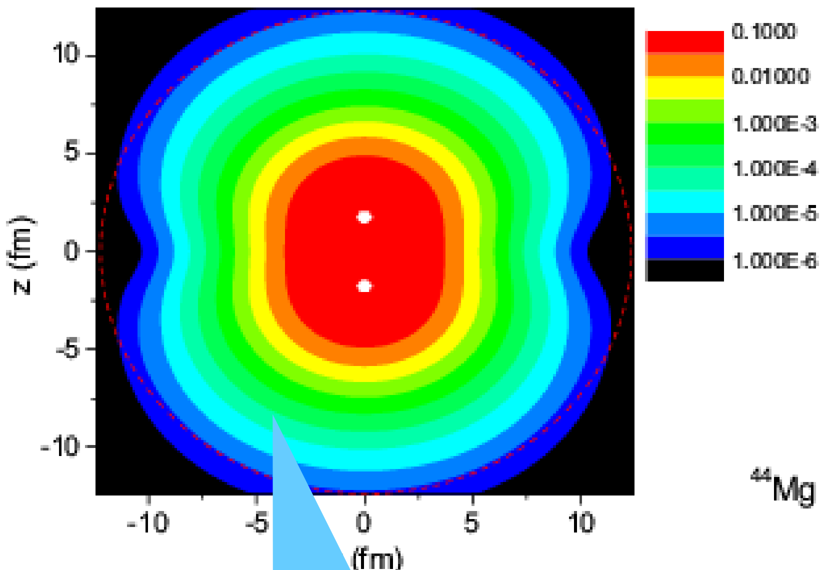
SGZ_Meng_Ring_Zhao 2010 PRC82-011301R
Li_Meng_Ring_Zhao_SGZ 2012 PRC85-024312

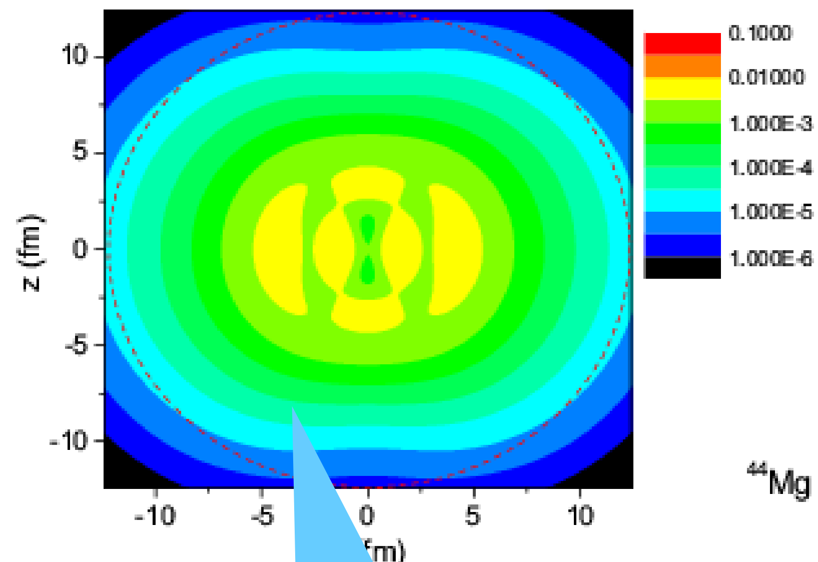




- Prolate deformation
- Large spatial extension in neutron density distribution

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





Core: prolate

halo: oblate

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

- Two-neutron separation energy

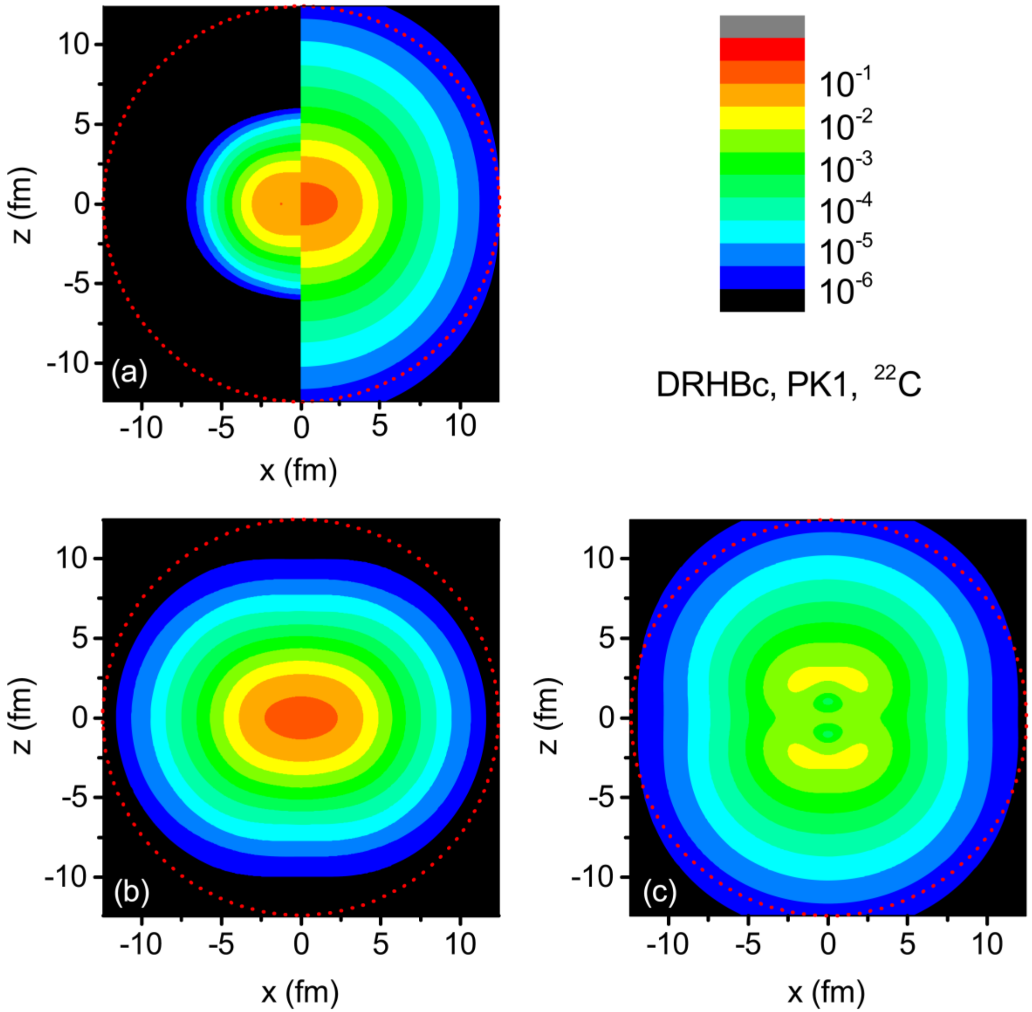
Refs.	AME2003	AME2012	Gaudefroy et al. 2012 PRL109-202503	AME2016
S_{2n} (MeV)	0.420 ±0.940#	0.110±0.060	–0.14±0.46	0.035±0.020

- 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: Halo (?) & shape decoupling

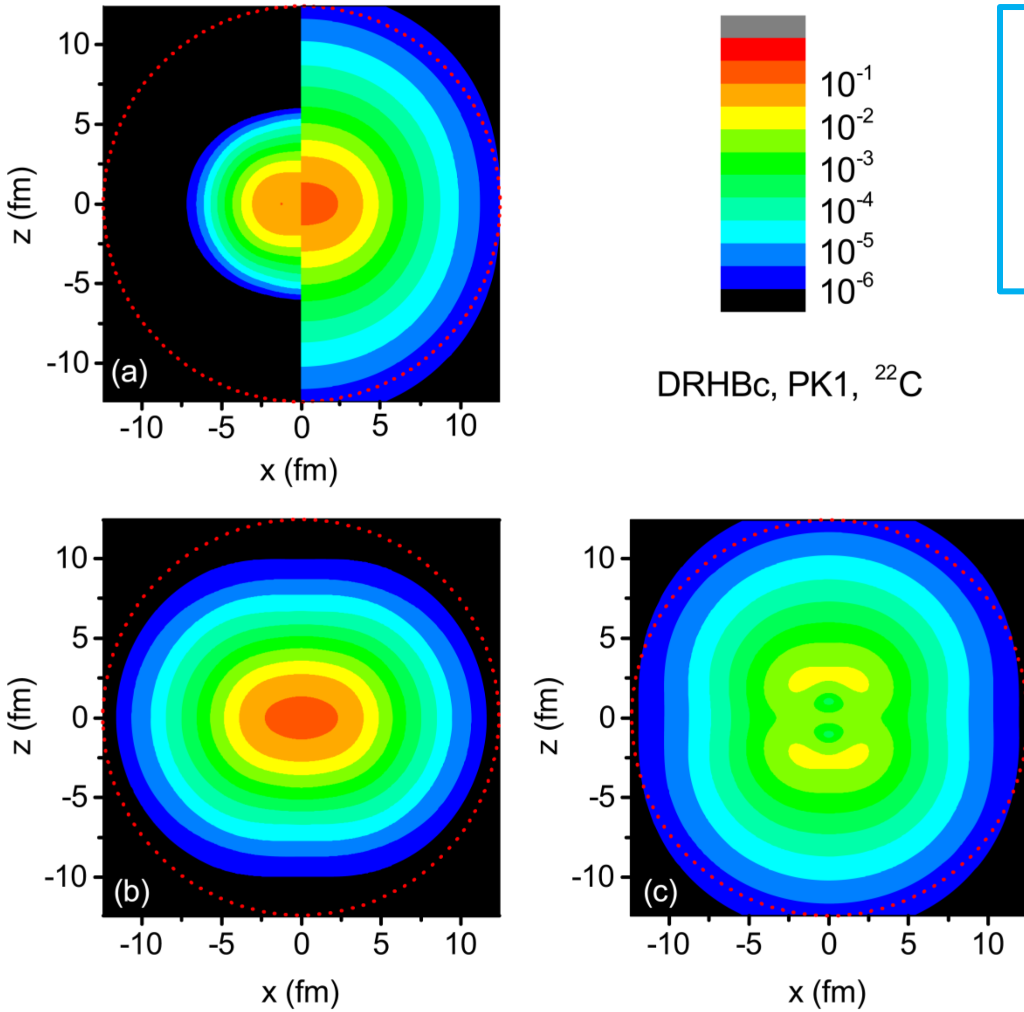


PK1

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



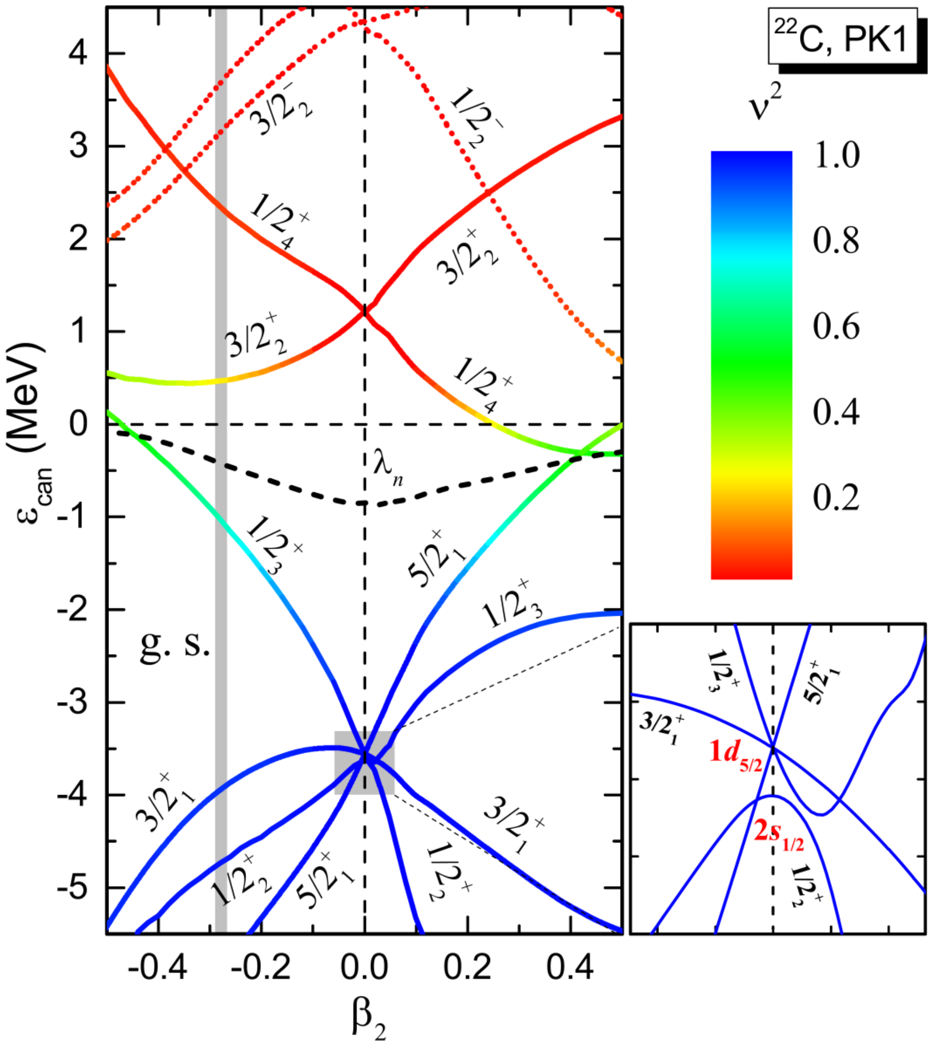
- $2s_{1/2}$: ~25% $\Rightarrow$ Halo
- Mixture of ($2s_{1/2}$, $1d_{5/2}$) $\Rightarrow$ Prolate halo

PK1

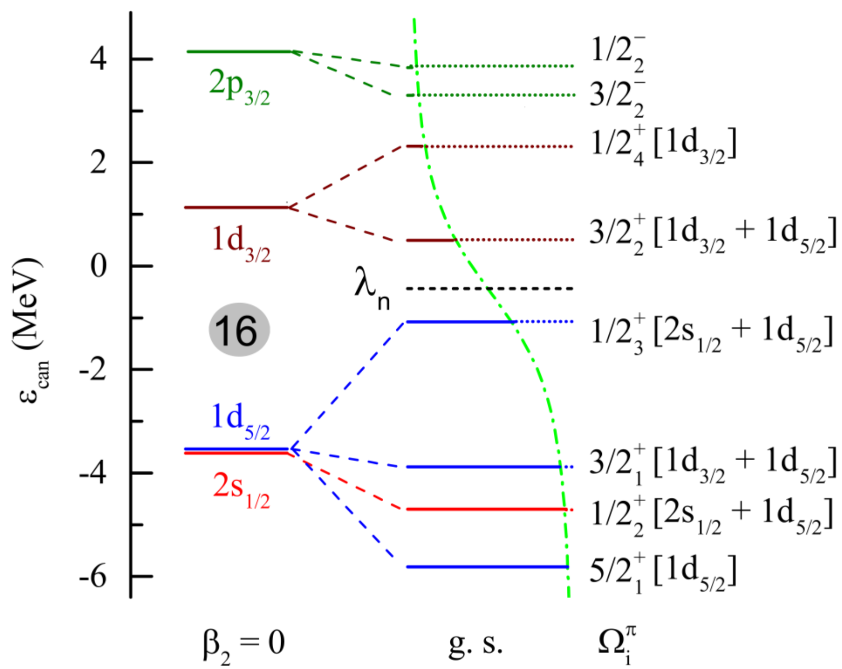
S_{2n} = 0.43 MeV
r_m = 3.25 fm
β_2 = –0.27

Sun_Zhao_SGZ 2018_PLB785-530

^{22}C: Single neutron levels



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



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pseudospin symmetry

Volume 30B, number 8 PHYSICS LETTERS 8 December 1969

PSEUDO *LS* COUPLING AND PSEUDO SU_3 COUPLING SCHEMES *

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M. HARVEY
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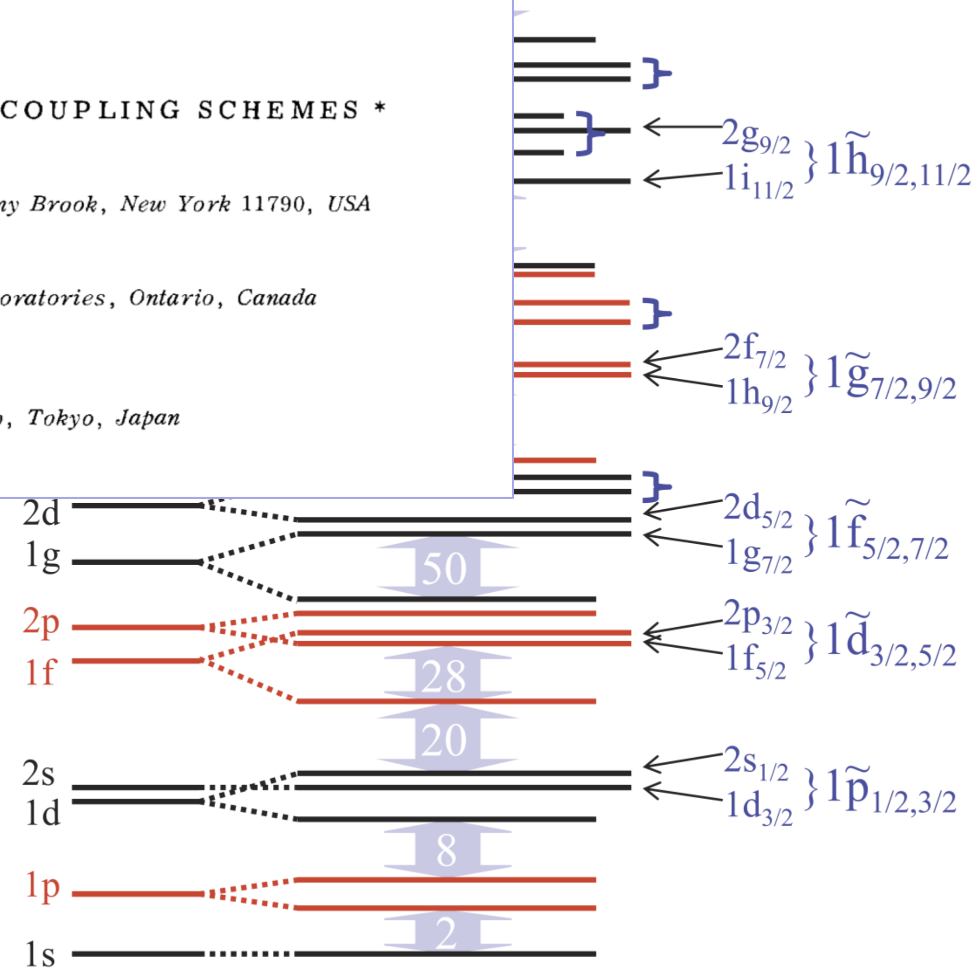
Received 20 October 1969



Arima_Harvey_Shimizu 1969_PLB30-517

Hecht_Adler 1969_NPA137-129

Justification of PSS in Renonant 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

Justification of PSS in Renonant States

The 8th China-Japan Joint Nuclear Physics Symposium
(CJJNPS 2012)
15-19 October 2012 Beijing, China

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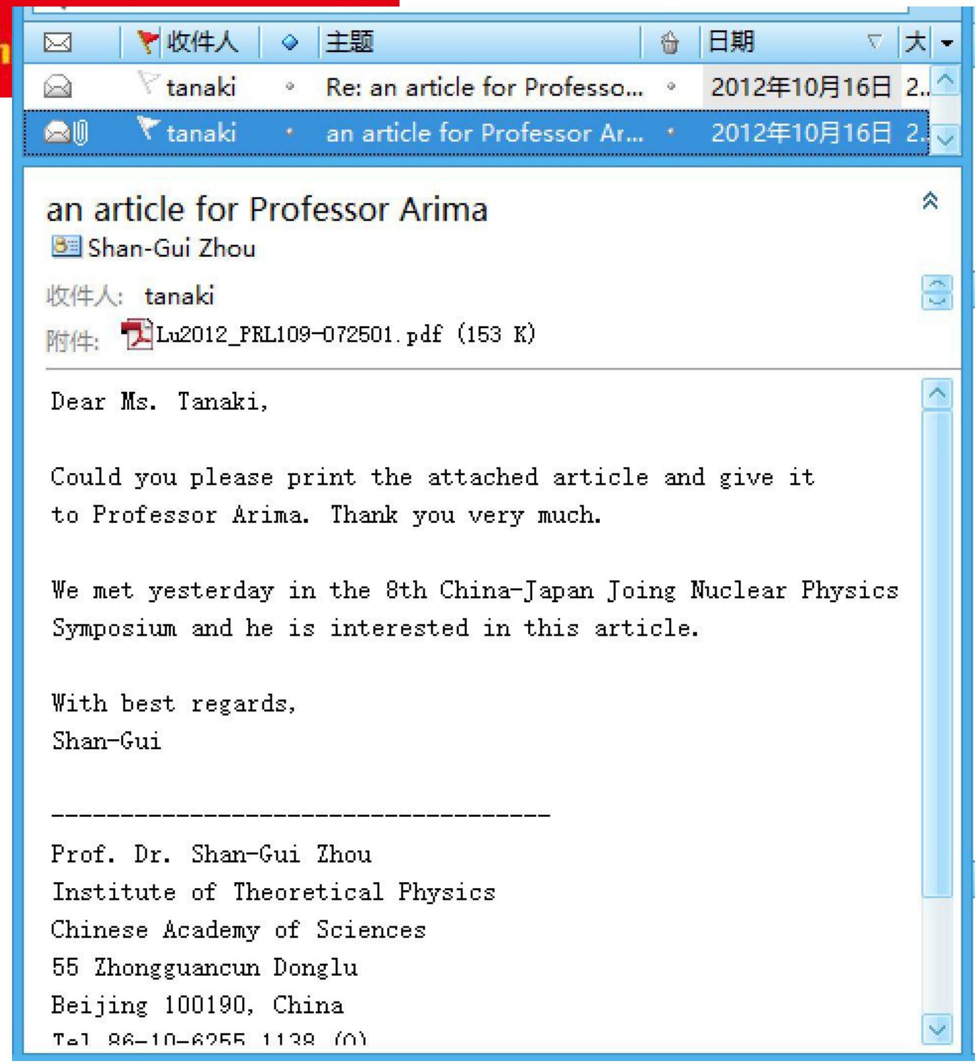

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	tanaki		Re: an article for Professo...		2012年10月16日	2..
	tanaki		an article for Professor Ar...		2012年10月16日	2..

an article for Professor Arima
Shan-Gui Zhou

收件人: tanaki
附件: Lu2012_PRL109-072501.pdf (153 K)

Dear Ms. Tanaki,

Could you please print the attached article and give it
to Professor Arima. Thank you very much.

We met yesterday in the 8th China-Japan Joing Nuclear Physics
Symposium and he is interested in this article.

With best regards,
Shan-Gui

Prof. Dr. Shan-Gui Zhou
Institute of Theoretical Physics
Chinese Academy of Sciences
55 Zhongguancun Donglu
Beijing 100190, China
Tel 86-10-6255 1138 (O)

pseudospin symmetry

Volume 30B, number 8 PHYSICS LETTERS 8 December 1969

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Liang_Meng_SGZ 2015
PhysRep570-1

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Physics Reports 570 (2015) 1–84

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Hidden pseudospin and spin symmetries and their origins in atomic nuclei

Haozhao Liang [a,b], Jie Meng [a,c,d,*], Shan-Gui Zhou [e,f]

pseudospin symmetry

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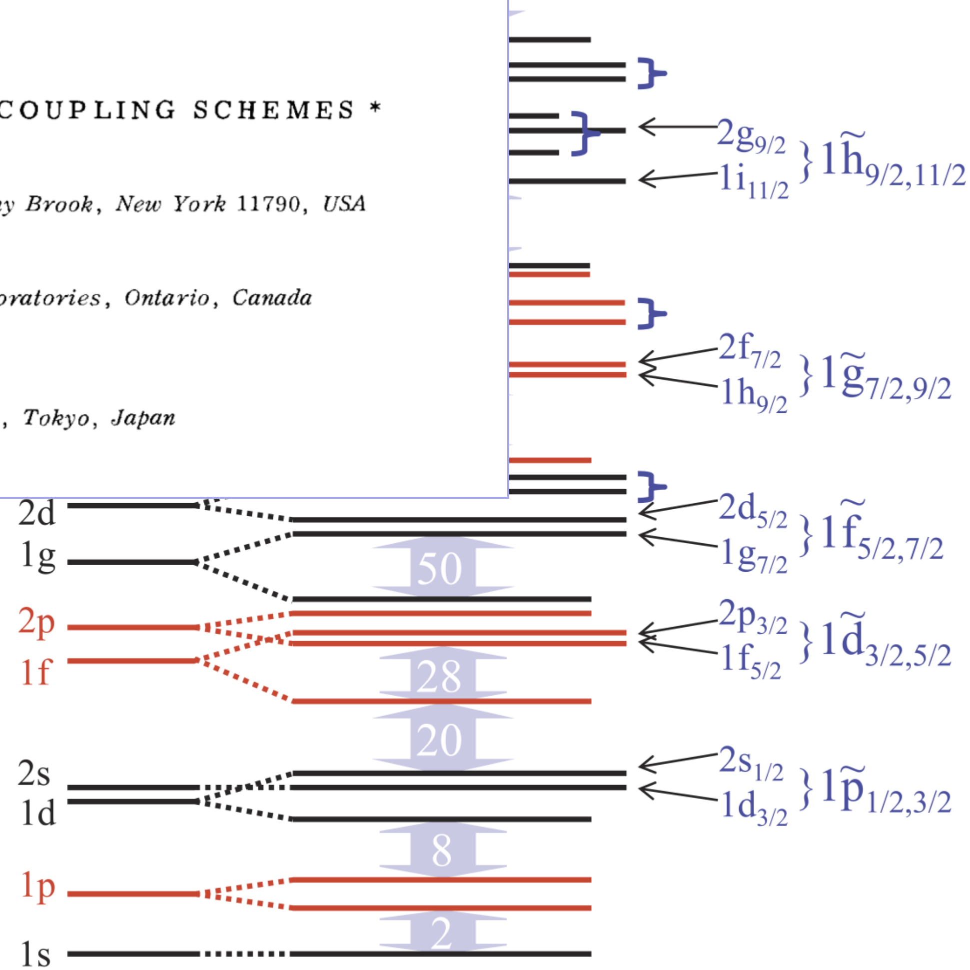

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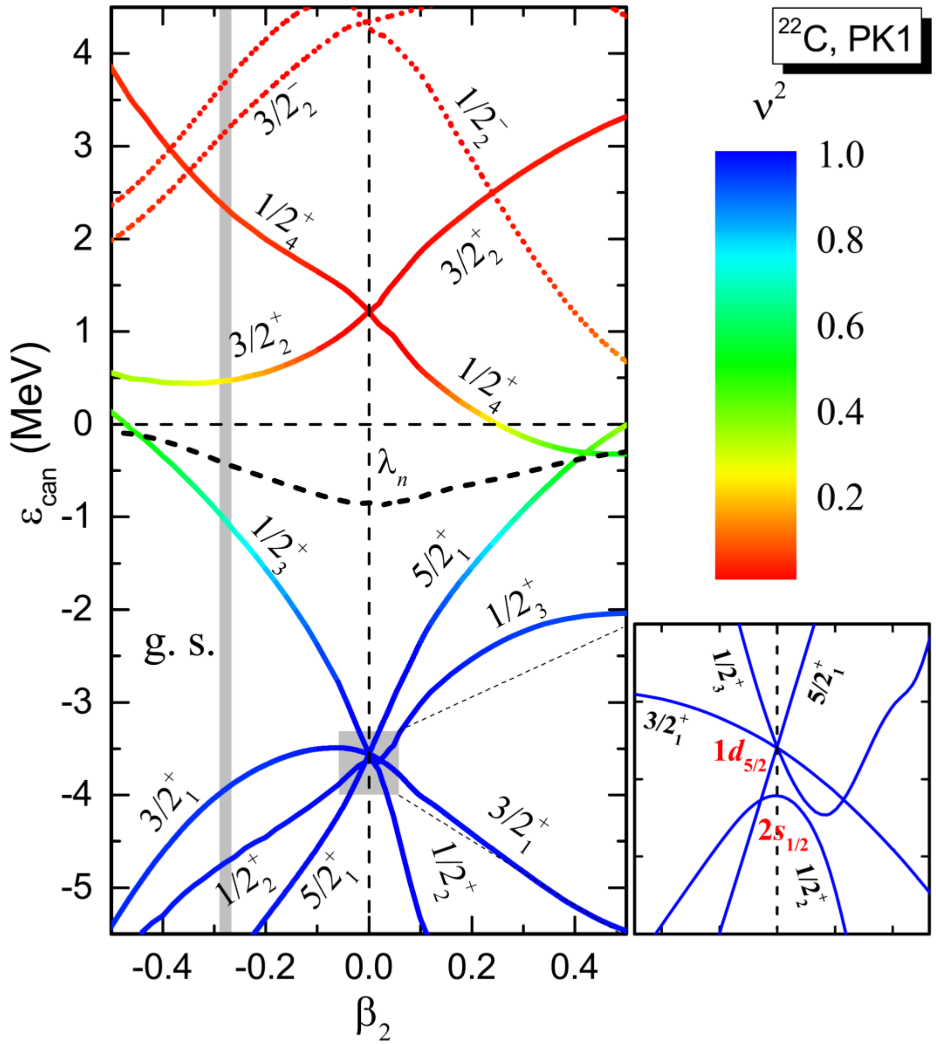
Hecht_Adler 1969_NPA137-129

Breaking of pseudospin symmetry?



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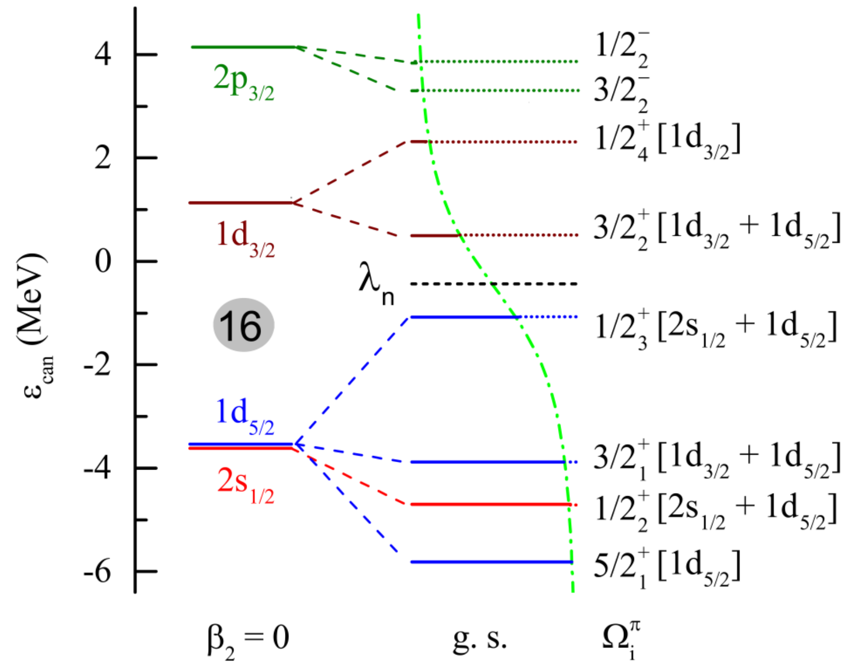

Sun_Zhao_SGZ 2018_PLB785-530

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Many symmetries are not made for conservation: They can be broken but not conserved.

Liang_Meng_SGZ 2015 PhysRep570-1

Arima_Harvey_Shimizu 1969_PLB30-517

Hecht_Adler 1969_NPA137-129

Physics Reports 570 (2015) 1–84

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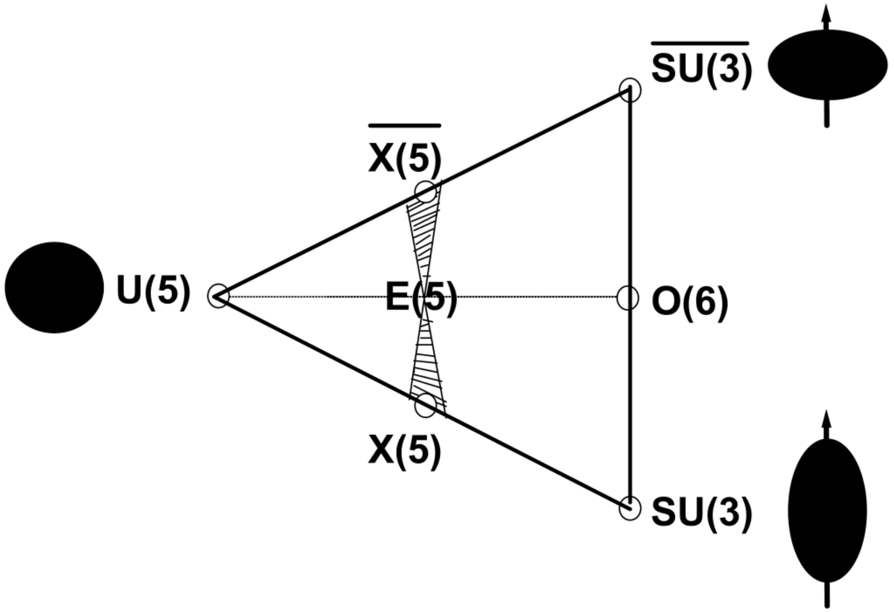
Hidden pseudospin and spin symmetries and their origins in atomic nuclei

CrossMark

Haozhao Liang [a,b], Jie Meng [a,c,d,*], Shan-Gui Zhou [e,f]

Extended Casten triangle

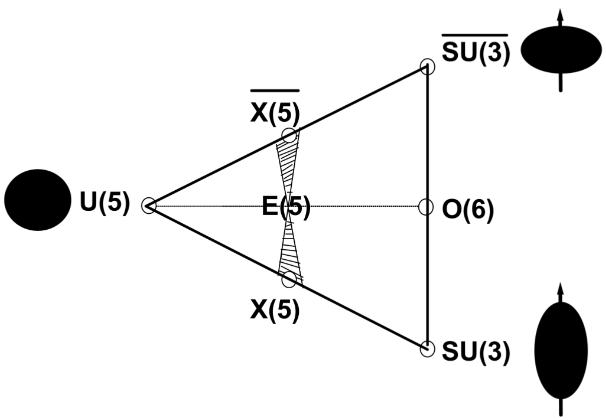


Pan_Wang_Huo_Draayer2006_IJMPE15-1723

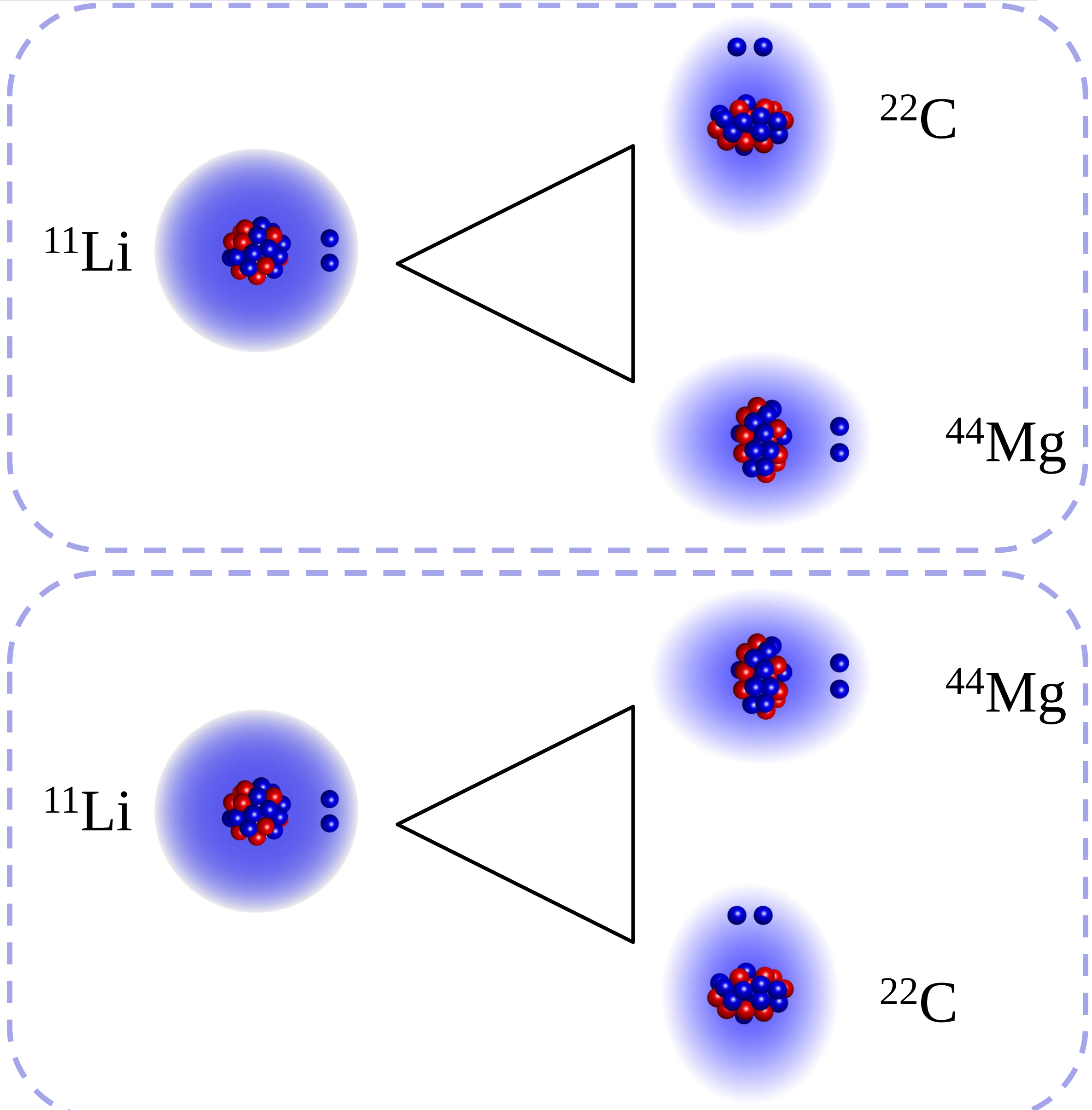
Triangle of Borromean nuclei: ^{11}Li, ^{22}C & ^{44}Mg

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

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



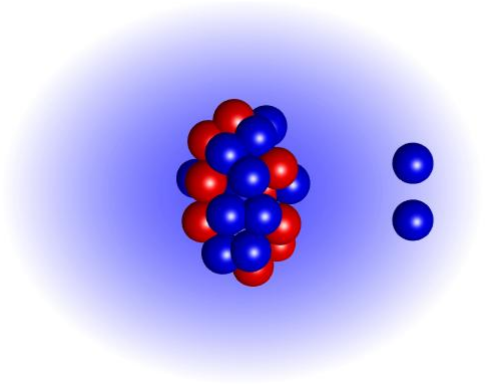
Pan_Wang_Huo_Draayer
2006_IJMPE15-1723



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

How to probe the shape decoupling?

- Larger cross section
- Narrower momentum distribution
  - Bimodal ?



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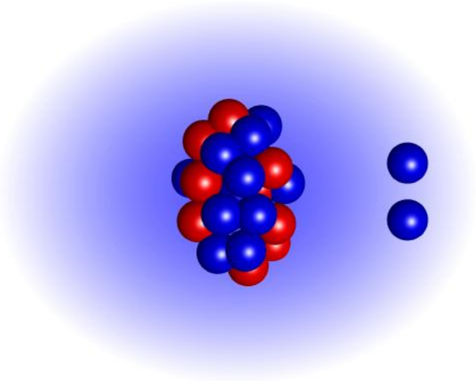
Navin…1997_PRL81-5089

Sakharuk_Zelevinsky1998_PRC61-014609



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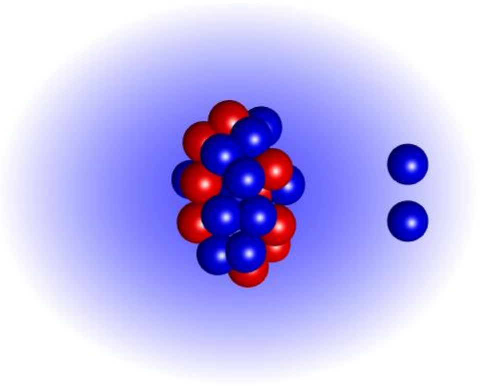

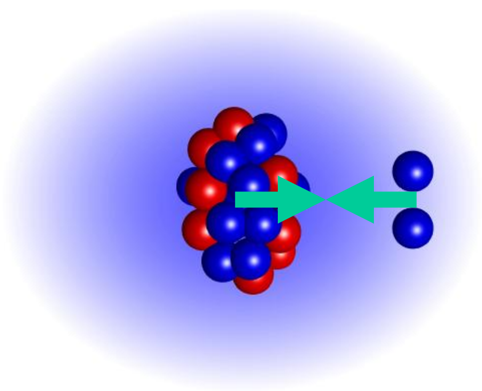

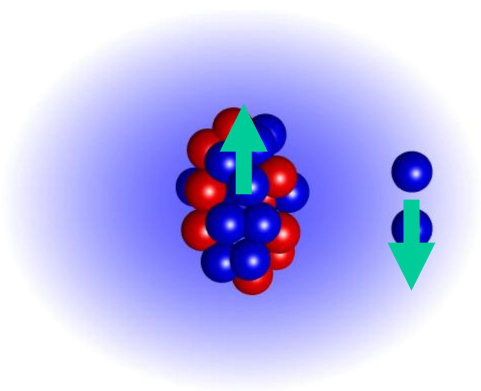

Picture(s): courtesy of Xin-Hui Wu (吴鑫辉)

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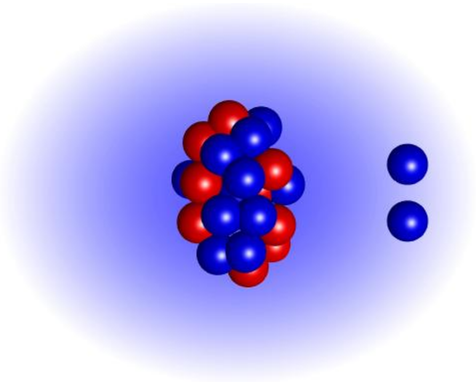

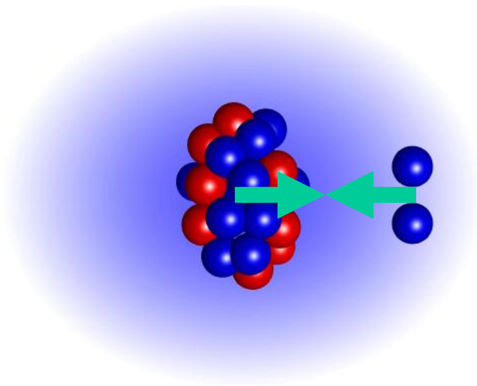

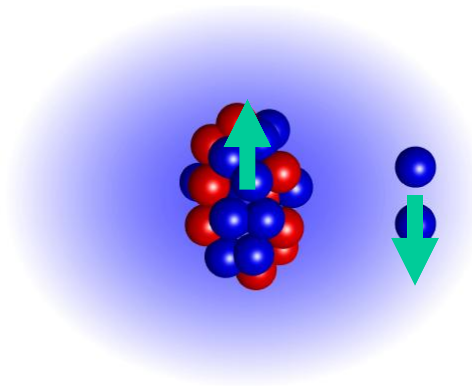

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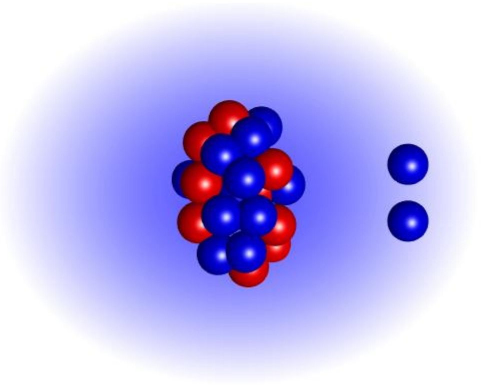

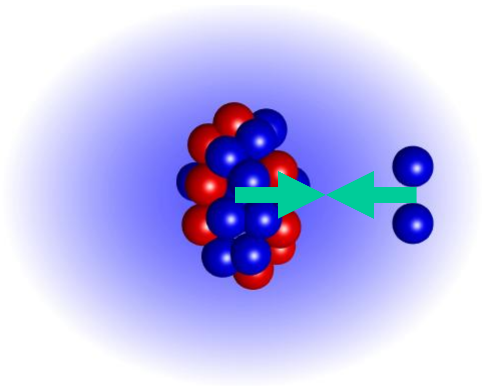

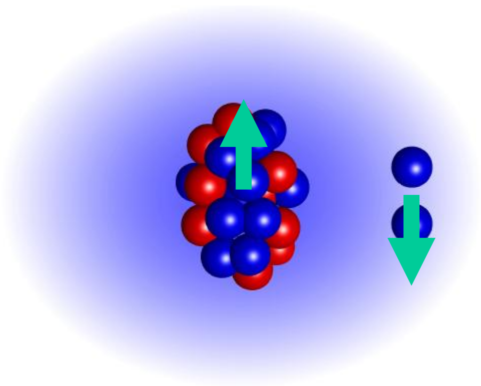

Picture(s): courtesy of Xin-Hui Wu (吴鑫辉)

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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祝有马朗人先生

福如东海，寿比南山！