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)

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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)

Symmetries in Arts, Culture and Nature

Akito Arima
What I learned from Prof. Arima (continued)

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.


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

- **Drip-line Nuclei**
- **Weakly-bound feature**
- **Halo – large-spatial extension**
  - Low-density nuclear matter
  - Di-nucleon correlations
- **Threshold effects**
- **Continuum**
- **Open quantum systems**
- **Halo – deformation effects**
- **Shell evolution**
- **New radioactivities**
  - 1p emission
  - 2p emission
  - 2n emission
- **Clustering effects**

**Shape decoupling**

SGZ, PoS (INPC2016) 373
Physics in exotic nuclear structure

(a) Drip-line Nuclei

(b) Weakly-bound feature

(c) Low-density nuclear matter

(d) Di-nucleon correlations

Threshold effects
Continuum
Open quantum systems

Shell evolution

Halo – deformation effects

Shape decoupling

New radioactivities
1p emission
2p emission
2n emission

Clustering effects
Spherical
Deformed
Clustered
Bound
Unbound

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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Bulgac1980; nucl-th/9907088
Dobaczewski_Flocard_Treiner1984_NPA422-103
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)

\[ \mathcal{L} = \bar{\psi}_i (i \slashed{\partial} - M) \psi_i + \frac{1}{2} \partial_{\mu} \sigma \partial^{\mu} \sigma - U(\sigma) - g_\sigma \bar{\psi}_i \sigma \psi_i \]

\[ - \frac{1}{4} \Omega_{\mu\nu} \Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - g_\rho \bar{\psi}_i \rho \psi_i \]

\[ - \frac{1}{4} \vec{R}_{\mu\nu} \vec{R}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \vec{\rho}^\mu - g_\rho \bar{\psi}_i \vec{\rho} \psi_i \]

\[ - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \frac{1 - \tau_3}{2} \vec{A} \psi_i, \]

Serot_Walsecka1986_ANP16-1
Reinhard1989_RPP52-439
Ring1996_PPNP37-193
Vretenar_Afanasjev_Lalazissis_Ring2005_PR409-101
Meng_Toki_SGZ_Zhang_Long_Geng2006_PPNP57-470

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

\[ (\nabla^2 + m_\sigma^2) \sigma = -g_\sigma \rho_s - g_2 \sigma^2 - g_3 \sigma^3 \]

\[ (\nabla^2 + m_\omega^2) \omega = g_\omega \rho_V - c_3 \omega^3 \]

\[ (\nabla^2 + m_\rho^2) \rho = g_\rho \rho_3 \]

\[-\nabla^2 A = e \rho_c \]

Liang_Meng_SGZ2015_PR570-1
Meng_SGZ2015_JPG42-093101
Deformed RHB theory in continuum

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

\[
U_k(r\sigma p) = \sum_{i\kappa} \begin{pmatrix}
\tilde{u}_{k,(i\kappa)}^{(m)} \\
\tilde{v}_{k,(i\kappa)}^{(m)}
\end{pmatrix} \varphi_{ikm}(r\sigma p)
\]

\[
V_k(r\sigma p) = \sum_{i\kappa} \begin{pmatrix}
\tilde{u}_{k,(i\kappa)}^{(m)} \\
\tilde{v}_{k,(i\kappa)}^{(m)}
\end{pmatrix} \varphi_{ikm}(r\sigma p)
\]

\[
\varphi_{ikm}(r\sigma) = \frac{1}{r} \begin{pmatrix}
iG_{i\kappa}(r)Y_{jm}^l(\Omega\sigma) \\
-F_{i\kappa}(r)Y_{jm}^{\tilde{l}}(\Omega\sigma)
\end{pmatrix}
\]

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

\[
\mathcal{U} = \begin{pmatrix}
\tilde{u}_{k,(i\kappa)}^{(m)}
\end{pmatrix}, \quad \mathcal{V} = \begin{pmatrix}
\tilde{v}_{k,(i\kappa)}^{(m)}
\end{pmatrix}
\]
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
Conditions for occurrence of a halo & its shape

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References:
- 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

- Prolate deformation
- Large spatial extension in neutron density distribution

SGZ_Meng_Ring_Zhao 2010 PRC82-011301R
Li_Meng_Ring_Zhao_SGZ 2012 PRC85-024312
$^{44}\text{Mg}$: Density of core & halo shape decoupling

Core: prolate

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

- **Two-neutron separation energy**

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<tbody>
<tr>
<td>$S_{2n}$ (MeV)</td>
<td>0.420 ±0.940#</td>
<td>0.110±0.060</td>
<td>−0.14±0.46</td>
<td>0.035±0.020</td>
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</tbody>
</table>

- **RMS matter radius**

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</thead>
<tbody>
<tr>
<td>$r_m$ (fm)</td>
<td>5.4±0.9</td>
<td>3.44±0.08</td>
<td>3.38±0.10</td>
<td>1.2 $A^{1/3}$ fm</td>
</tr>
</tbody>
</table>

- **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)
$^{22}\text{C}: \text{Halo (?) & shape decoupling}$

$S_{2n} = 0.43 \text{ MeV}$

$r_m = 3.25 \text{ fm}$

$\beta_2 = -0.27$
$^{22}\text{C}: \text{Halo (?) & shape decoupling}$

- $2s_{1/2}: \sim 25\% \implies \text{Halo}$
- Mixture of $2s_{1/2}, 1d_{5/2}$ \implies \text{Prolate halo}

PK1

$S_{2n} = 0.43 \text{ MeV}$

$r_m = 3.25 \text{ fm}$

$\beta_2 = -0.27$

Sun_Zhao_SGZ 2018_PLB785-530
$^{22}$C: Single neutron levels

Inversion of ($2s_{1/2}$, $1d_{5/2}$)
No shell closure at $N = 16$
PSEUDO LS COUPLING AND PSEUDO SU₃ COUPLING SCHEMES *

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Received 20 October 1969

Arima_Harvey_Shimizu 1969_PLB30-517
Hecht_Adler 1969_NPA137-129
Pseudospin Symmetry in Single Particle Resonant States

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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.

Justification of PSS in Resonant States

The 8th China-Japan Joint Nuclear Physics Symposium
(CJJNPS 2012)
15-19 October 2012 Beijing, China
Justification of PSS in Resonant States

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an article for Professor Arima

Shan-Gui Zhou

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 Joint Nuclear Physics Symposium and he is interested in this article.

With best regards,
Shan-Gui

Prof. Dr. Shan-Gui Zhou
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Tel: 86-10-6255 1128 (0)
Breaking of pseudospin symmetry

PSEUDO LS COUPLING AND PSEUDO SU3 COUPLING SCHEMES *

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Hidden pseudospin and spin symmetries and their origins in atomic nuclei

Haozhao Liang\textsuperscript{a,b}, Jie Meng\textsuperscript{a,c,d,*}, Shan-Gui Zhou\textsuperscript{e,f}
PSEUDO LS COUPLING AND PSEUDO SU\(_3\) COUPLING SCHEMES *

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Hecht_Adler 1969_NPA137-129
Breaking of pseudospin symmetry?

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

\[\begin{align*}
\varepsilon_{\text{can}} \quad \text{(MeV)}
\end{align*}\]

\[\begin{align*}
\beta_2 = 0 & \quad \text{g. s.} & \quad \Omega_i^5 \\
1d_{5/2} & \quad 2s_{1/2} & \quad 1d_{3/2} \\
3/2^+ \{1d_{3/2} + 1d_{5/2}\} & \quad 1/2^+ \{2s_{1/2} + 1d_{5/2}\} & \\
3/2^+ \{1d_{3/2} + 1d_{5/2}\} & \quad 1/2^+ \{2s_{1/2} + 1d_{5/2}\} & \quad 1/2^+ \{1d_{3/2}\} \\
3/2^- & \quad 3/2^- & \quad 1/2^- \\
1d_{3/2} & \quad 1d_{3/2} & \quad 1d_{3/2} \\
\lambda_n & \quad \lambda_n & \quad \lambda_n \\
2p_{3/2} & \quad 3/2^- & \quad 1/2^- \\
\end{align*}\]

\[\begin{align*}
\beta_2 = 0 & \quad \text{g. s.} & \quad \Omega_i^5 \\
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3/2^+ \{1d_{3/2} + 1d_{5/2}\} & \quad 1/2^+ \{2s_{1/2} + 1d_{5/2}\} & \\
3/2^+ \{1d_{3/2} + 1d_{5/2}\} & \quad 1/2^+ \{2s_{1/2} + 1d_{5/2}\} & \quad 1/2^+ \{1d_{3/2}\} \\
3/2^- & \quad 3/2^- & \quad 1/2^- \\
1d_{3/2} & \quad 1d_{3/2} & \quad 1d_{3/2} \\
\lambda_n & \quad \lambda_n & \quad \lambda_n \\
2p_{3/2} & \quad 3/2^- & \quad 1/2^- \\
\end{align*}\]
Many symmetries are not made for conservation: They can be broken but not conserved.
Extended Casten triangle

Pan_Wang_Huo_Draayer2006_IJMPE15-1723
Triangle of Borromean nuclei: $^{11}\text{Li}$, $^{22}\text{C}$ & $^{44}\text{Mg}$

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

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

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

Picture(s): courtesy of Xin-Hui Wu (吴鑫辉)
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- New dipole modes?

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

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- Larger cross section
- Narrower momentum distribution
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- 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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祝有马朗人先生
福如东海，寿比南山！