Particle-particle RPA applied to beryllium isotopes

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CEA, DAM, DIF

Limits of existence of light nuclei, ECT*

26/10/10

Plan

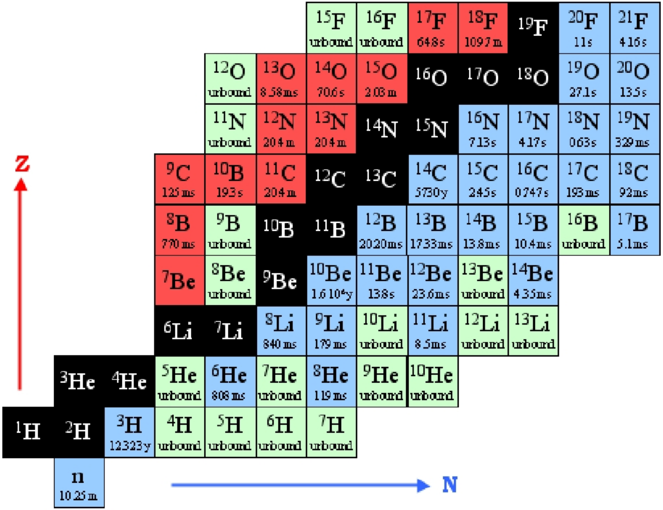
Problematic

Method: Particle-particle RPA

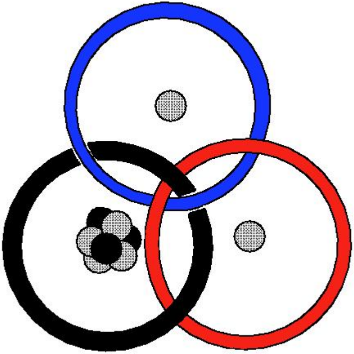
Description of even-even $^{8-12}$Be from a ^{10}Be core

Description of even-even $^{10-14}$Be from a ^{12}Be core

Nuclear chart



Halo nuclei



- Light neutron rich nuclei
- One- or two-neutron halo nuclei
- Large spatial extension
- Borromean (core+n, n+n systems are unbound)
- Three-body calculations

Method: Particle-particle RPA (pp-RPA)

- pp-RPA
  - Three-body model
  - Takes into account the two-body correlations
- Ingredients
  - Neutron-core interaction
  - Neutron-neutron interaction
- Information obtained with the RPA
  - Two-body amplitudes between the core and the core $\pm$ 2 neutrons
  - S_{2n}(A) and S_{2n}(A+2)

pp-RPA equations (1)

For a given spin and parity the RPA amplitudes X and Y satisfy the system of equations:

$$(E - \epsilon_a)x_a - \sum_b \langle a|V_{nn}|b\rangle x_b - \sum_\beta \langle a|V_{nn}|\beta\rangle x_\beta = 0,$$

$$(E - \epsilon_\alpha)x_\alpha - \sum_b \langle \alpha|V_{nn}|b\rangle x_b - \sum_\beta \langle \alpha|V_{nn}|\beta\rangle x_\beta = 0,$$

with $a = (a_1, a_2)$ as a two-neutron configuration with the neutrons in states a_1, a_2... unoccupied in the Hartree-Fock core ground state, and α, β... as two-neutron configurations with the neutrons in occupied states.

(J. C. Pacheco and N. Vinh Mau, Phys. Rev. C65 044004 (2002).)

pp-RPA equations (2)

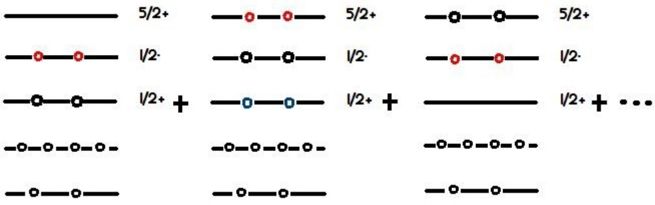
RPA amplitudes

$$
\begin{aligned}
X_{ab}^{(N)} &= \langle N|B_{ab}^{\dagger}|\tilde{0}\rangle \\
X_{\alpha\beta}^{(N)} &= \langle N|B_{\alpha\beta}|\tilde{0}\rangle \\
Y_{\alpha\beta}^{(M)} &= \langle M|B_{\alpha\beta}^{\dagger}|\tilde{0}\rangle \\
Y_{ab}^{(M)} &= \langle M|B_{ab}|\tilde{0}\rangle
\end{aligned}
$$

With the following orthonormalization

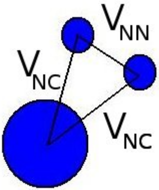
$$
\begin{aligned}
\sum_a X_a^{(n)} X_a^{(n')} - \sum_\alpha X_\alpha^{(n)} X_\alpha^{(n')} &= \delta_{nn'} \\
\sum_a Y_a^{(m)} Y_a^{(m')} - \sum_\alpha Y_\alpha^{(m)} Y_\alpha^{(m')} &= -\delta_{mm'}
\end{aligned}
$$

pp-RPA (3)



- If we stop to the first term: pp-TDA.
- Account for two-body correlations in the core nucleus.
- Inert core (in a 0^+ state).

Interactions



- NN effective interaction: Gogny D1S
- Neutron-core interaction:
  WS + phenomenological particle-vibration coupling

$$
\begin{aligned}
U(r) &= V_{WS} + \delta V, \\
\delta V(r) &= 16\alpha e^{2(r-R)/a}/(1+e^{(r-R)/a})^4
\end{aligned}
$$

(N. Vinh Mau, Nucl. Phys. A 592, 33 (1995).)

Purpose

- Description of even-even $^{8-12}$Be from ^{10}Be core
  We look also at ^{12}Be as ^{11}Be structure is known, it is a good test for the model.

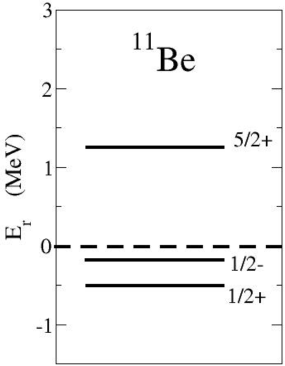
- Description of even-even $^{10-14}$Be from ^{12}Be core
  We calculate the characteristics of ^{14}Be to constrain the ^{13}Be structure which is not well known.

(Blanchon et al., PRC 00, 004300 (2010).)

Description of even-even $^{8-12}$Be from a ^{10}Be core

- ^{11}Be: Experimentally
- Single-particle spectrum fitted from experiment with the phenomenological pv coupling.
- pp-RPA built on top of sp spectrum.
- Inversion between $1/2^+$ and $1/2^-$ states.
- ^{10}Be: $E^*(2^+)$=3.36 MeV with $B(E2)$= 52 e^2fm^4.

(F. Ajzenberg-Selove, NPA506,1 (1990); G. Audi and A. H. Wapstra, NPA595, 409 (1995).)



^{12}Be: Ground state properties (1)

Table: Theoretical and experimental values of S_{2n} (MeV) in ^{10}Be and ^{12}Be (from Ref.[1]), $\langle \mathbf{r}^2 \rangle^{1/2}$ (fm), $\langle \boldsymbol{\lambda}^2 \rangle^{1/2}$ (fm) and $\langle \boldsymbol{\rho}^2 \rangle^{1/2}_{A+2}$ (fm) in ^{12}Be (from Ref.[2]).

	$S_{2n}(^{10}\mathrm{Be})$	$S_{2n}(^{12}\mathrm{Be})$	$\langle \mathbf{r}^2 \rangle^{1/2}_{A+2}$	$\langle \boldsymbol{\rho}^2 \rangle^{1/2}$	$\langle \boldsymbol{\lambda}^2 \rangle^{1/2}$
Theory	8.49	3.62	2.76	4.89	4.10
Exp.	8.48	3.67±0.01	2.59±0.06	-	-

[1] G. Audi et al., NPA729, 337 (2003).

[2] A. Ozawa et al., NPA693, 32, (2001).

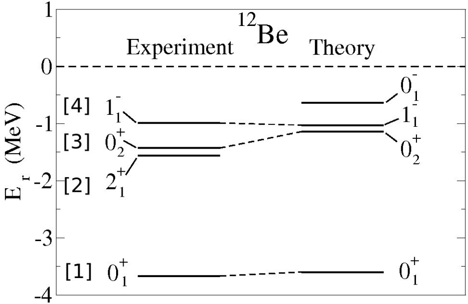
^{12}Be: Ground state properties (2)

Table: Main pp-RPA amplitudes of 0_1^+ ground state in ^{12}Be.

X_{ab}				$X_{\alpha\beta}$
$(1p_{1/2})^2$	$(1p_{1/2}, 2p_{1/2})$	$(2s_{1/2})^2$	$(1d_{5/2})^2$	$(1p_{3/2})^2$
0.76	0.31	0.50	0.43	0.57

- *Kanungo PLB 690, 245 (2010)* $\Rightarrow$ s-wave spectroscopic factor of 0.28 for 0_1^+.
- Strong correlations in the ^{10}Be core.
- Indication of a breakdown of the $N = 8$ shell closure in ^{12}Be. *(A. Navin et al. PRL 85, 266 (2000).)*

^{12}Be: Excited states



[1] G. Audi et al., NPA729, 337 (2003).
[2] M. Bernas et al., PLB116, 7 (1982).
[3] S. Shimoura et al., PLB560, 31 (2003).
[4] H. Iwasaki et al., PLB491, 8 (2000).

- 0^- excited state (nearly pure $(1p_{1/2}, 2s_{1/2})$) Agreement with *Romero-Redondo et al., PLB660,32(2008).*

- Good results for 0^+ and 1^- excited states.
- Not able to describe 2^+ states: inert core assumption. Can be solved using a deformed core. *(Nunes et al. NPA 703, 593 (2002).)*

^{12}Be: 0_2^+

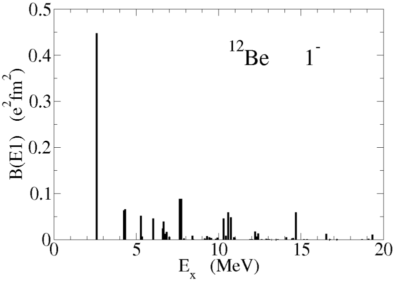
cea

Table: Main pp-RPA amplitudes of 0_2^+ state in ^{12}Be. $X_{\alpha\beta}$ amplitudes are found negligible.

X_{ab}			
$(1p_{1/2})^2$	$(2s_{1/2})^2$	$(1p_{1/2},2p_{1/2})$	$(2s_{1/2},3s_{1/2})$
-0.48	-0.86	0.11	0.10

- *Kanungo PLB 690, 245 (2010)* $\Rightarrow$ s-wave spectroscopic factor of 0.73 for 0_2^+

^{12}Be: B(E1)



- Soft dipole contribution to B(E1) (inert core assumption).
- 1_1^- state is a nearly pure ($1p_{1/2}$, $2s_{1/2}$ configuration).
- Experimental $Ex(1^-) = 2.68$ MeV
  with $B(E1)= 0.051(13)\ e^2\text{fm}^2$.

^{12}Be: Summary

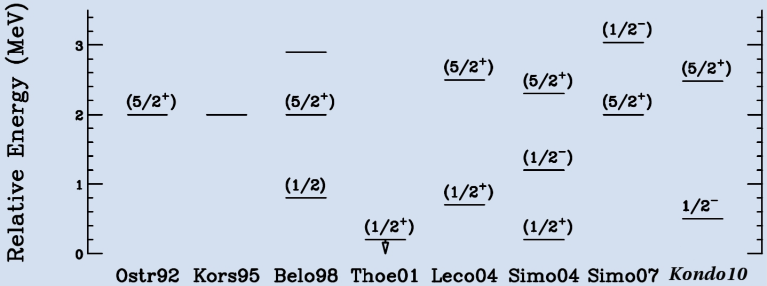
- Good results for ground state properties.
- Good results for 1^- and 0^+ excited states.
- Results for 0^- state in agreement with Romero-Redondo even if the state has never been observed experimentally.
- Problem: B(E1) strength too high.
- Problem: 2_1^+ excited state,
  that is built as $|^{12}Be(2^+)\rangle \otimes (2n)_{0^+}$
  Need for a deformed core.

Description of even-even $^{10-14}$Be from a ^{12}Be core

- ^{14}Be
  - Drip-line nucleus
  - Two neutron halo
  - Borromean (^{12}Be+n, n+n systems are unbound)
  - No bound excited states

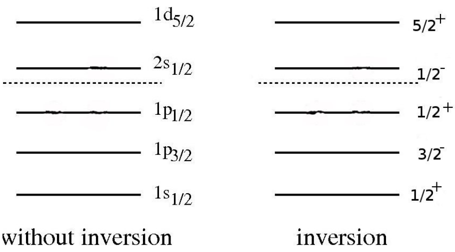
- ^{13}Be
  - Unbound nucleus
  - Low-lying levels are not clarified

^{13}Be: Experimentally



(From Kondo et al.)

With/without shell inversion in ^{13}Be



- Strategy: We test two scenarios for ^{13}Be spectrum.
- Inversion: ^{12}Be: $E(2_1^+)$=2.6 MeV with $B(E2; 0_1^+ \rightarrow 2_1^+) \approx 50 e^2 fm^4$.

^{14}Be: Three-body models

Two scenarios for ^{13}Be:

- Normal shell ordering
- Faddeev calculation.
  (Zhukov and Thompson, PRC 49, 1904 (1994).)
- Generatrice coordinate model.
  (Descouvemont, PRC 52, 704 (1995).)
- Lagrangian mesh calculation.
  (Adahchour et al., PLB 356, 445 (1995).)
- Macroscopic model with deformation.
  (Tarutina et al., NPA 733, 53 (2004).)

- Shell inversion
- Two-neutron pairing model.
  (Labiche et al. PRC60, 027303 (1999).)
- Particle-particle RPA (g.s.).
  (Pacheco and Vinh Mau, PRC 65, 0440044 (2002).)
- Particle-particle RPA (excited).
  (Blanchon et al., PRC 00, 004300 (2010).)

^{14}Be: Ground state properties (1)

Table: Theoretical and experimental values of S_{2n} (MeV) in ^{12}Be and ^{14}Be (from Ref.[1]), $\langle \mathbf{r}^2 \rangle^{1/2}_{A+2}$ (fm), $\langle \boldsymbol{\lambda}^2 \rangle^{1/2}$ (fm) and $\langle \boldsymbol{\rho}^2 \rangle^{1/2}$ (fm) in ^{14}Be (from Refs. [1,2]) in the two cases of non-inversion (A) and inversion (B) of the $2s_{1/2}$ and $1p_{1/2}$ shells.

	$S_{2n}(^{12}\text{Be})$	$S_{2n}(^{14}\text{Be})$	$\langle \mathbf{r}^2 \rangle^{1/2}_{A+2}$	$\langle \boldsymbol{\rho}^2 \rangle^{1/2}$	$\langle \boldsymbol{\lambda}^2 \rangle^{1/2}$
A	2.91	0.51	3.45	8.45	5.45
B	3.71	1.29	2.91	4.56	4.02
Exp.	3.673±0.015	1.26 ± 0.01	3.10±0.15	5.4±1.0	4.2±1.7

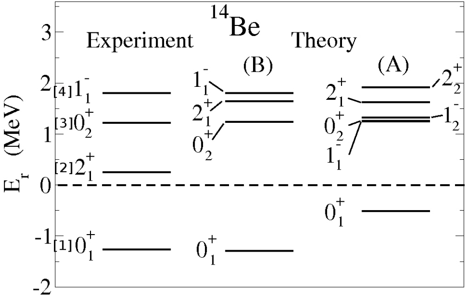
([1] A. Ozawa et al., NPA693, 32 (2001). [2] F. M. Marqués et al. PLB476, 219 (2000).)

^{14}Be: Ground state properties (2)

Table: Main pp-RPA amplitudes for 0_1^+ ground state in ^{14}Be without (A) and with (B) inversion of $2s_{1/2}$-$1p_{1/2}$ shells.

	X_{ab}			$X_{\alpha\beta}$	
	$(2s_{1/2})^2$	$(1d_{5/2})^2$		$(1p_{3/2})^2$	$(1p_{1/2})^2$
A	-0.93	-0.49		0.32	0.36
	$(1d_{5/2})^2$	$(1p_{1/2})^2$	$(1p_{1/2}\ 2p_{1/2})$	$(1p_{3/2})^2$	$(2s_{1/2})^2$
B	-0.56	0.70	-0.63	0.59	-0.45

^{14}Be: Excited states

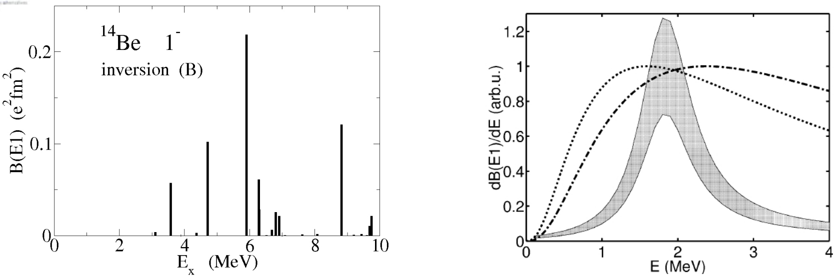


[1] Audi, NPA729, 337 (2003).
[2] Bohlen, NPA 583, 775(1995).
[3] Simon, NPA 791, 267(2007).
[4] Labiche, PRL 86, 600(2001).

- 0^- at $E_x = 3.16$MeV ($E_r = 1.87$MeV).

- **(A)** non inversion.
- **(B)** inversion $\rightarrow$ gives better results.

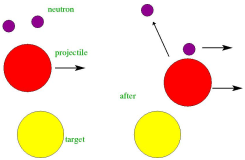
^{14}Be: B(E1)

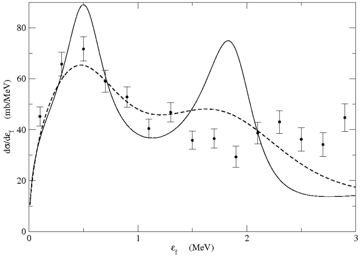


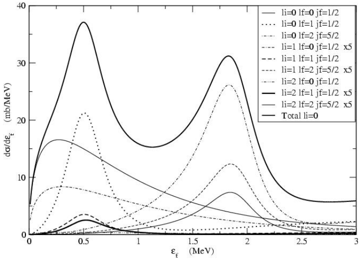
(C. Forssén et al., NPA706, 48 (2002).)

- No E1 strength concentration at low energy.
- Indication of a different structure in ^{14}Be in comparison with other Borromean nuclei.
- Effect of the p intruder state.

^{13}Be: fragmentation reaction ^{14}Be on ^{12}C @ 250 A.MeV







(Blanchon et al., NPA784, 49 (2007)).

- Importance of the p-intruder to fit data.
- Large $d_{5/2}$-resonance (convolution with experimental resolution)
  (L. Chulkov & Simon, NPA 734 (2004)).

Outlooks

- Inversion in the ^{13}Be spectrum.
  Agreement with Kondo et al.

- pp-RPA is a simple and powerful tool to study halo nuclei.

- Calculation of the particle-vibration coupling microscopically.