Core excitation in breakup reactions: semi-microscopic folding models for the structure of halo nuclei

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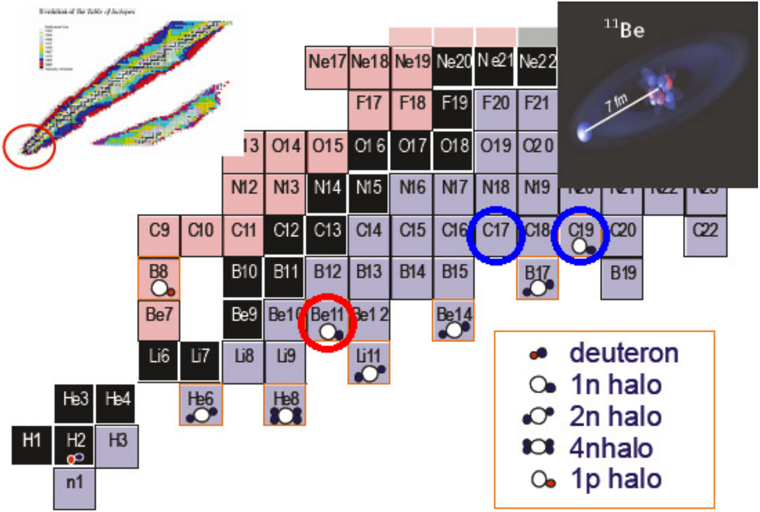
1. Motivation
   - Discretizing the Continuum
   - Core excitations

2. Structure
   - Halo nuclei with excitations of the core
   - PS discretization method
   - Semi-microscopic model

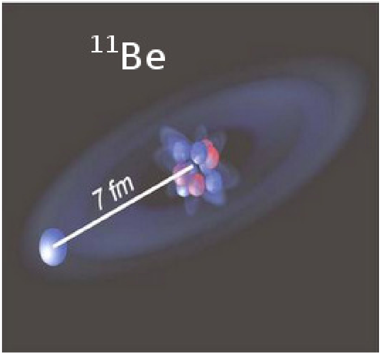
3. Results
   - Structure of ^{11}Be, ^{19}C, and ^{21}C
   - More reactions with ^{19}C


11Be
7 fm
Ne17 Ne18 Ne19 Ne20 Ne21 Ne22
F17 F18 F19 F20 F21
O14 O15 O16 O17 O18 O19 O20
N12 N13 N14 N15 N16 N17 N18 N19
C9 C10 C11 C12 C13 C14 C15 C16 C17 C18 C19 C20 C22
B8 B10 B11 B12 B13 B14 B15 B17 B19
Be7 Be9 Be10 Be11 Be12 Be14
Li6 Li7 Li8 Li9 Li11
He3 He4 He6 He8
H1 H2 H3
n1
deuteron
1n halo
2n halo
4nhalo
1p halo

Simplest model for ^{11}Be and other halo nuclei

Single Particle Model

1. Two-body model for ^{11}Be (n+^{10}Be)
2. Ignore possible core-excited components of ^{10}Be.
3. Reaction treated within CDCC formalism



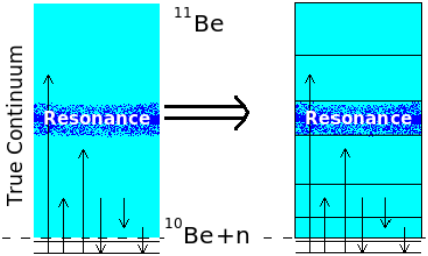
!! contribution of ^{10}Be in its 1st excited state 2^+

The Continuum problem in CDCC

Discretization methods:

- Binning:

$$u_l^i(k) = \sqrt{\frac{2}{\pi N_i}} \int_{k_{i-1}}^{k_i} f_i(k)\phi_l(k,r)dk.$$



The Continuum problem in CDCC

Discretization methods:

- Binning:

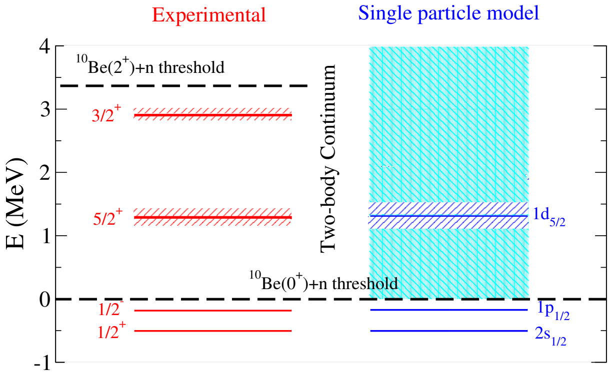
$$u_l^i(k) = \sqrt{\frac{2}{\pi N_i}} \int_{k_{i-1}}^{k_i} f_i(k)\phi_l(k,r)dk.$$

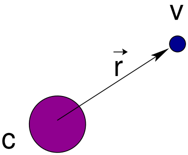
- Pseudo-states.

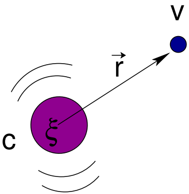
  ⇒ The Continuum is described through a basis (HO, Sturmian) of square-integrable states.

  ⇒ It improves the convergence rate in the case of narrow resonances.

^{11}Be in a single particle model







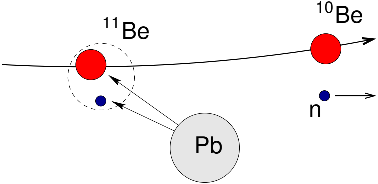
× No core excitations

$$|^{11}\text{Be}(1/2^+)\rangle = 1|^{10}\text{Be}(0^+\text{ g.s.}) \otimes \nu\, s_{1/2}\rangle$$

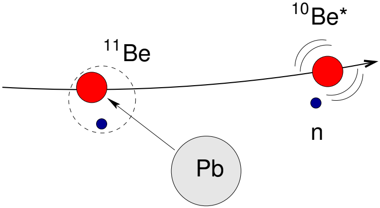
✓ Core excitations

$$|^{11}\text{Be}(1/2^+)\rangle = \alpha|^{10}\text{Be}(0^+\text{ g.s.}) \otimes \nu s_{1/2}\rangle + \beta|^{10}\text{Be}(2^+) \otimes \nu d_{5/2}\rangle + \ldots$$

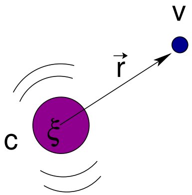
$|\alpha|^2, |\beta|^2$ = spectroscopic factors



× Pure valence excitation



✓ Core-excitation mechanism



Hamiltonian with core excitation

$$\mathcal{H}_p = T(\vec{r}) + h_{core}(\xi) + V_{NC}(\vec{r}, \vec{\xi})$$

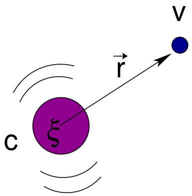
Model for the core $h_{core}(\xi)$

- Selecting the model space $\Rightarrow$ which states are included
- The model for core excitations will determine $V_{NC}(\vec{r}, \vec{\xi})$

Same formalism for different interaction models:

- Particle-Rotor model (deformed core)
- Particle-Vibration
- From microscopic transition densities
- ...

Weak coupling limit



Hamiltonian with core excitation

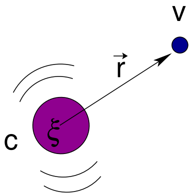
$$\mathcal{H}_p = T(\vec{r}) + h_{core}(\xi) + V_{NC}(\vec{r}, \vec{\xi})$$

We look for a basis including core degrees of freedom

Coupling core $\varphi_I(\vec{\xi})$ and single particle $\mathcal{Y}_{\ell sj}(\hat{r})$ to the total J_p

$\Rightarrow$ n_α different possible combinations or channels $\alpha = \{l, s, j, I\}$

Generalization of Pseudo-states (PS) discretization method



Hamiltonian with core excitation

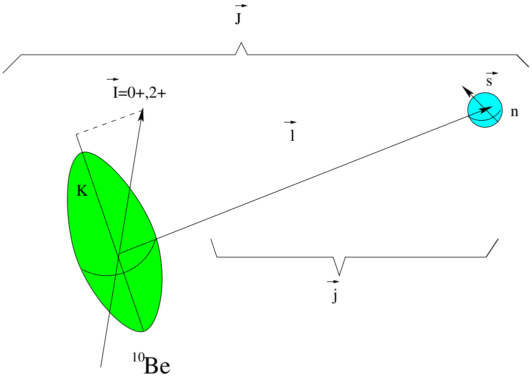
$$\mathcal{H}_p = T(\vec{r}) + h_{core}(\xi) + V_{NC}(\vec{r},\vec{\xi})$$

Set of $\mathcal{L}^2$ functions in this scheme:

$$|\phi_{i,J_p}(\vec{r},\vec{\xi})\rangle = \sum_\alpha R^{THO}_{i,\alpha}(r)\left[\mathcal{Y}_{\ell sj}(\hat{r})\otimes\varphi_I(\vec{\xi})\right]_{J_p} \quad i = 1,..,N$$

⇒ Total number of functions: N times the number of channels

An example is: Particle-Rotor Model



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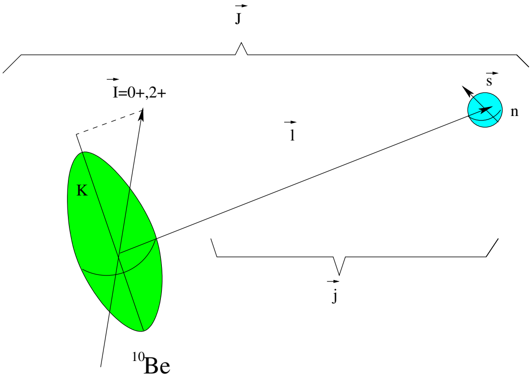


The valence-core interaction in first order:

$$V_{NC}(\vec{r},\vec{\xi}) = V_{NC}(r - R_0 - \Delta(\hat{\Omega})) \approx V_{Cent}(r) - \delta_2 \frac{dV_{Cent}}{dr} Y_{20}(\hat{r})$$

Pseudo-states (PS) discretization method

- Discrete set of $\mathcal{L}^2$ functions: $|\phi_n\rangle$

Completeness condition:

$$\sum^{N} |\phi_i\rangle\langle\phi_i| \approx \mathrm{I}$$

- To diagonalize the internal Hamiltonian of a projectile $\mathcal{H}_p$

Matrix elements:

$$\mathcal{H}_p \longmapsto \sum_{n,n'} |\phi_n\rangle\langle\phi_n|\mathcal{H}_p|\phi_{n'}\rangle\langle\phi_{n'}|$$

Pseudo-states (PS) discretization method

Eigenstates of the matrix NxN:

$$|\varphi_n^{(N)}\rangle = \sum^{N} C_i^n |\phi_i\rangle$$

- $\begin{cases} n_b \text{ states with } \varepsilon_n < 0 \text{ representing the bound states.} \\ N\text{-}n_b, \varepsilon_n > 0 \Rightarrow \text{discrete representation of the Continuum} \end{cases}$
- Orthogonal and normalizable.

What is the most suitable basis? Lagrange, Sturmian, Harmonic Oscillator?

Transformed Harmonic Oscillator basis

Analytic LST from Karataglidis *et al.*,PRC71,064601(2005)

$$s(r) = \frac{1}{\sqrt{2}b}\left[\frac{1}{\left(\frac{1}{r}\right)^m + \left(\frac{1}{\gamma\sqrt{r}}\right)^m}\right]^{\frac{1}{m}}$$

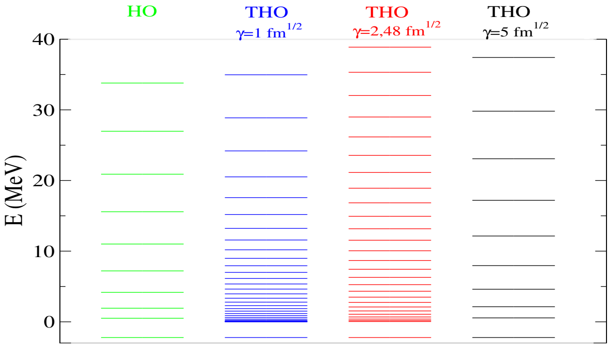
HO vs THO:

$$\phi(s) \longmapsto e^{-\left(\frac{s}{b}\right)^2} \quad \Longrightarrow \quad \phi[s(r)] \longmapsto e^{-\frac{\gamma^2}{2b^2}r}$$

- Correct asymptotic behaviour for bound states.
- Range controlled by the parameters of the LST.

THO parameters

- b is treated as a variational parameter to minimize g.s. energy
- Then $\frac{\gamma}{b}$ controls the density of states:

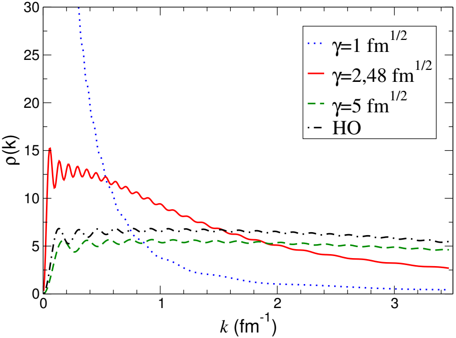


- γ can be also used to look for resonances

Energy distribution of pseudo-states

Density of states

$$\rho_\ell^{(N)}(k) = \sum_{n=1}^{N} \langle \varphi_\ell(k) | \varphi_{n,\ell}^{(N)} \rangle$$



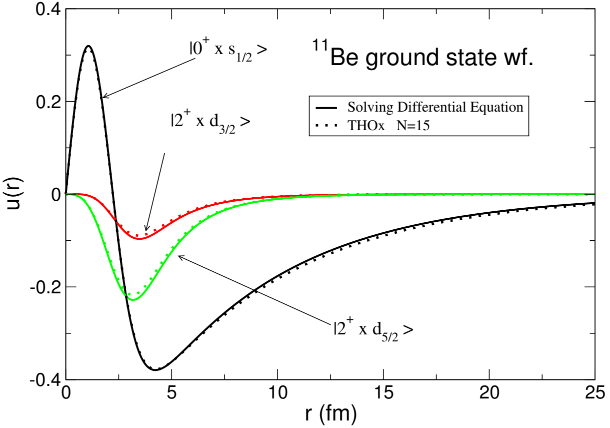
The Smoothing Process

For any operator

$$
\begin{aligned}
O(\varepsilon) &= \langle k|\hat{O}|g.s.\rangle \\
&= \langle k|\sum_n |n\rangle\langle n|\hat{O}|g.s.\rangle \\
&= \sum_n \rho^{(n)}(k)\langle n|\hat{O}|g.s.\rangle
\end{aligned}
$$

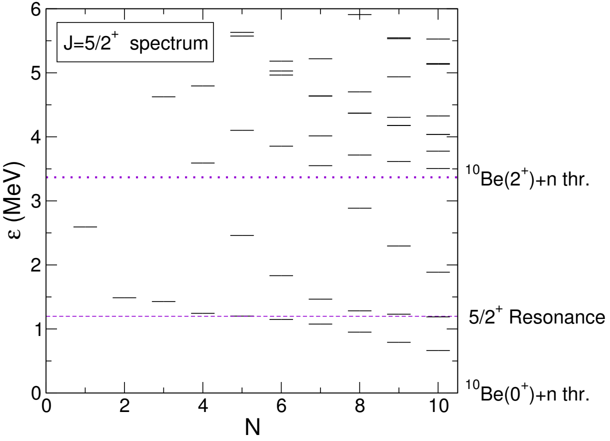
$\Rightarrow$ A continuous distribution in energy from discrete values of S matrix, B(Eλ), cross sections...

Particle-Rotor Model

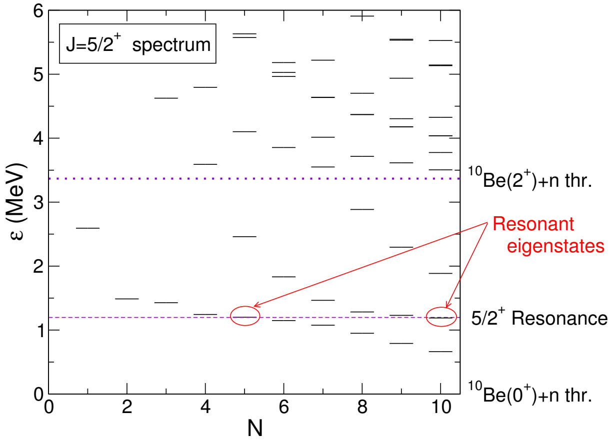


The g.s. wavefunction is well described using a small THO basis

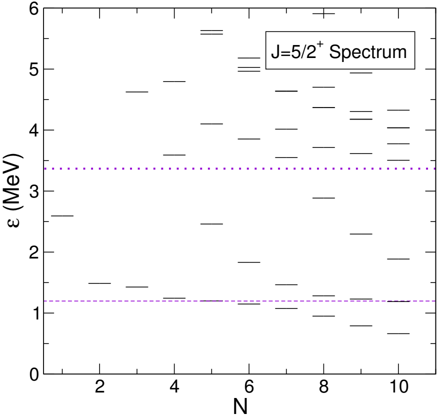
Finding Resonances

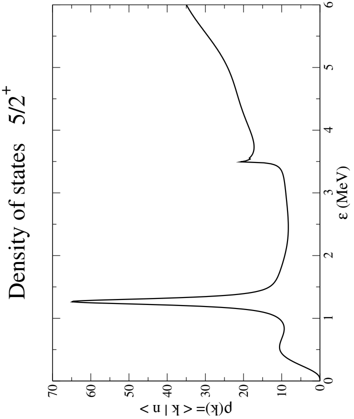


Finding Resonances

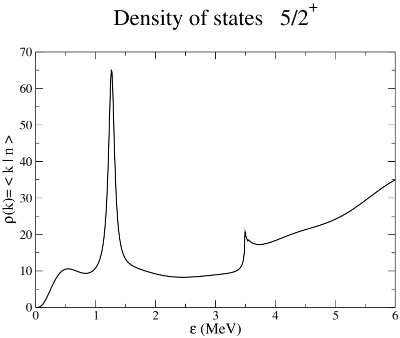


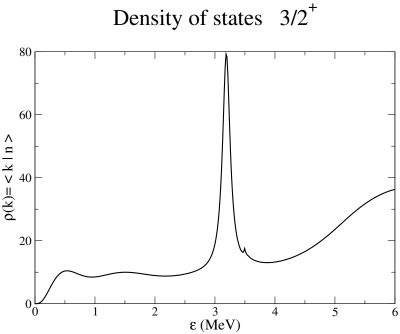
Spectrum


J=5/2$^+$ Spectrum
ε (MeV)
N
0
1
2
3
4
5
6
2
4
6
8
10


Density of states 5/2$^+$
ε (MeV)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70

Energy distribution of pseudo-states

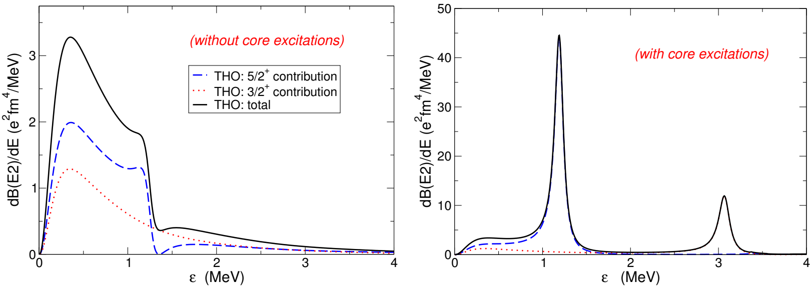




$\Rightarrow$ Widths of 125 KeV and 140 KeV respectively.

$\Rightarrow$ Experimental values of 100 ± 10 KeV and 122 ± 8 KeV.

Electromagnetic Transition Probabilities



⇒ B(E2) dominated by collective excitation of the core

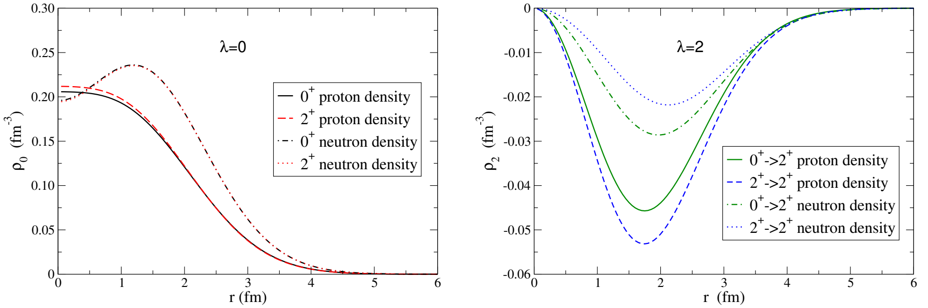
PRM "drawbacks"

PRM needs:

- The core to be a rotor
- A phenomenological potential based on the following parametres:

$$E(2^+),\ \beta_2,\ V_c,\ r,\ a,\ V_{so}, r_{so},\ a_{so}$$

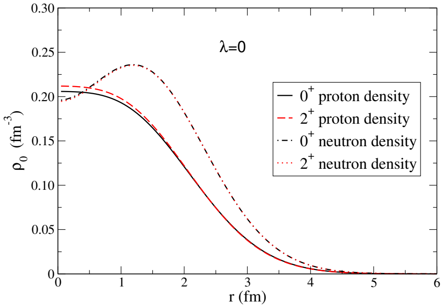
P-AMD

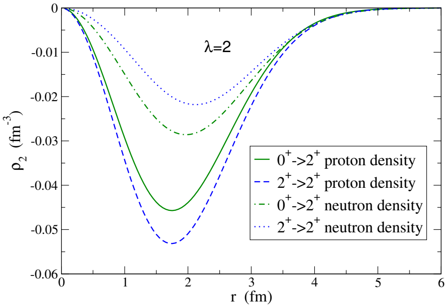


Densities from Antisymmetrized Molecular Dynamics (AMD)

Y. Kanada-En'yo *et al.* Phys. Rev. C 60, 064304 (1999)

P-AMD

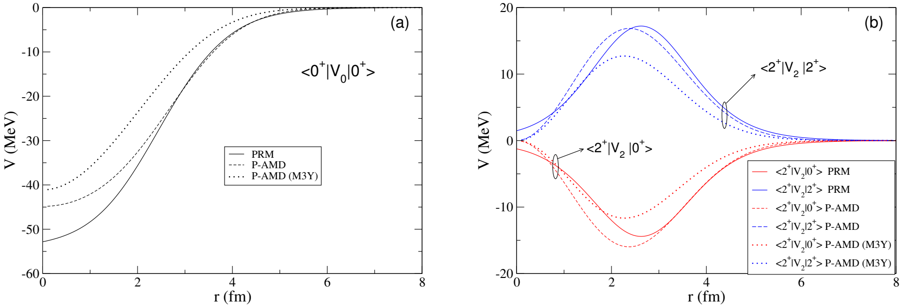




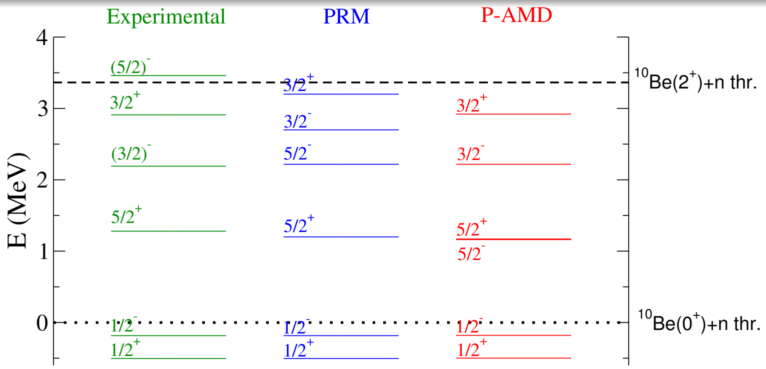
$$\langle I || V^{\lambda}_{NC}(r,\vec{\xi}) || I' \rangle = \int dr' \left[\langle I || \rho_{\lambda}(r',\xi) || I' \rangle v_{nn}(|\vec{r} - \vec{r'}|) \right]$$

JLM interaction Phys. Rev. C 16, 80 (1977).

P-AMD


(a)
<0+|V0|0+>
PRM
P-AMD
P-AMD (M3Y)
V (MeV)
r (fm)
0
-10
-20
-30
-40
-50
-60
0
2
4
6
8
(b)
<2+|V2 |2+>
<2+|V2 |0+>
<2+|V2|0+> PRM
<2+|V2|2+> PRM
<2+|V2|0+> P-AMD
<2+|V2|2+> P-AMD
<2+|V2|0+> P-AMD (M3Y)
<2+|V2|2+> P-AMD (M3Y)
V (MeV)
r (fm)
20
10
0
-10
-20
0
2
4
6
8

P-AMD



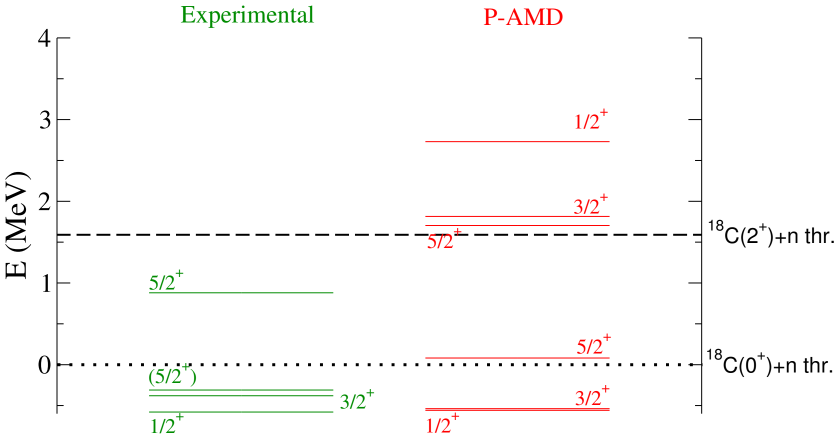
Renormalization factors

$$\lambda_+ = 1.058 \text{ and } \lambda_- = 0.995$$

PRC 70, 054606 (2004); PRC 81, 034321 (2010); PL B 611, 239 (2005).

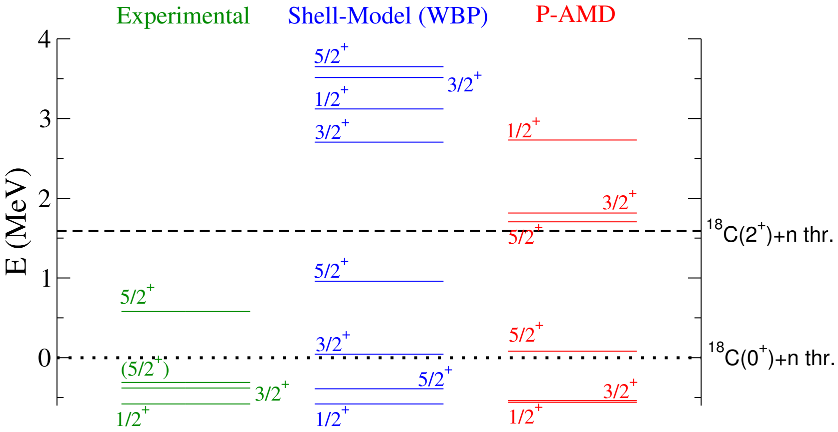
State	Model	$\|0^+ \otimes (\ell s)j\rangle$	$\|2^+ \otimes s_{1/2}\rangle$	$\|2^+ \otimes d_{3/2}\rangle$	$\|2^+ \otimes d_{5/2}\rangle$
$1/2^+$	PRM	0.857	–	0.021	0.121
	P-AMD	0.849	–	0.031	0.121
	WBT	0.762	–	0.002	0.184
$5/2^+$	PRM	0.702	0.177	0.009	0.112
	P-AMD	0.674	0.189	0.014	0.124
	WBT	0.682	0.177	0.009	0.095
$3/2^+$	PRM	0.165	0.737	0.017	0.081
	P-AMD	0.316	0.565	0.031	0.089
	WBT	0.068	0.534	0.008	0.167

^{19}C Spectrum



PL B 660, 320 (2008); PL B 614, 174 (2005).

^{19}C Spectrum



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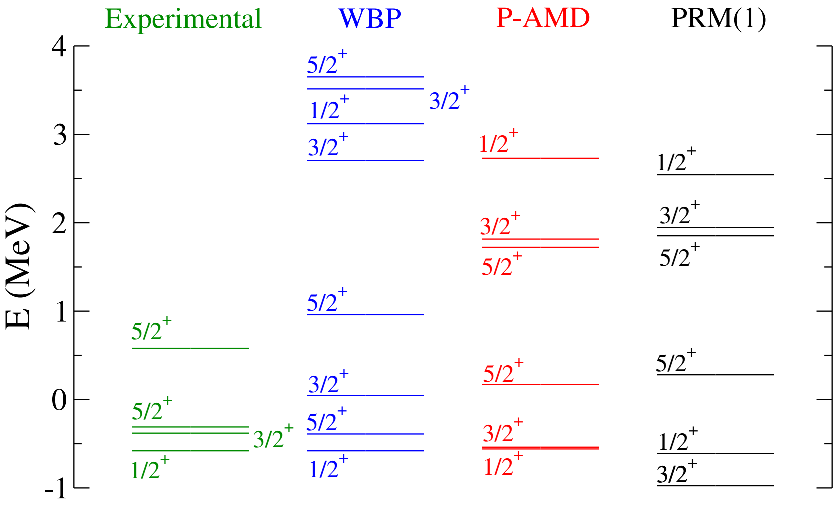
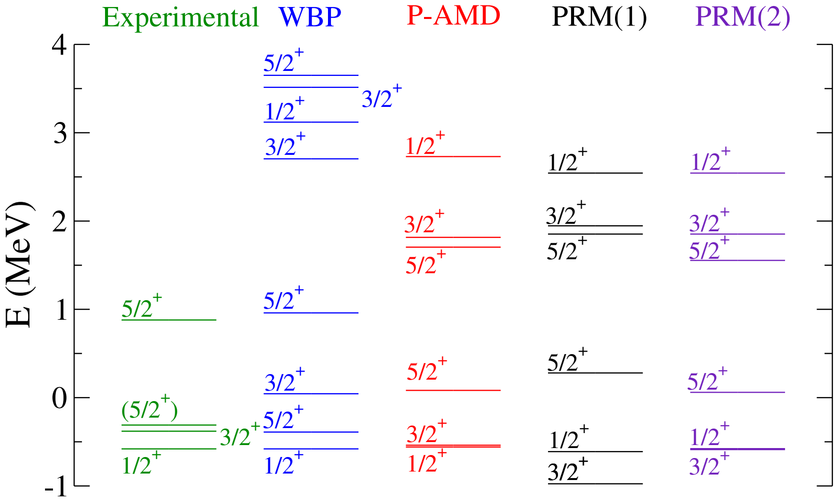
^{19}C Spectrum



PL B 660, 320 (2008); PL B 614, 174 (2005).

^{19}C Spectrum

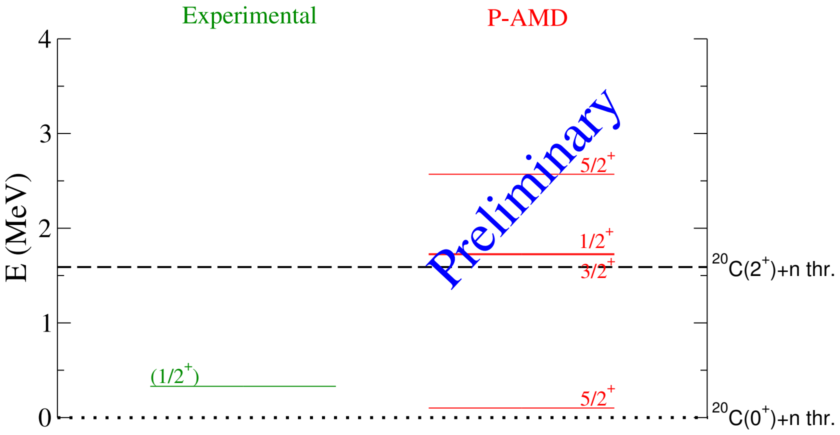


PL B 660, 320 (2008); PL B 614, 174 (2005).

Nucleus	rms (fm)	$\langle 0\|\hat{\delta}_2\|2\rangle_{\mathrm{AMD}}$ (fm)	$\langle 0\|\hat{\delta}_2\|2\rangle_{\mathrm{rot}}$ (fm)
^{10}Be	2.538	1.90	1.66
^{18}C	2.776	1.20	1.50

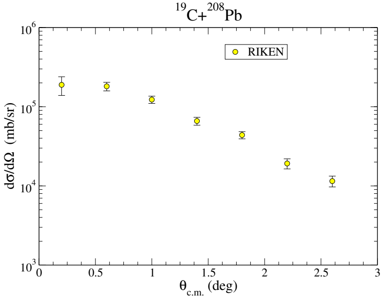
State	Model	$\|0^+ \otimes (\ell s)j\rangle$	$\|2^+ \otimes s_{1/2}\rangle$	$\|2^+ \otimes d_{3/2}\rangle$	$\|2^+ \otimes d_{5/2}\rangle$
$1/2^+_1$	P-AMD	0.529	–	0.035	0.436
	PRM(1)	0.517	–	0.081	0.402
	PRM(2)	0.505	–	0.033	0.462
	WBP	0.600	–	0.002	0.184
$5/2^+_1$	P-AMD	0.276	0.721	0.000	0.003
	PRM(1)	0.285	0.716	0.000	0.003
	PRM(2)	0.278	0.719	0.000	0.003
	WBP	0.383	0.015	0.000	0.751
$5/2^+_2$	P-AMD	0.200	0.142	0.002	0.657
	PRM(1)	0.217	0.178	0.004	0.602
	PRM(2)	0.207	0.100	0.002	0.690
	WBP	0.035	0.609	0.009	0.291

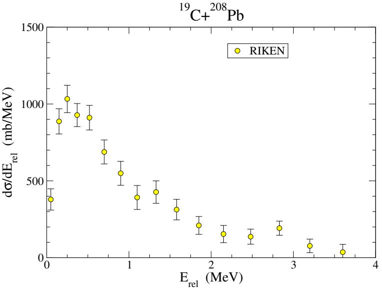
^{21}C Spectrum



PRC86, 054604

$^{19}C+^{208}Pb$ @ 67 MeV/u





- Coulomb Excitation

T. Nakamura *et al.*, Phys. Rev. Lett. 83, 1112 (1999).

$^{19}C+^{208}Pb$ @ 67 MeV/u

Semiclassical calculations

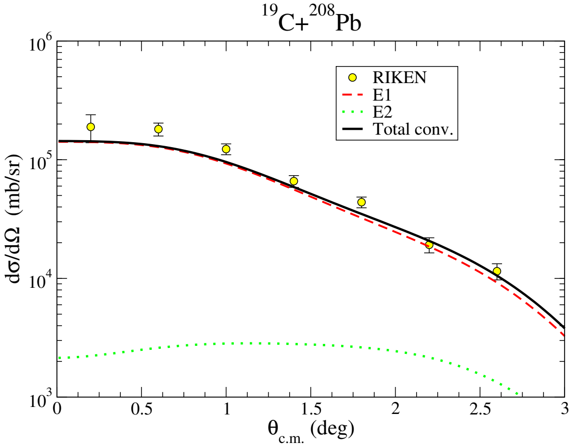
Equivalent Photon Method

- ⇒ Only includes first order Coulomb excitation.
- ⇒ Actually this is only a first test before using the basis with DWBAx/XCDCC.

$$\left.\frac{d\sigma_\lambda}{d\Omega\ dE}\right|_{bu} = \frac{4\pi^3}{9}\frac{d\mathcal{B}(E1)}{dE}\frac{dN_{E1}}{d\Omega}$$

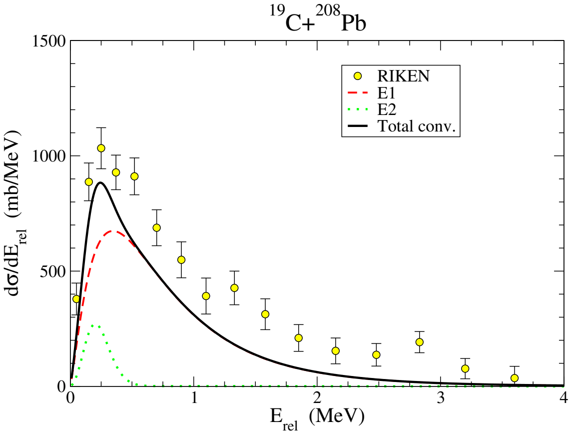
$^{19}C+^{208}Pb$ @ 67 MeV/u

T. Nakamura *et al.*, Phys. Rev. Lett. 83, 1112 (1999).



- The reaction is dominated by E1 first order Coulomb excitation as expected

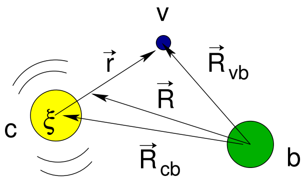
$^{19}C+^{208}Pb$ @ 67 MeV/u



- Resonant E2 contribution more important due to its low excitation energy

$^{19}C+p$ @ 67 MeV/u

DWBAx calculations

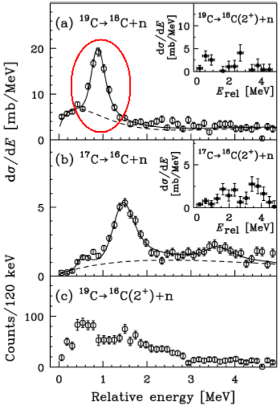


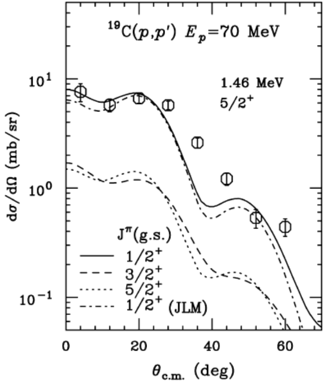
No-recoil approach

- ⇒ Only first order excitation.
- ⇒ Core and Valence contributions explicitly separates in the calculation. A. M. Moro & R. Crespo, Phys. Rev. C 85, 054613 (2012).
- ⇒ Same results for these energies than XCDCC. A. M. Moro *et al.* AIP Conf. Proc. 1491, 335 (2012)

^{19}C+p @ 67 MeV/u

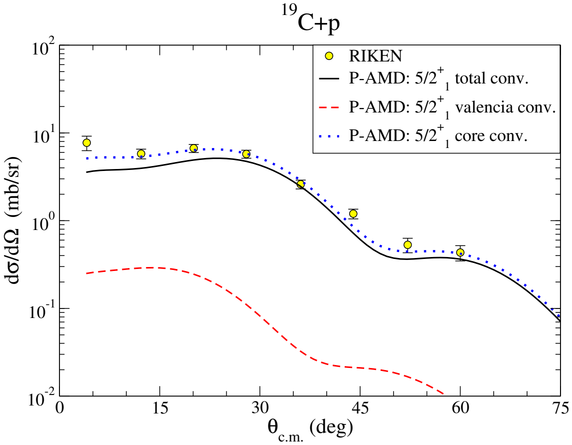
Y. Satou *et al.*, Phys. Lett. B 660, 320 (2008).



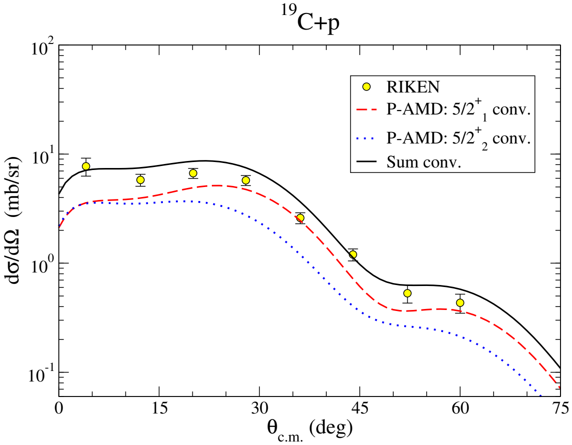


Microscopic DWBA calculations suggest a $1/2^+ \Rightarrow 5/2^+$ transition

^{19}C+p @ 67 MeV/u


19C+p
10^2
10^1
10^0
10^-1
10^-2
dσ/dΩ (mb/sr)
0
15
30
45
60
75
θc.m. (deg)
RIKEN
P-AMD: 5/2+1 total conv.
P-AMD: 5/2+1 valencia conv.
P-AMD: 5/2+1 core conv.

^{19}C+p @ 67 MeV/u



19C+p
RIKEN
P-AMD: 5/2+1 conv.
P-AMD: 5/2+2 conv.
Sum conv.
dσ/dΩ (mb/sr)
θc.m. (deg)
10^2
10^1
10^0
10^-1
0
15
30
45
60
75

Suitable discrete description of the continuum

The generalization of the THO basis for this case continues giving:

- A converged description of the continuum with a reduced number of functions.
- Natural and accurate treatment of narrow resonances.

Particle-Rotor Model

Accurate description of even-odd halo nuclei within deformed regions like ^{11}Be and ^{19}C.

P-AMD

- Accurate semi-microscopic description of even-odd halo nuclei.
- Predictive power for unknown halo nuclei like ^{19,21}C.
- Could be able to include core excitations from different sources.

Application to reactions with heavy targets

- Core excitations may interfere the extraction of $\mathcal{B}(E1)$ distributions.
- Low lying quadrupole resonances can be populated through core excitation in these reactions.

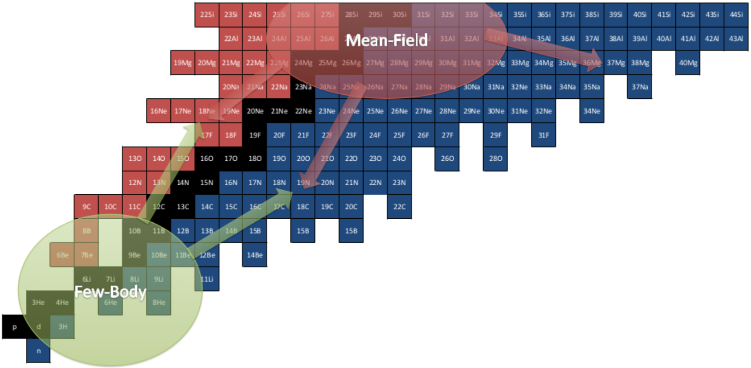
Application to reactions within DWBAx framework

- The interplay between core and valence contributions is crucial to understand angular distribution of the break up of halo nuclei.
- Break up reactions are sensitive to spectroscopic factors of resonant states difficult to populate in traditional transfer reactions.

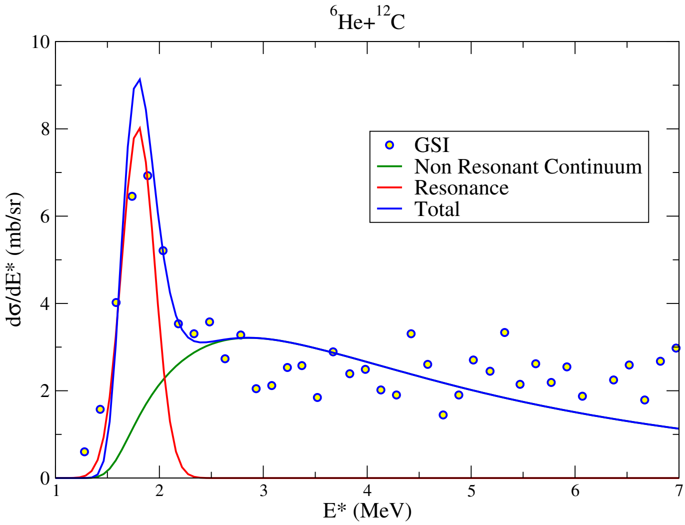
Next steps

- Apply the P-AMD model to other halo nuclei.
- Check the use of other microscopic densities.
- Perform full PS-XCDCC calculations with the THO basis and the P-AMD model.
- Use the density distributions of the PS to obtain energy distribution of the cross sections.

1. To add mean field features to few-body approaches (already with a right treatment of the Continuum)
2. To add the knowledge about Continuum to mean-field approaches



3. This nuclear structure should be included in nuclear reactions frameworks in order to analyse a wider variety of experimental data



T. Aumann et al. PRC59 (1999) 1252

Spectrum