Break up reactions with exotic nuclei and the impact of core excitations: from ^{19}C to ^{31}Ne

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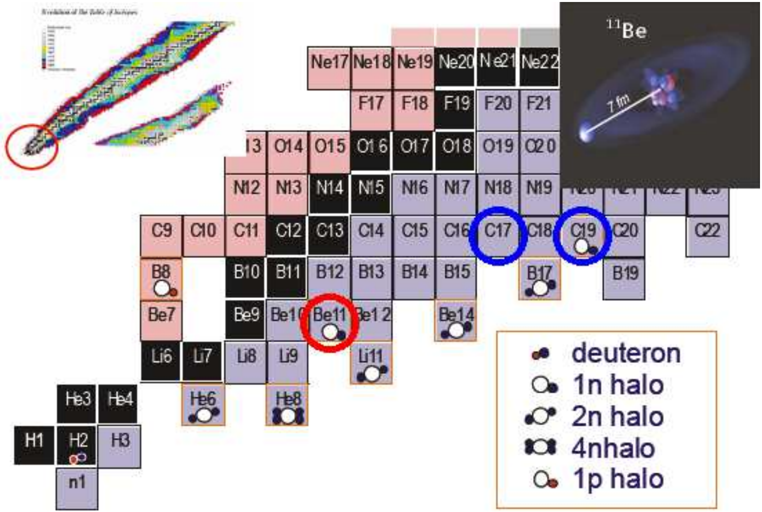
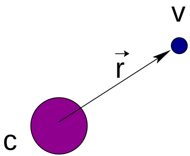
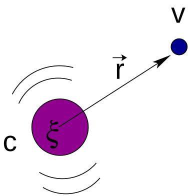
Halifax, 13th July 2016


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 Be11 Be14
Li6 Li7 Li8 Li9 Li11
He3 He4 He6 He8
H1 H2 H3
n1
deuteron
1n halo
2n halo
4nhalo
1p halo





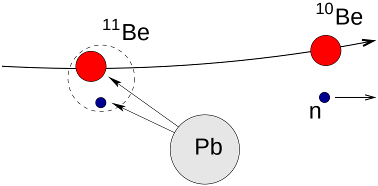
× No core excitations

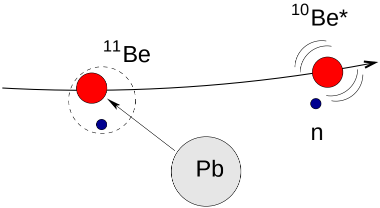
$$|^{11}\mathrm{Be}(1/2^+)\rangle = 1|^{10}\mathrm{Be}(0^+\ \mathrm{g.s.}) \otimes \nu\ s_{1/2}\ \rangle$$

✓ Core excitations

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

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

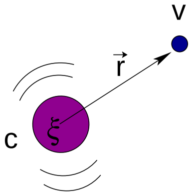




× Pure valence excitation

✓ Core-excitation mechanism

Structure



Hamiltonian with core excitation

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

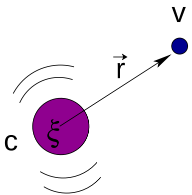
Model for the core $h_{core}(\xi)$

- 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

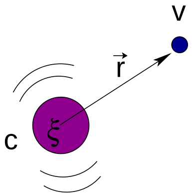
$$\mathcal{H}_p = T(\vec{r}) + h_{core}(\xi) + V_{NC}(\vec{r},\vec{\xi})$$

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

$$\boxed{N \cdot n_\alpha}$$

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:

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

- $\left\{ \begin{array}{c} \text{n}_b \text{ states with } \varepsilon_n < 0 \text{ representing the bound states.} \\ \text{N-n}_b, \varepsilon_n > 0 \Rightarrow \text{discrete representation of the Continuum} \end{array} \right.$
- Orthogonal and normalizable.

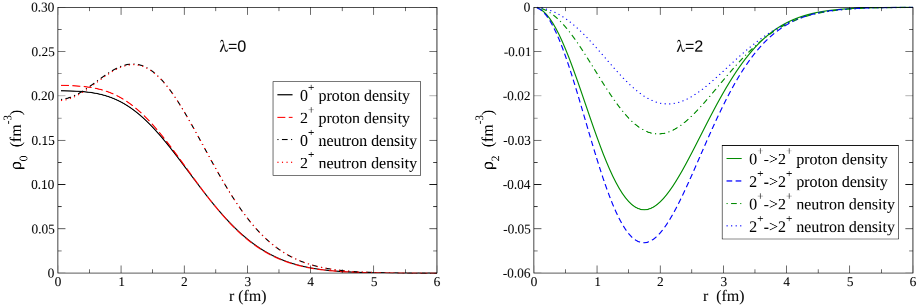
What is the most suitable basis? Lagrange, Sturmian, Harmonic Oscillator?

HO vs THO:

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

Structure
Semi-microscopic model

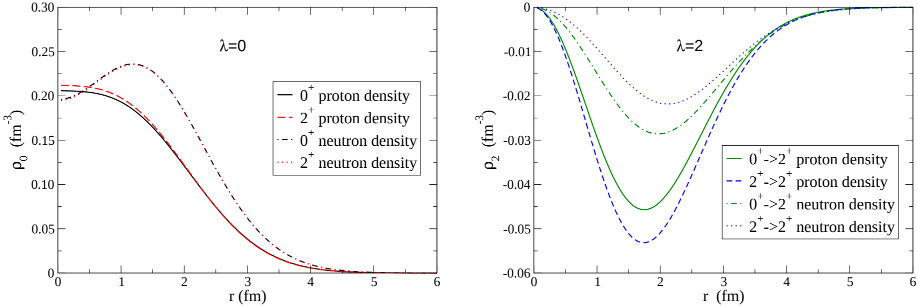
P-AMD



Densities from Antisymmetrized Molecular Dynamics (AMD)

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

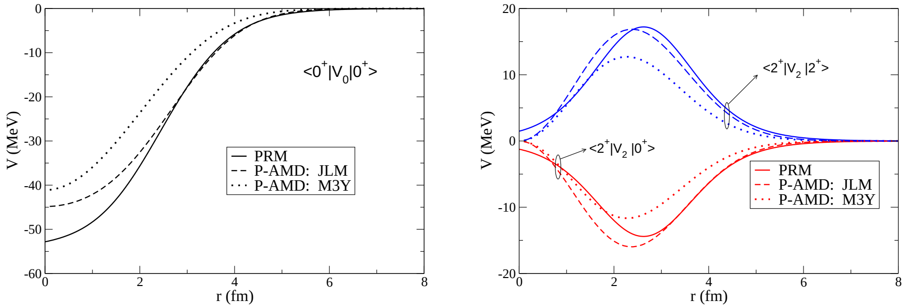
P-AMD



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

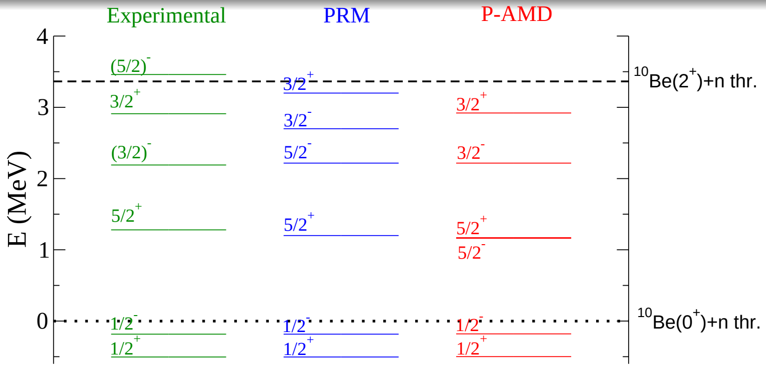
JLM interaction Phys. Rev. C 16, 80 (1977).

P-AMD



PRC89, 014333 (2014)

P-AMD

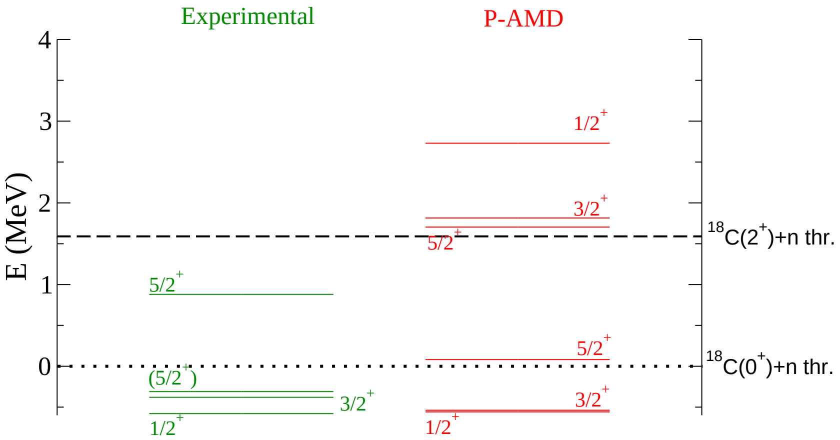


Renormalization factors

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

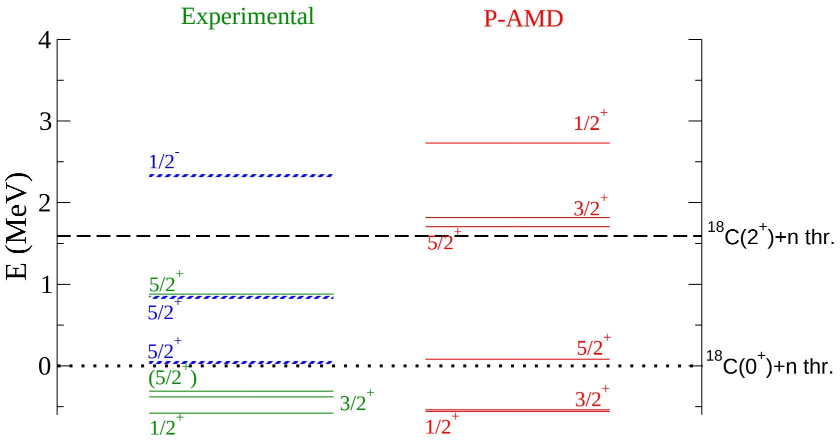
PRC 70, 054606 (2004); PRC 81, 034321 (2010); PL B 611, 239 (2005).

^{19}C Spectrum



PLB660, 320 (2008); PLB614, 174 (2005).

^{19}C Spectrum



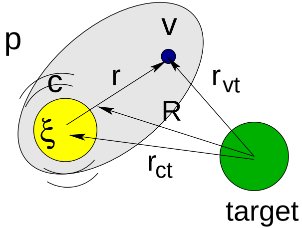
PLB660, 320 (2008); PLB614, 174 (2005) SAMURAI EPJWoC113, 06014

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
	WBP	0.600	–	0.002	0.184
$3/2_1^+$	P-AMD	0.028	0.386	0.121	0.464
	WBP	0.027	0.494	0.001	0.076
$5/2_1^+$	P-AMD	0.276	0.721	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
	WBP	0.035	0.609	0.009	0.291

J. A. Lay *et al.*, PRC89, 014333

Reactions
DWBAx

DWBAx calculations

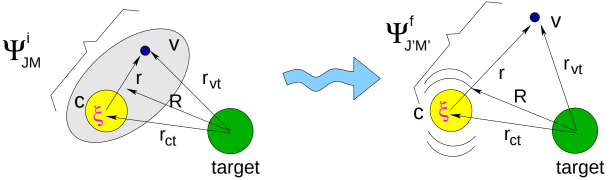


No-recoil approach

⇒ Only first order excitation.

⇒ Same results for these energies than XCDCC.
A. M. Moro *et al.* AIP Conf. Proc. 1491, 335 (2012)

⇒ Core and valence particle contributions evaluated separately
A. M. Moro & R. Crespo, Phys. Rev. C 85, 054613 (2012)



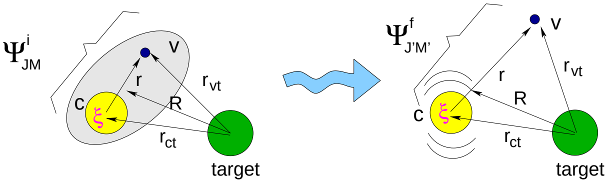
$$T_{if}^{JM,J'M'} = \langle \chi_f^{(-)}(\vec{R}) \Psi^f_{J'M'}(\vec{r},\xi) | V_{vt}(\vec{r}_{vt}) + V_{ct}(\vec{r}_{ct},\xi) | \chi_i^{(+)}(\vec{R}) \Psi^i_{JM}(\vec{r},\xi) \rangle$$

Core excitation affects in two ways:

1. $\Psi_{JM}(\vec{r},\xi)$ = projectile states ⇒ "static" deformation effect).

$$\Psi_{JM}(\vec{r},\xi) = \sum_{\ell,j,I} \left[\varphi^{J}_{\ell,j,I}(\vec{r}) \otimes \Phi_I(\xi) \right]_{JM}$$

2. $V_{ct}(\vec{r}_{ct},\xi)$ can modify the core state ⇒ dynamic core excitation.



$$T_{if}^{JM,J'M'} \approx T_{val}^{JM,J'M'} + T_{core}^{JM,J'M'}$$

Only first order plus no-recoil:

1. $T_{val}^{JM,J'M'} \Rightarrow$ Valence excitations
2. $T_{core}^{JM,J'M'} \Rightarrow$ Core excitations

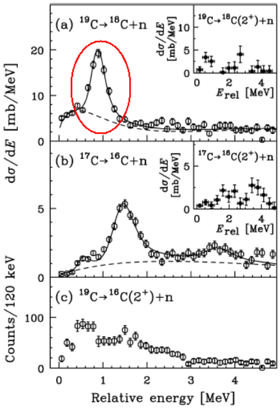
$\Rightarrow$ They explicitly separates in the calculation
A. M. Moro & R. Crespo, Phys. Rev. C 85, 054613 (2012)

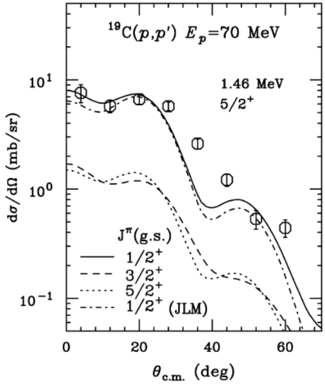
Reactions

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

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

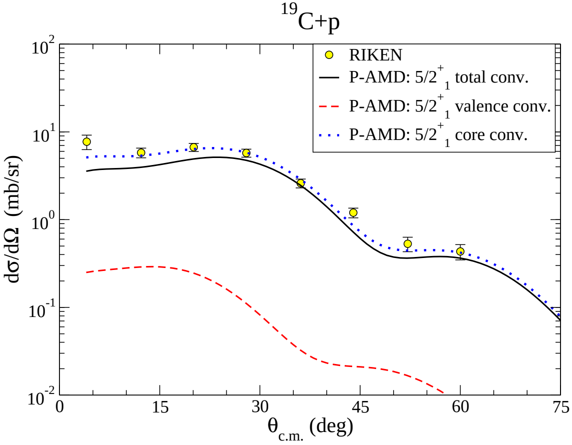
Y. Satou *et al.*, Phys. Lett. B 660, 320 (2008).





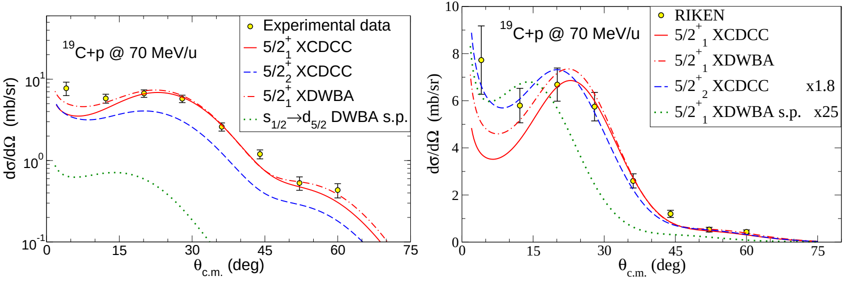
Microscopic DWBA calculations suggest a $1/2^+ \Rightarrow 5/2^+$ transition

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



^{19}C+p
RIKEN
P-AMD: $5/2^+_1$ total conv.
P-AMD: $5/2^+_1$ valence conv.
P-AMD: $5/2^+_1$ core conv.
dσ/dΩ (mb/sr)
10^2
10^1
10^0
10^{-1}
10^{-2}
0
15
30
45
60
75
$\theta_{c.m.}$ (deg)

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



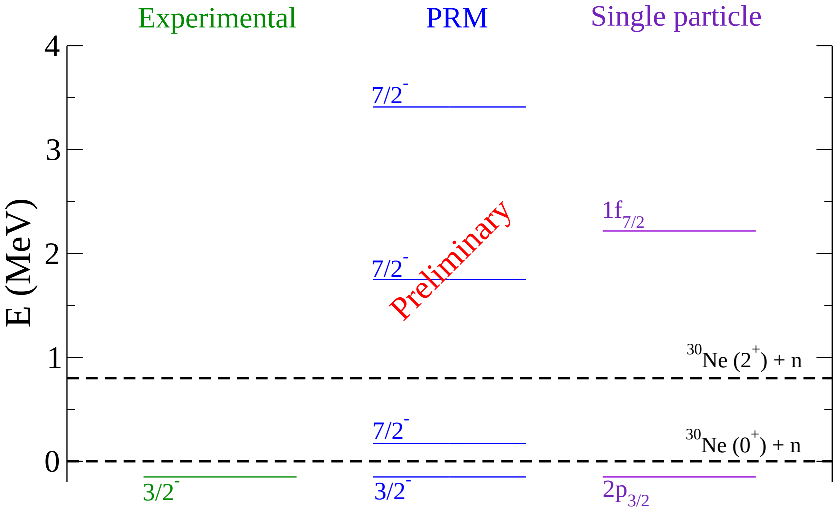
⇒ J. A. Lay *et al.*, Submitted to PRC(R) arXiv:1605.09723

⇒ A. M. Moro & J. A. Lay, Phys. Rev. Lett. 109, 232502 (2012)

Reactions

^{31}Ne+p @ 70 MeV/u

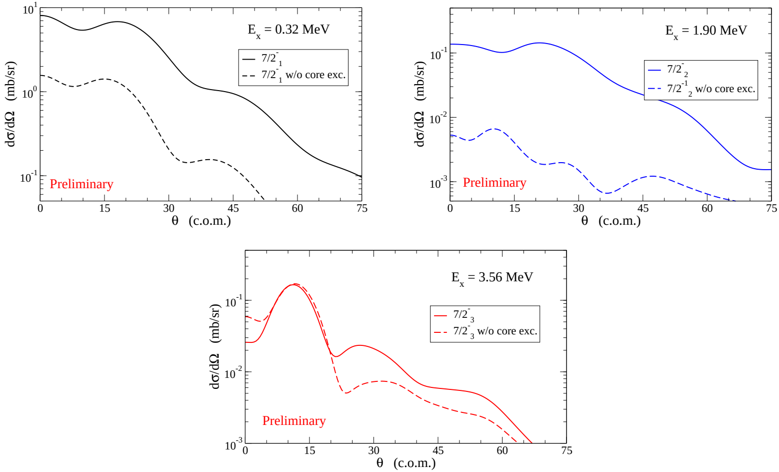
^{31}Ne Spectrum



PRL 112, 142501 (2014).

^{31}Ne+p @ 70 MeV/u

$\Rightarrow$ $3/2^- \longrightarrow 7/2^-$

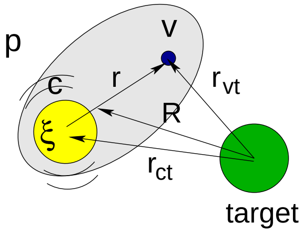


- The third one is the only one mainly $p_{3/2} \longrightarrow f_{7/2}$

Reactions
XCDCC

Full CDCC

XCDCC calculations



Including core excitations in CDCC

- ⇒ We already showed how to discretize the continuum with core excitations
- ⇒ DWBA only valid for intermediate and high energies
- ⇒ CDCC also includes the effect of break up in the elastic cross section

XCDCC calculations for ^{11}Be+^{197}Au at sub-barrier energies

- Experiment: TRIUMF (Aarhus - LNS/INFN - Colorado - GANIL - Gothenburg -Huelva - Louisiana - Madrid - St. Mary - Sevilla - York collaboration)

☞ *M. J. G. Borge's talk on Friday*
☞ *V. Pesudo's PhD Thesis*
☞ *Submitted to PRL*

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

Nuclear Break up

- Evidence of a strong dynamic core excitation in ^{19}C resonant break up
- The interplay between core and valence contributions is crucial to understand resonant break up of halo nuclei
- Break up reactions are sensitive to spectroscopic factors of resonant states difficult to populate in traditional transfer reactions

Thank you!!

And also to:

Theory

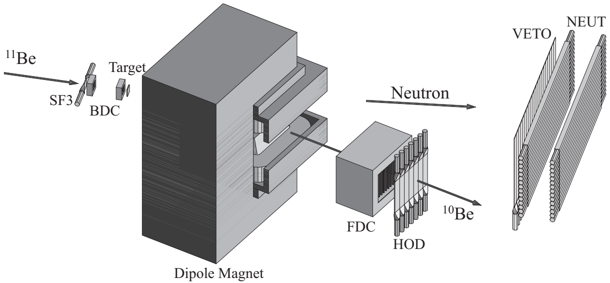
- University of Seville : J. Gómez-Camacho, M. Gómez-Ramos
- University of Lisbon : R. Crespo
- University of Surrey : R. C. Johnson
- Yukawa Institute, Kyoto University : Y. Kanada-En'yo

Experiment

- IEM-CSIC, Madrid : V. Pesudo, M. J. G. Borge, O. Tengblad
- S1202 Collaboration (formerly E1104)

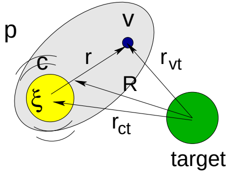
^{11}Be+^{12}C @ 67 MeV/nucleon

RIKEN: N. Fukuda *et al.*, Phys. Rev. C70, 054606 (2004)



⇒ Measurement of Break up Cross Sections of ^{11}Be on ^{12}C and ^{208}Pb

- Hamiltonian:



$$H_p = T_r + V_{vc}(\vec{r}, \xi) + h_{\rm core}(\xi)$$
$$H = H_p + V_{vt}(r_{vt}) + V_{ct}(\vec{r}_{ct}, \xi)$$

- Model wavefunction:

$$\Phi(\vec{R}, \vec{r}, \xi) = \sum_{\alpha} \chi_{\alpha}(\vec{R}) \Psi^{\alpha}_{J'M'}(\vec{r}, \xi)$$

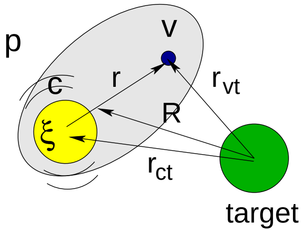
- Coupled equations: $[H - E]\Phi(\vec{R}, \vec{r}, \xi) = 0$

$$\left[E - \varepsilon_{\alpha} - T_R - V_{\alpha,\alpha}(\vec{R})\right] \chi_{\alpha}(\vec{R}) = \sum_{\alpha' \neq \alpha} V_{\alpha,\alpha'}(\vec{R}) \chi_{n'}(\vec{R})$$

- Transition potentials:

$$V_{\alpha;\alpha'}(\vec{R}) = \langle \Psi^{\alpha'}_{J'M'}(\vec{r}, \xi) | V_{vt}(\vec{r}_{vt}) + V_{ct}(\vec{r}_{ct}, \xi) | \Psi^{\alpha}_{JM}(\vec{r}, \xi) \rangle$$

Coupling potentials: CDCC vs. XCDCC



- Standard CDCC. ⇒ uses coupling potentials:

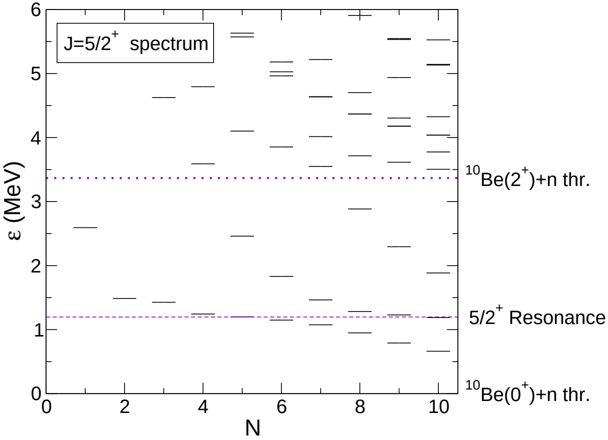
$$V_{\alpha;\alpha'}(\vec{R}) = \langle \Psi^{\alpha'}_{J'M'}(\vec{r}) | V_{vt}(r_{vt}) + V_{ct}(r_{ct}) | \Psi^{\alpha}_{JM}(\vec{r}) \rangle$$

- Extended CDCC ⇒ uses generalized coupling potentials

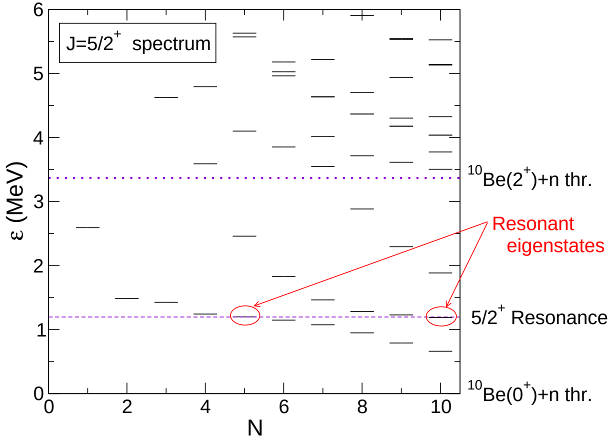
$$V_{\alpha;\alpha'}(\vec{R}) = \langle \Psi^{\alpha'}_{J'M'}(\vec{r}, \xi) | V_{vt}(\vec{r}_{vt}) + V_{ct}(\vec{r}_{ct}, \xi) | \Psi^{\alpha}_{JM}(\vec{r}, \xi) \rangle$$

R. de Diego *et al*, PRC89 (2014) 064609 (PS discretization)
also for binning Summers *et al*, PRC74 (2006) 014606

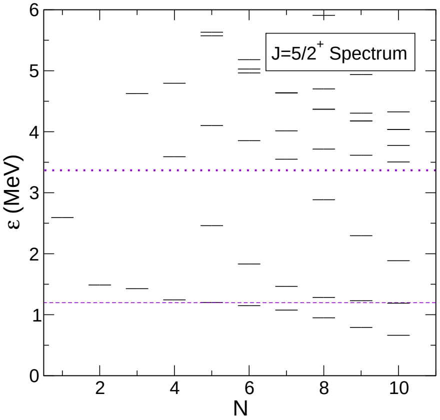
Finding Resonances

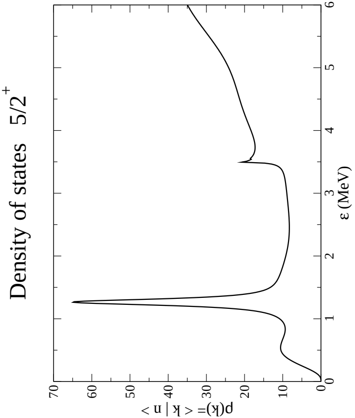


Finding Resonances

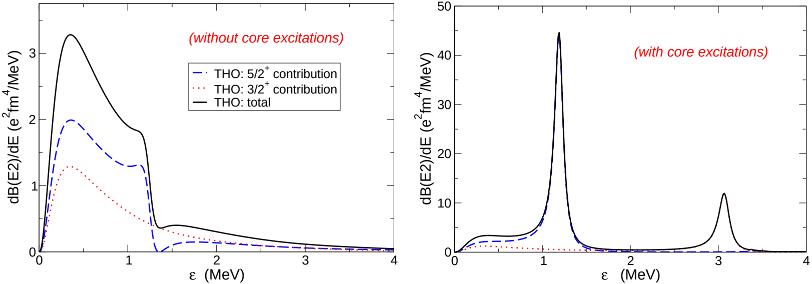


Spectrum


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


Density of states 5/2+
ρ(k)= < k | n >
ε (MeV)
0
10
20
30
40
50
60
70
0
1
2
3
4
5
6

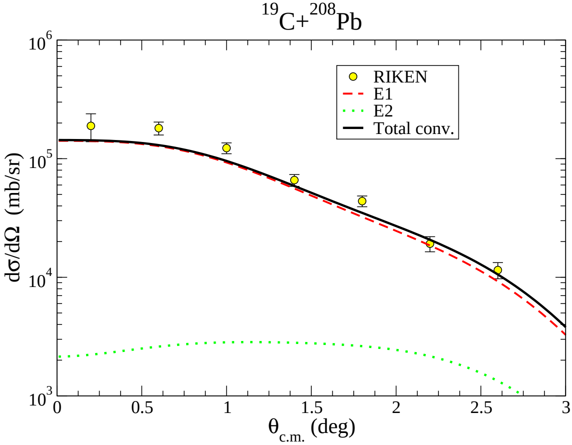
Electromagnetic Transition Probabilities



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

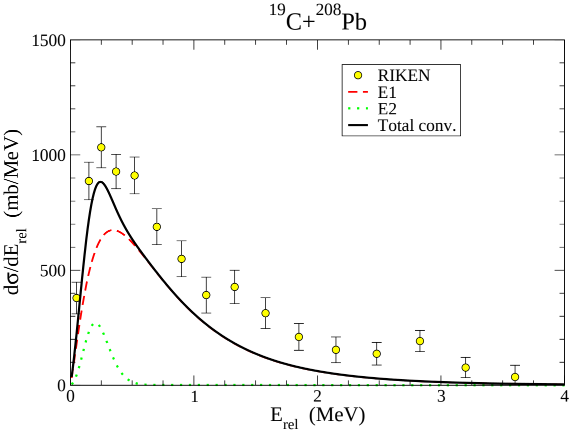
$^{19}C+^{208}Pb$ @ 67 MeV/u

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

State	Model	$\vert 0^+ \otimes (\ell s)j\rangle$	$\vert 2^+ \otimes s_{1/2}\rangle$	$\vert 2^+ \otimes d_{3/2}\rangle$	$\vert 2^+ \otimes d_{5/2}\rangle$
$5/2^+$	P-AMD	0.119	0.236	0.426	0.219
$1/2^+$	P-AMD	0.360	–	0.111	0.529

Transformed Harmonic Oscillator basis

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

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

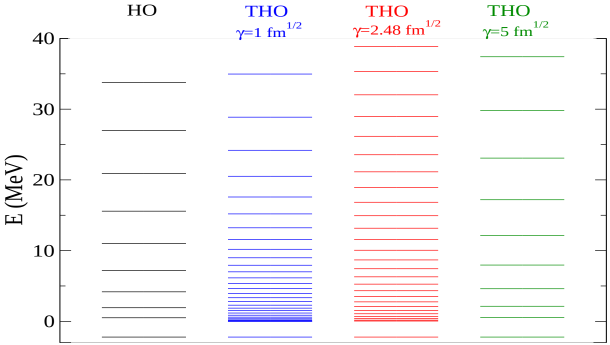
HO vs THO:

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

- 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

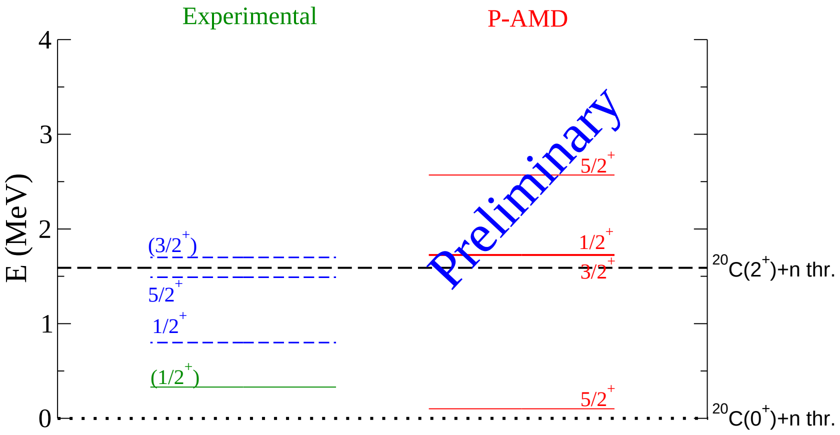
PRM "drawbacks"

PRM needs:

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

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

^{21}C Spectrum



PRC86, 054604; SAMURAI S. Leblond's talk #100

^{11}Be in a single particle model