

Impact of core excitations in break-up reactions with halo nuclei

José Antonio Lay

Universidad de Sevilla

Santiago, 25th October 2022



1 Motivation

2 Adding core excitations

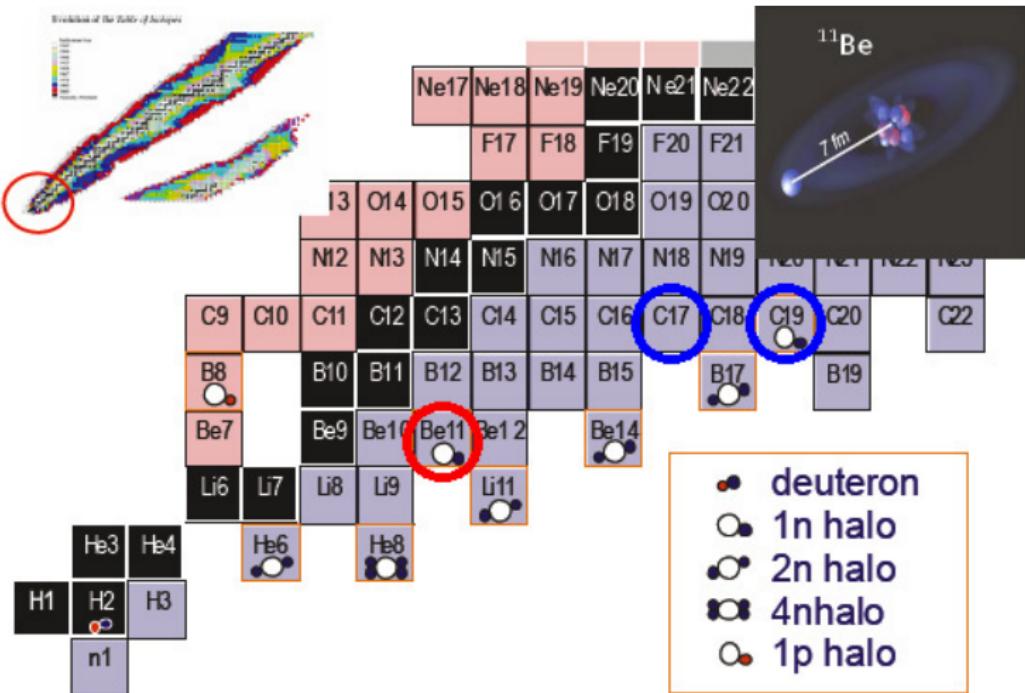
- Particle Rotor Model
- PAMD Model

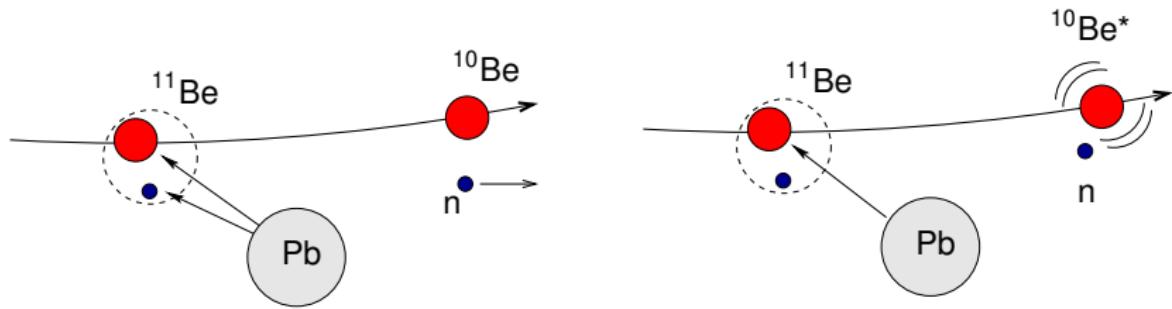
3 Reactions

- DWBAx
- XCDCC
- A long standing problem: ^{11}Be dipole response

4 Conclusions

Motivation





✗ Pure valence excitation

✓ Core-excitation mechanism



✗ No core excitations

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

✓ Core excitations

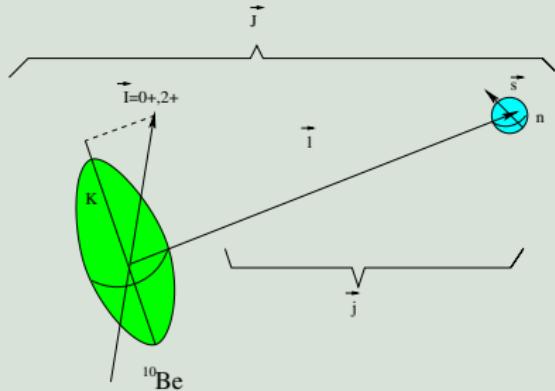
$$\begin{aligned} 1/2^+ = & \alpha |{}^{10}\text{Be}(0^+ \text{ g.s.}) \otimes \nu s_{1/2} \rangle \\ & + \beta |{}^{10}\text{Be}(2^+) \otimes \nu d_{5/2} \rangle + \dots \end{aligned}$$

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

Two options

Weak Coupling

⇒ h_{sp} is still a good approximation of H

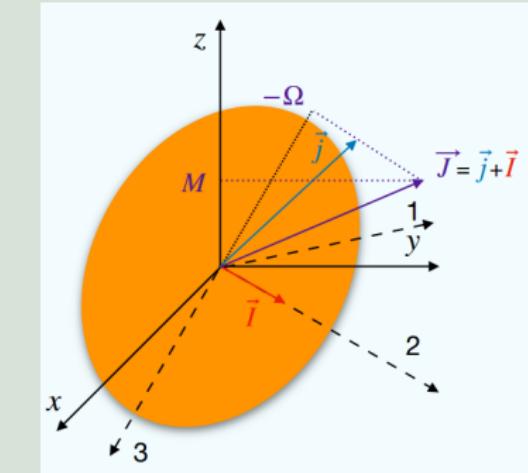


⇒ Different models:

- Particle-Rotor (PRM)
- Particle-Vibrator (PVM)
- Particle-AMD (PAMD)

Strong Coupling

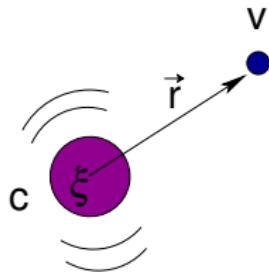
⇒ Start directly in a deformed potential ⇒ Nilsson Model



⇒ Talk by P. Punta on Thursday

Weak Coupling limit

Generalization of Pseudo-states (PS) discretization method



Hamiltonian with core excitation

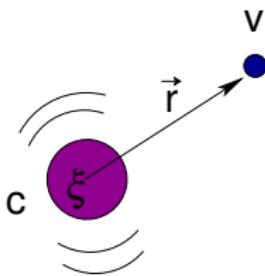
$$\mathcal{H}_p = T(\vec{r}) + h_{core}(\xi) + V_{NC}(\vec{r}, \vec{\xi})$$

We look for a basis including core degrees of freedom

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

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

Generalization of Pseudo-states (PS) discretization method



Hamiltonian with core excitation

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

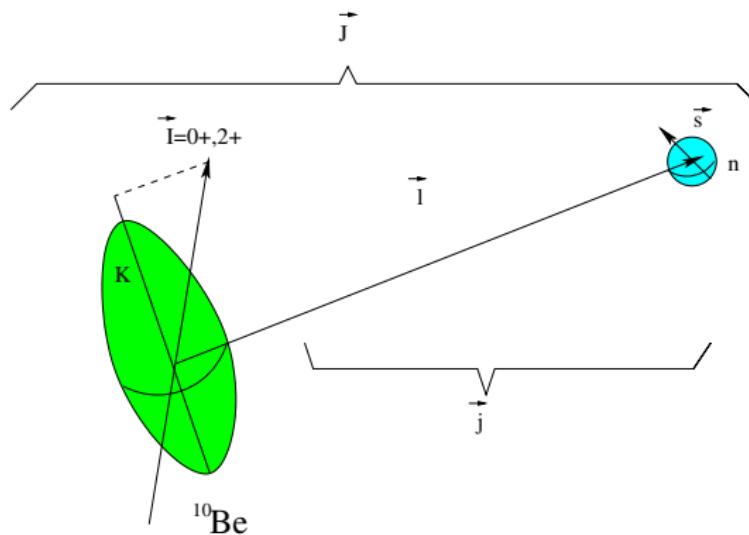
Set of \mathcal{L}^2 functions in this scheme:

$$\phi_{i,J_p}(\vec{r}, \vec{\xi}) = \sum_{\alpha} R_{i,\alpha}^{THO}(r) \left[\mathcal{Y}_{\ell s j}(\hat{r}) \otimes \varphi_I(\vec{\xi}) \right]_{J_p} \quad i = 1, \dots, N$$

⇒ Total number of functions: $N \cdot n_{\alpha}$

Particle Rotor Model

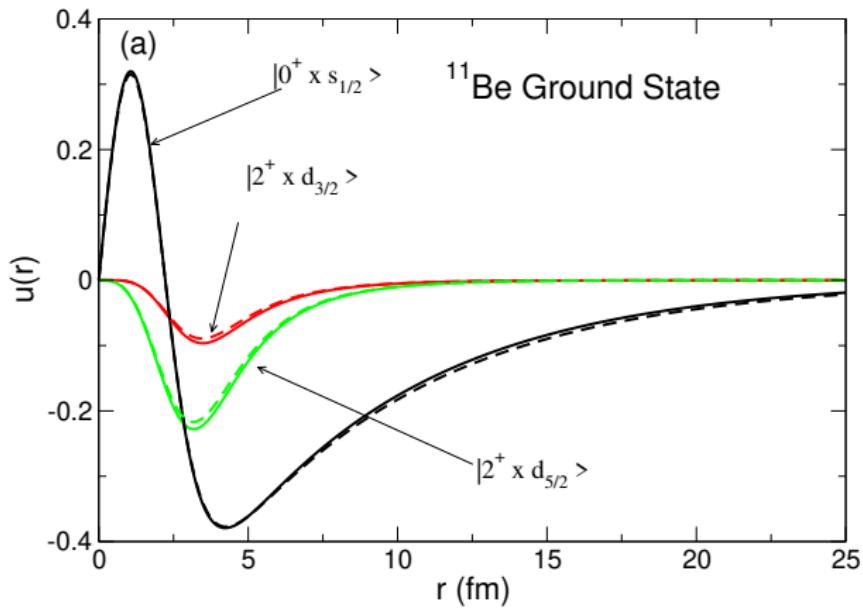
Particle-Rotor Model



$$V_{NC}(\vec{r}, \vec{\xi}) = V_{NC}(r - R_0[1 + \beta_2 Y_{20}(\theta', \phi')])$$

⇒ Deformation length is defined as $\delta_2 = R_0\beta_2$

Particle-Rotor Model



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

PRM “drawbacks”

PRM needs:

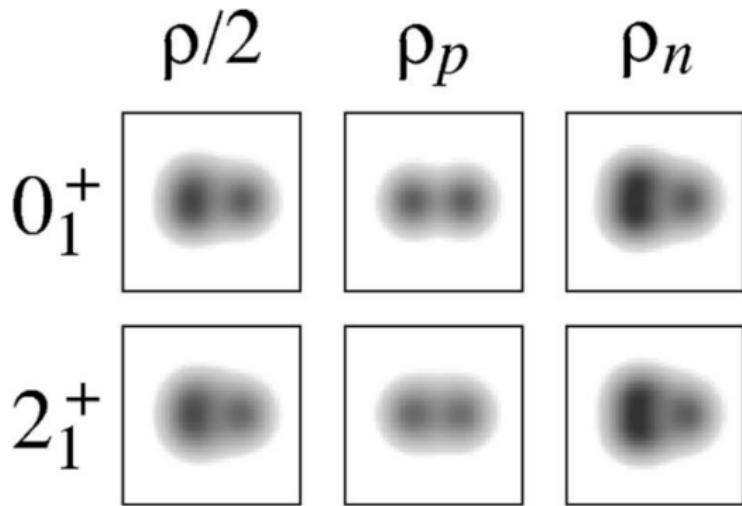
- The core to be a rotor
- A phenomenological potential based on the following parametres:

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

Particle-AMD Model

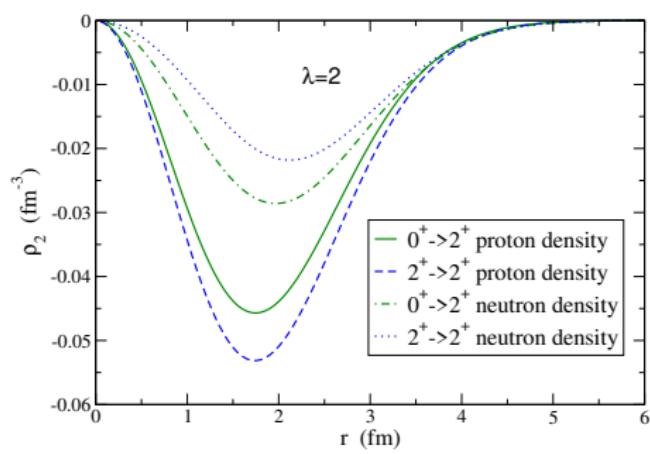
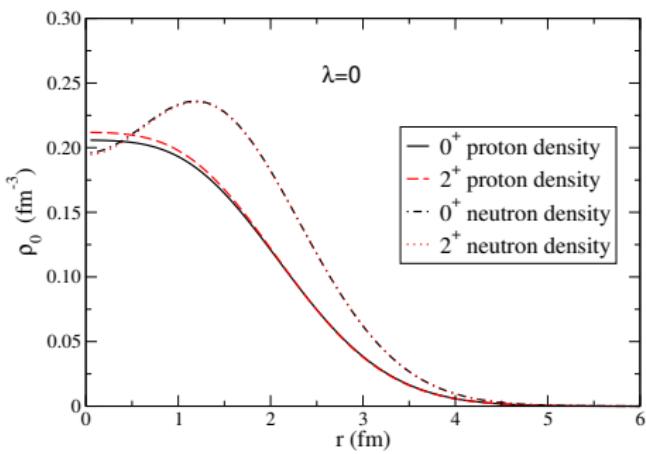
P-AMD

From Y. Kanada-En'yo and collaborators Phys. Rev. C 60, 064304 (1999)



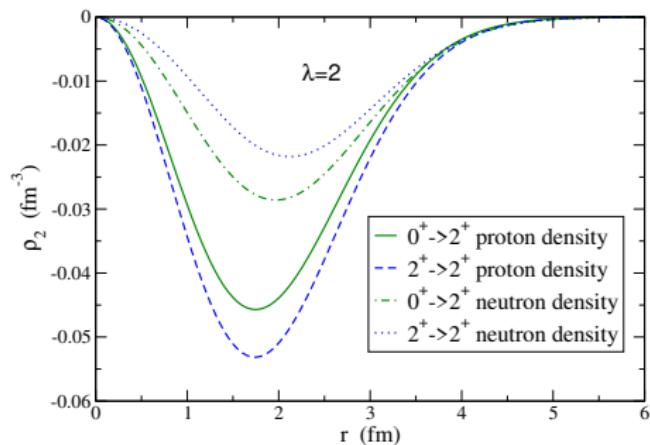
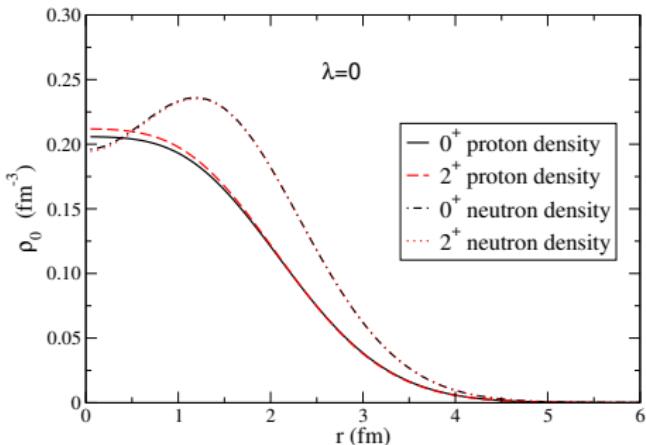
Densities from Antisymmetrized Molecular Dynamics (AMD)

P-AMD



Densities from Antisymmetrized Molecular Dynamics (AMD)

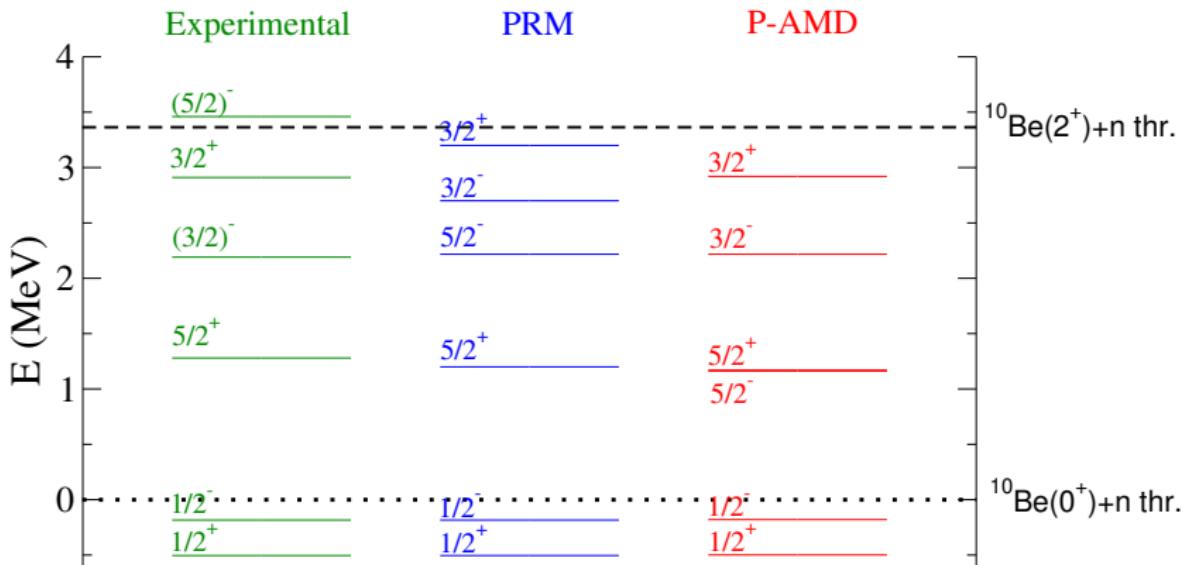
P-AMD



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

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

PRC89, 014333 (2014)

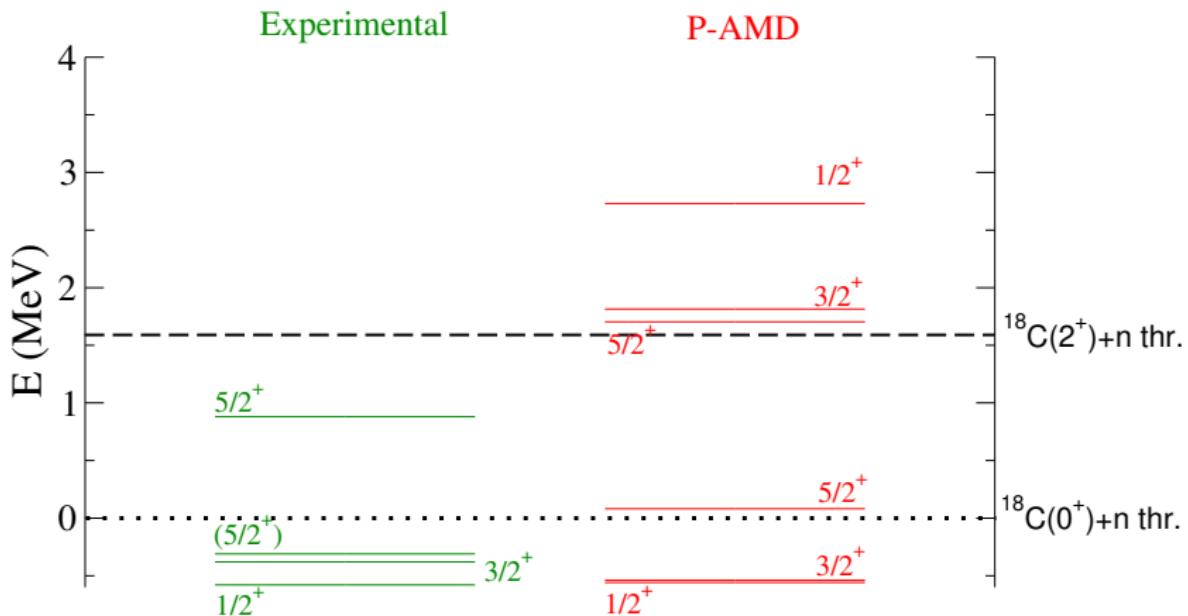


Renormalization factors

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

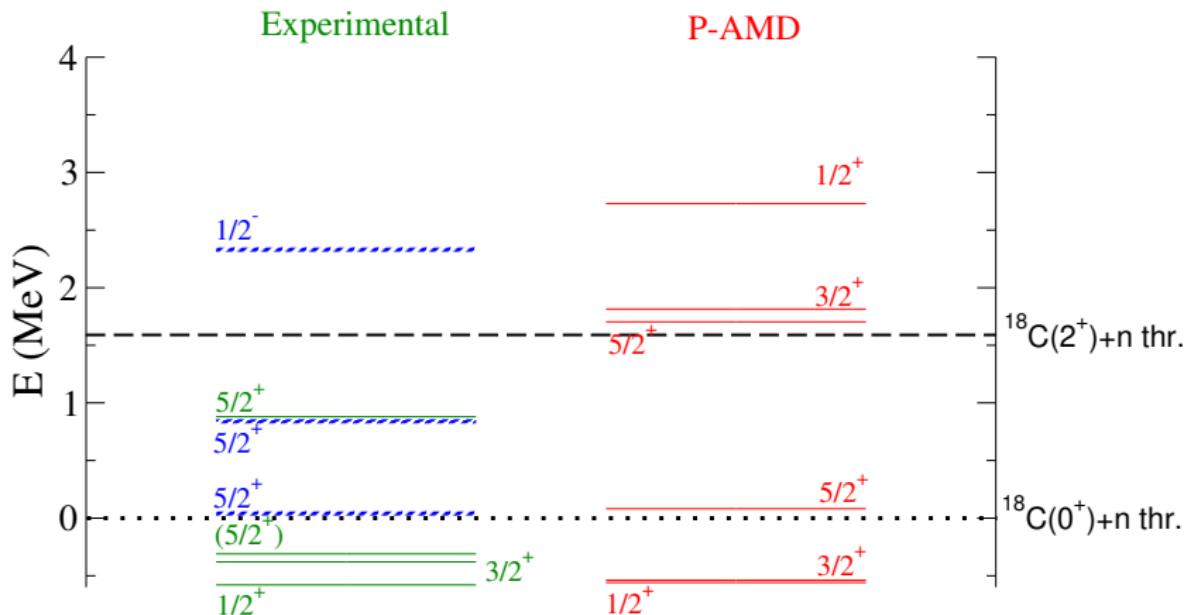
PRC 70, 054606 (2004); PRC 81, 034321 (2010); PLB 611, 239 (2005).

^{19}C Spectrum



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

^{19}C Spectrum



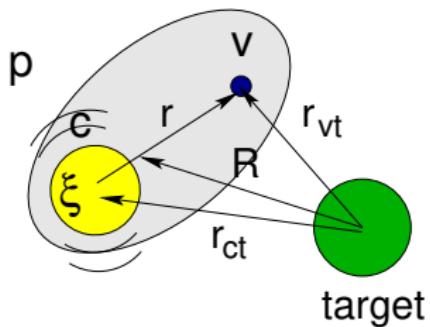
PLB 660, 320 (2008); PLB 614, 174 (2005) SAMURAI

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

Reactions

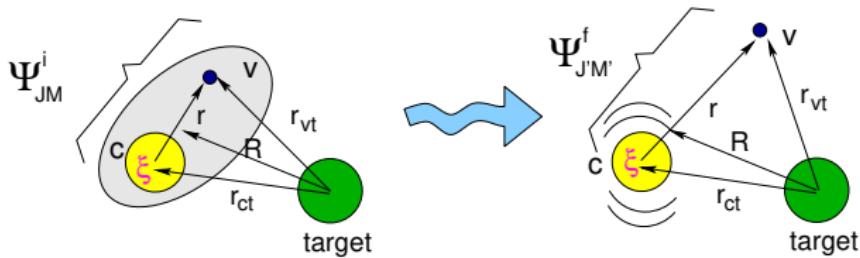
DWBAx or
NR-XDWBA

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)



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

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

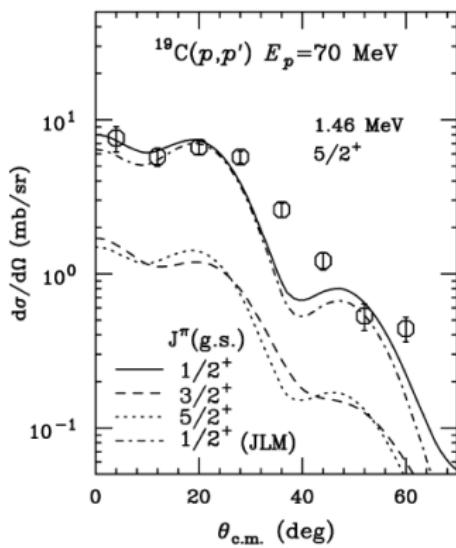
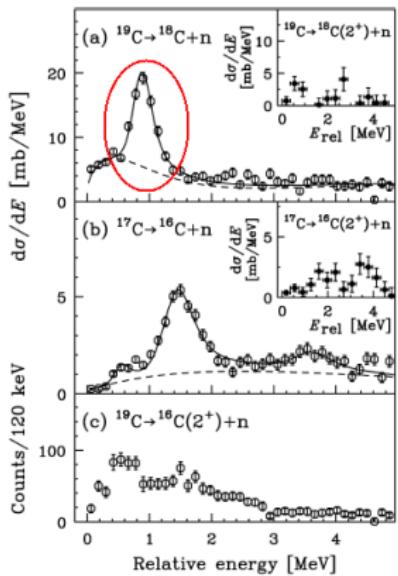
Only first order plus no-recoil:

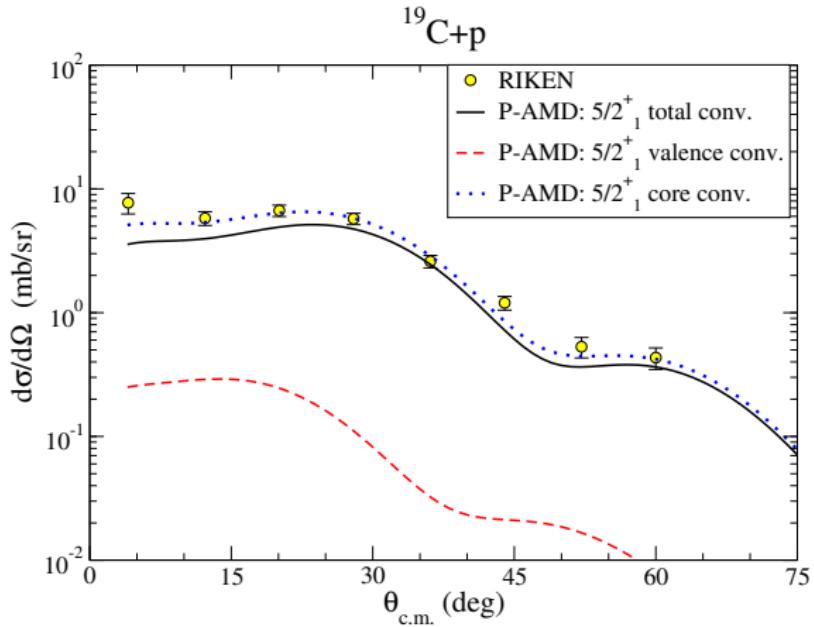
- ① $T_{val}^{JM, J'M'} \Rightarrow$ Valence excitations
 - ② $T_{core}^{JM, J'M'} \Rightarrow$ Core excitations
- \Rightarrow They explicitly separates in the calculation

A. M. Moro & R. Crespo, Phys. Rev. C 85, 054613 (2012)

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

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

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

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

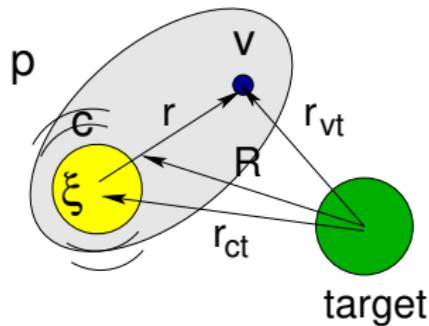
PRC94, 021602(R) (2016)

Reactions

XCDCC

Full CDCC

XCDCC calculations



Including core excitations in CDCC

- ⇒ DWBA only valid for intermediate and high energies
- ⇒ CDCC also includes the effect of break up in the elastic cross section

- Hamiltonian:

$$H_p = T_r + V_{vc}(\vec{r}, \xi) + h_{\text{core}}(\xi)$$

$$H = H_p + V_{vt}(r_{vt}) + V_{ct}(\vec{r}_{ct}, \xi)$$

- Model wavefunction:

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

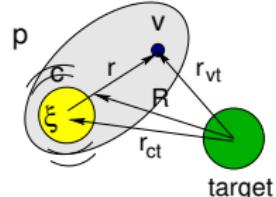
- Coupled equations: $[H - E]\Phi(\vec{R}, \vec{r}, \xi) = 0$

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

- Transition potentials:

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

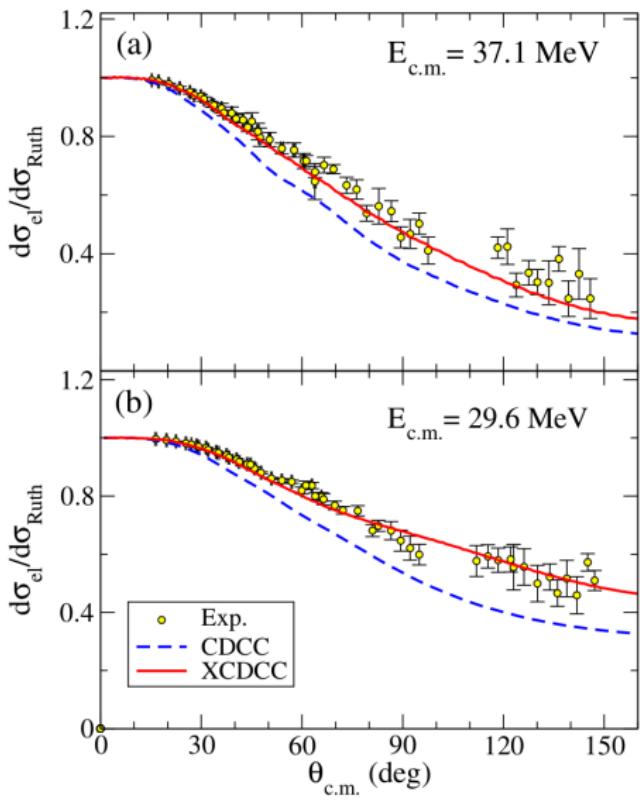
R. de Diego *et al*, PRC89 (2014) 064609 (PS discretization)
 also for binning Summers *et al*, PRC74 (2006) 014606



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

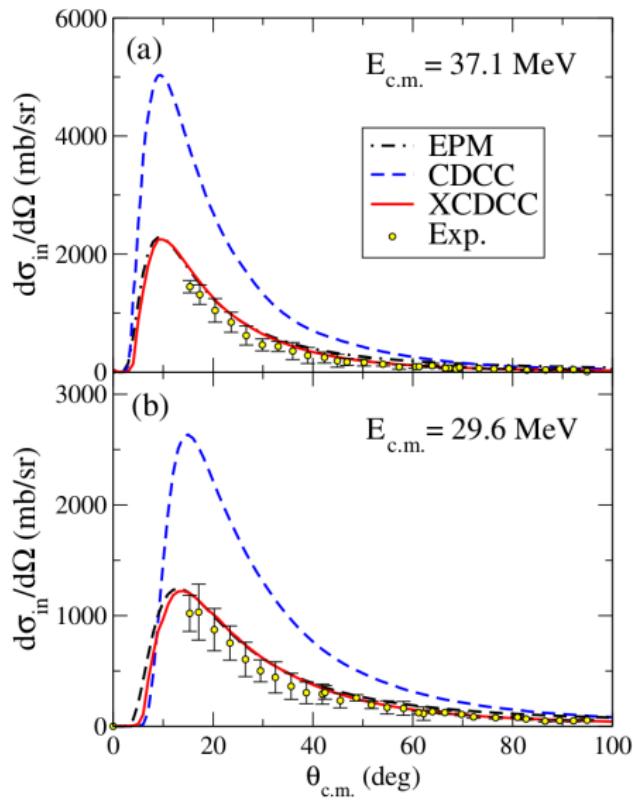
- Experiment: TRIUMF (Aarhus - LNS/INFN - Colorado - GANIL - Gothenburg -Huelva - Louisiana - Madrid - St. Mary - Sevilla - York collaboration)

☞ *V. Pesudo's PhD Thesis* and
Pesudo *et al.*, Phys. Rev. Lett. 118,
152502 (2017)



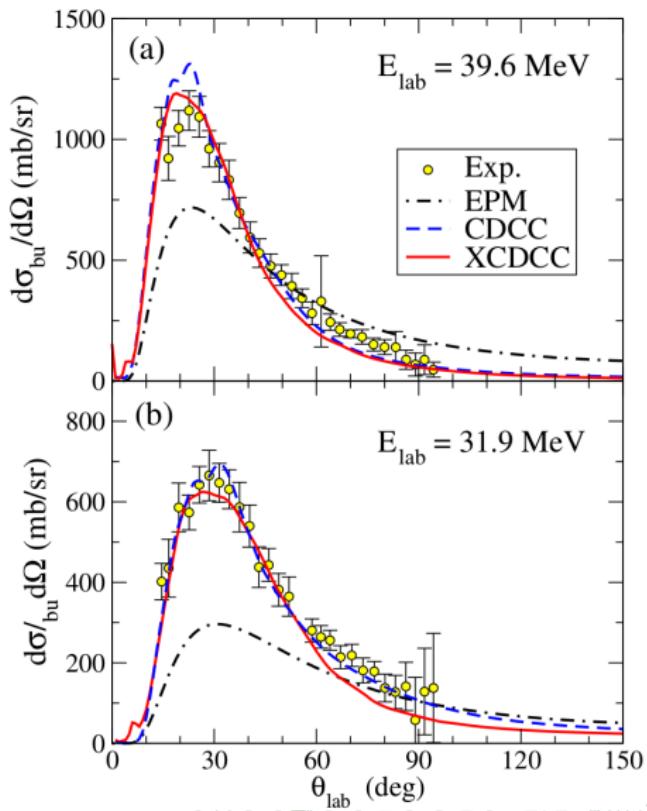
XCDCC calculations for $^{11}\text{Be} + ^{197}\text{Au}$ at sub-barrier energies

- Inelastic scattering probability:

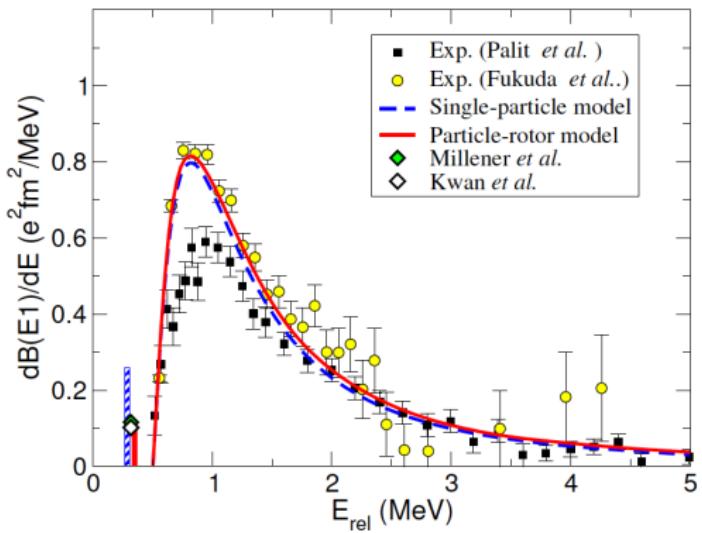


XCDCC calculations for $^{11}\text{Be} + ^{197}\text{Au}$ at sub-barrier energies

- Breakup scattering probability:

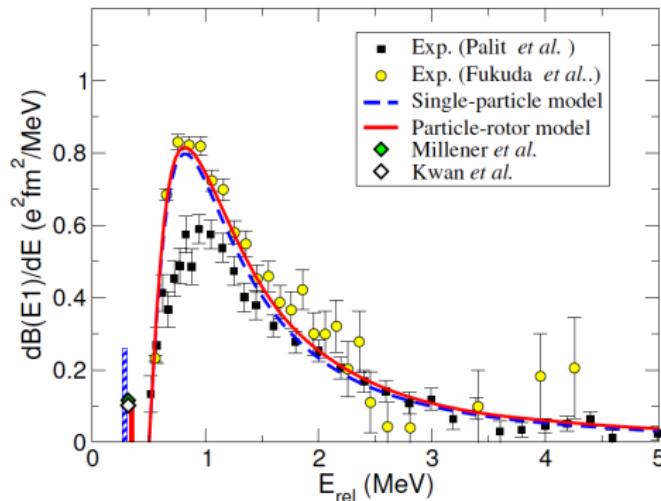
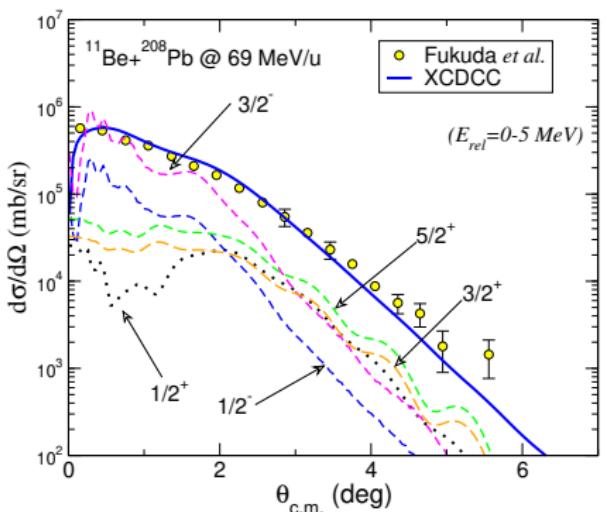


Electric B(E1) response of ^{11}Be



- The *inert-core* model of ^{11}Be cannot reproduce simultaneously the $B(E1)$ to bound and continuum states \Rightarrow cannot reproduce simultaneously inelastic and breakup.

XCDCC calculations for $^{11}\text{Be} + ^{208}\text{Pb}$ at 69 MeV/u



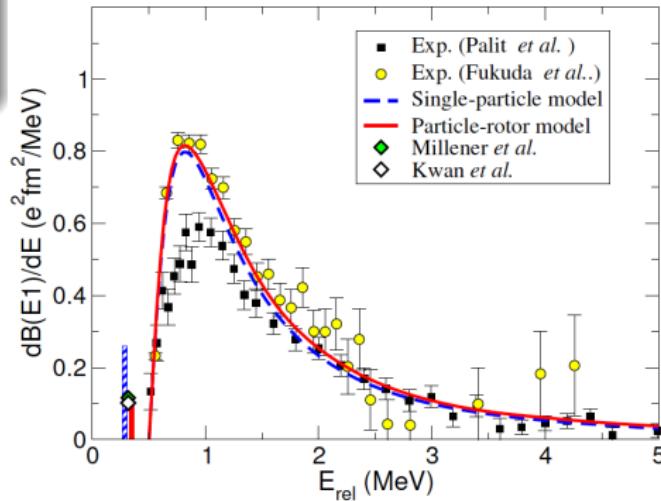
- Confirm dominance of $E1 (1/2^-, 3/2^-)$ for $\theta \ll$
- Dynamic** core excitation small, but mixing of core states important.
- Breakup treated to all orders.

A long-standing problem...

Equivalent Photon Method

⇒ Only includes first order
Coulomb excitation.

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

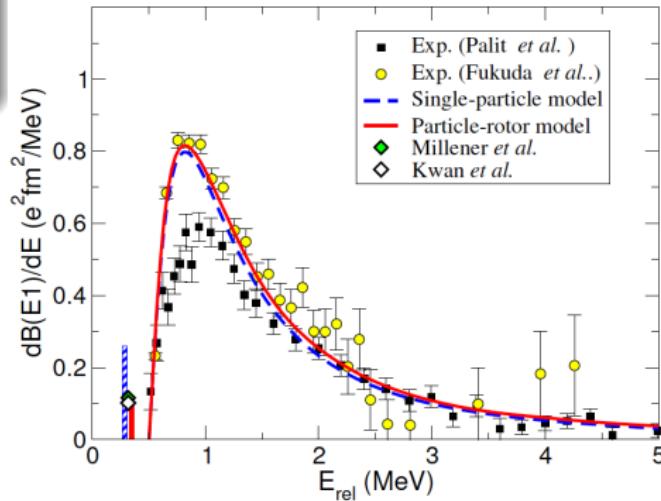


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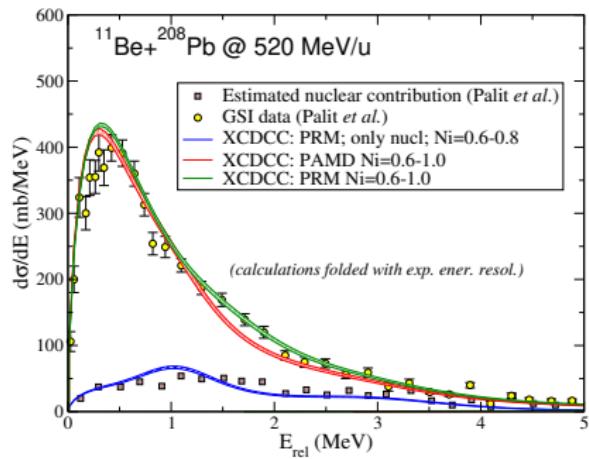
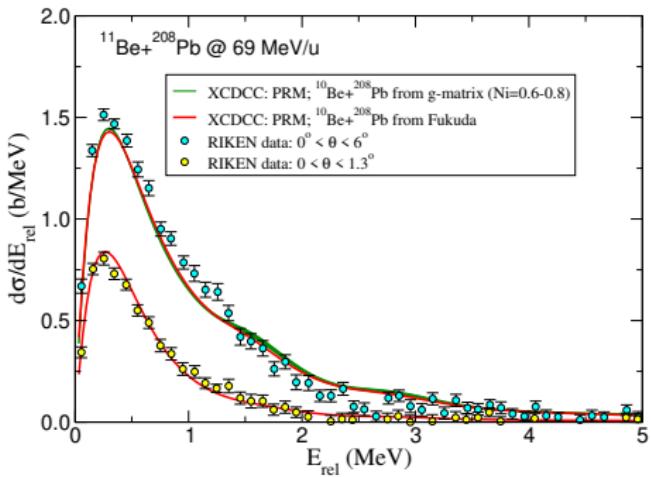
$$\frac{d\sigma_\lambda}{d\Omega \, dE} \Big|_{bu} = \frac{4\pi^3}{9} \frac{d\mathcal{B}(E1)}{dE} \frac{dN_{E1}}{d\Omega}$$



?

Can we do it better?

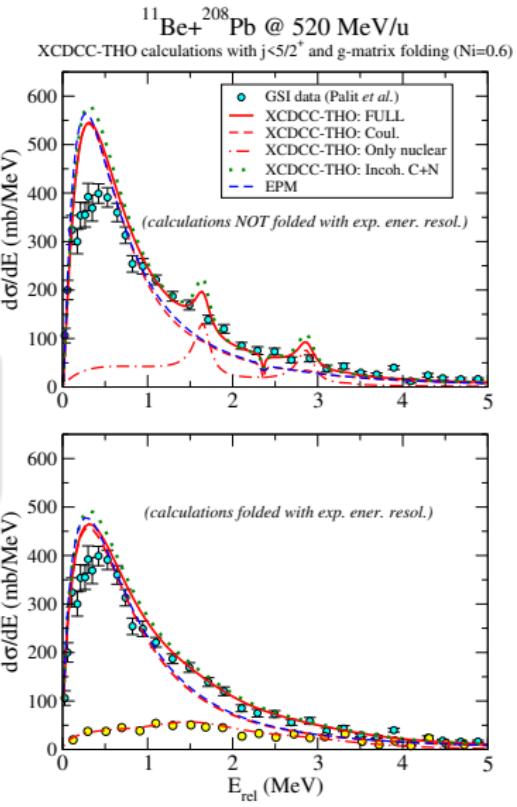
A long-standing problem...



A long-standing problem...

Different source of deviation:

- Convolution with exp. resolution
- Coul-Nucl interference



A long-standing problem...

? Can we extract the $B(E1)$ better?

$$M^m(E1, \varepsilon_i) \simeq M^0(E1, i)(1 + \delta(\varepsilon_i)),$$

$$B^m(E1, \varepsilon_i) \simeq B^0(E1, i)(1 + 2\delta(\varepsilon_i)),$$

$$\sigma_i^m \simeq \sigma_i^0 + \delta(\varepsilon_i) \sigma'_i.$$

A long-standing problem...

? Can we extract the $B(E1)$ better?

$$M^m(E1, \varepsilon_i) \simeq M^0(E1, i)(1 + \delta(\varepsilon_i)),$$

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$$\sigma_i^m \simeq \sigma_i^0 + \delta(\varepsilon_i) \sigma'_i.$$

I can invert the relation:

$$B^m(E1, \varepsilon_i) \simeq B^0(E1, \varepsilon_i) \left(1 + 2 \frac{\sigma_i^m - \sigma_i^0}{\sigma'_i}\right).$$

And if you want to arrive to the experimental cross section:

$$B^e(E1, \varepsilon_i) \simeq B^0(E1, \varepsilon_i) \left(1 + 2 \frac{\sigma_i^e - \sigma_i^0}{\sigma'_i}\right).$$

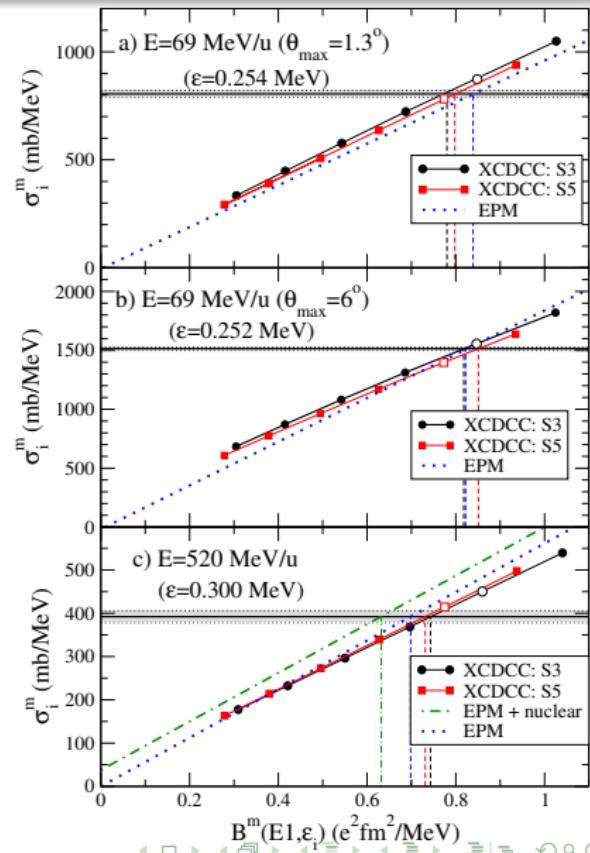
A long-standing problem...

?

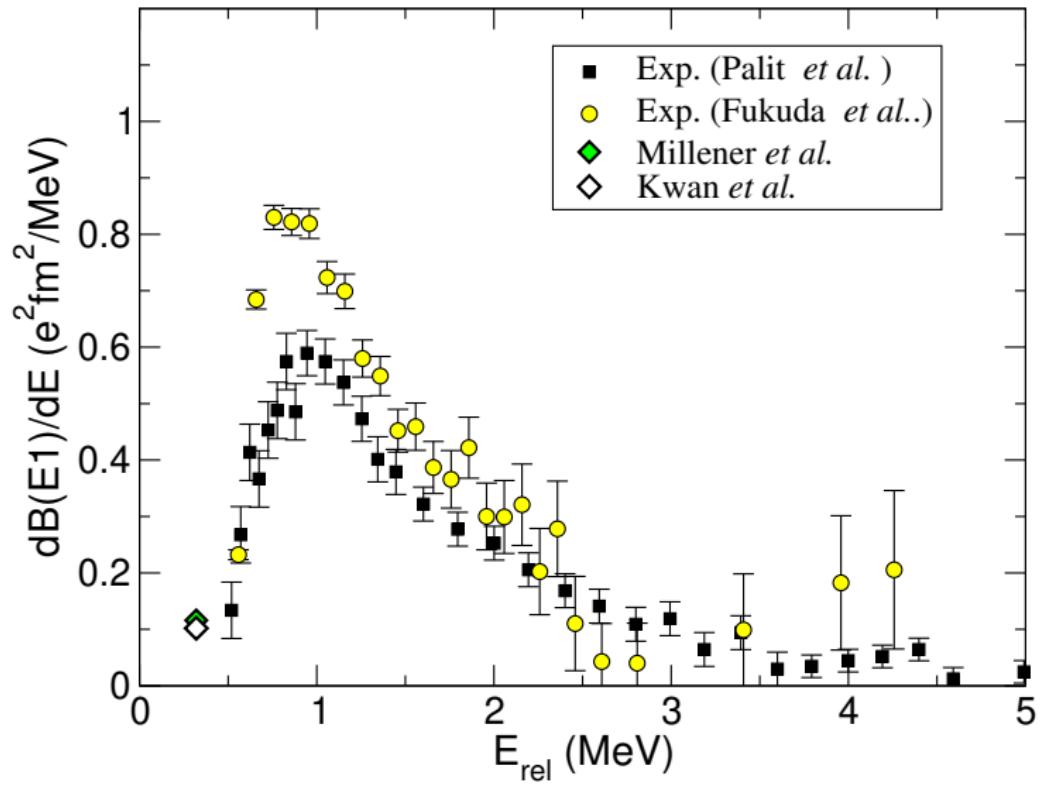
Is it really linear?

$$B^m(E1, \varepsilon_i) \simeq B^0(E1, \varepsilon_i) (1 + 2\delta(\varepsilon_i)).$$

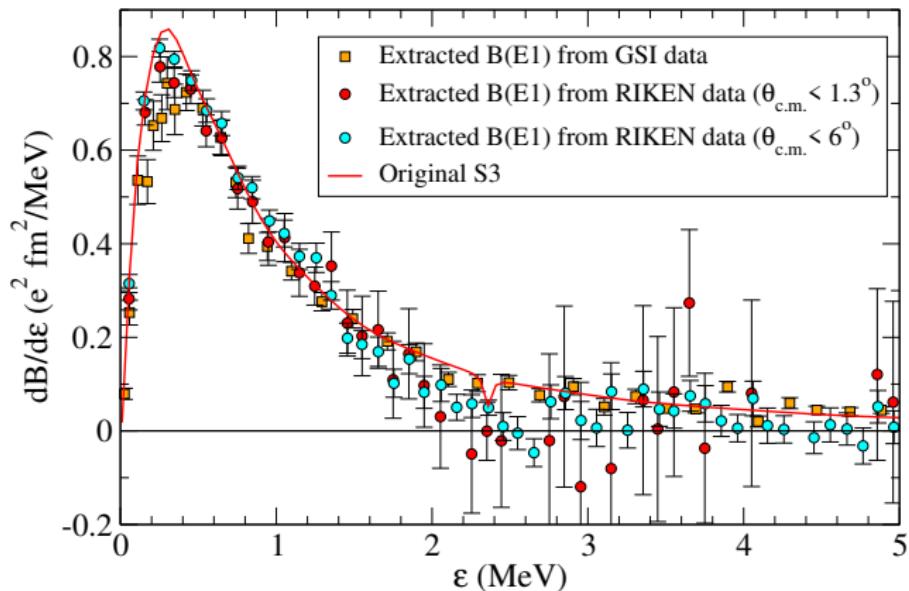
$$\sigma_i^m \simeq \sigma_i^0 + \delta(\varepsilon_i) \sigma'_i.$$



A long-standing problem... No more.



A long-standing problem... No more.



⇒ And it does not depend on experimental resolution (up to a point)

A. M. Moro, J. A. Lay, J. Gómez-Camacho PLB811, 135959 (2020)

Conclusions

P-AMD

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

Break up Reactions

- The interplay between core and valence contributions is crucial to understand resonant break up of halo nuclei
- Full XCDCC will clarify the effects of core excitations in different observables (elastic, energy distributions, inclusive data)
- We open the possibility to extract $B(E1)$ from XCDCC calculations

Thank you!!

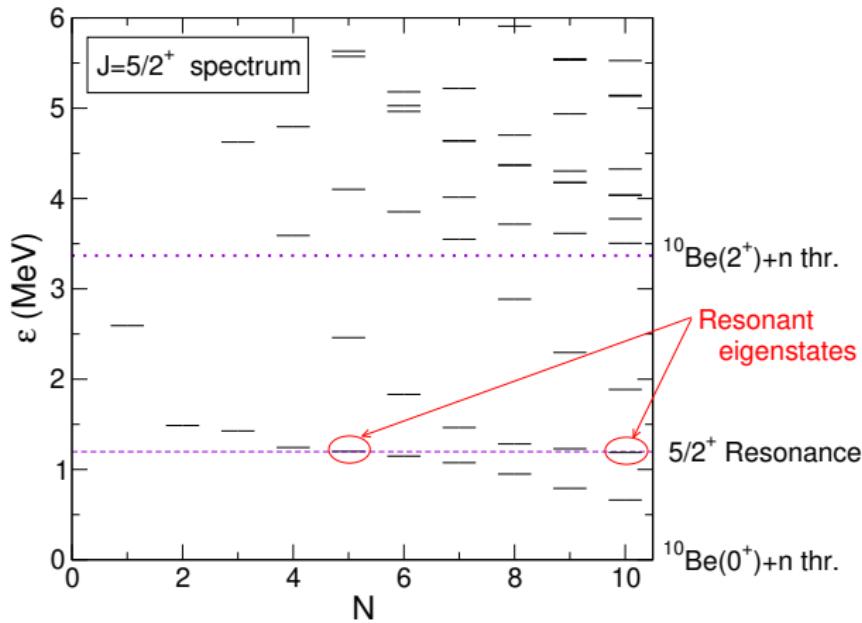


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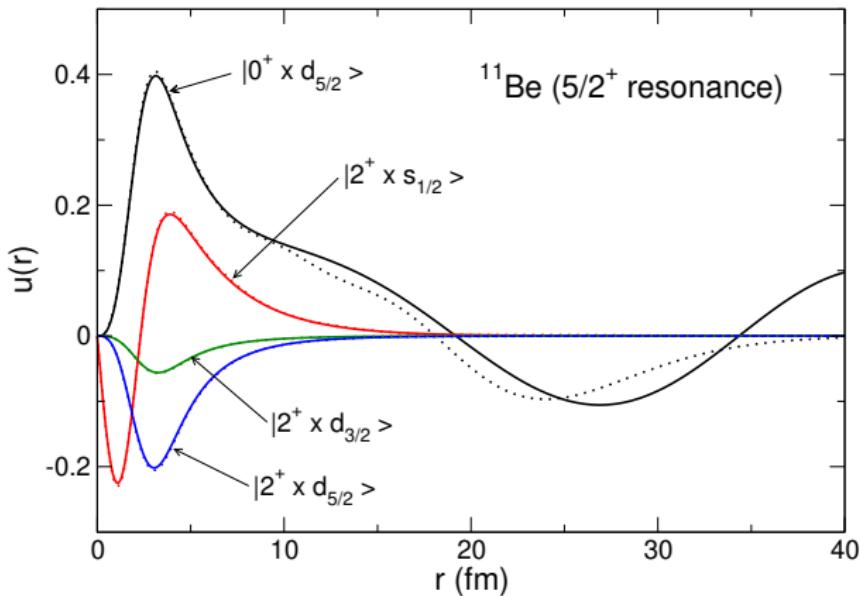


PAIDI P20-01247
ERDF "A way of making Europe"

Spectrum



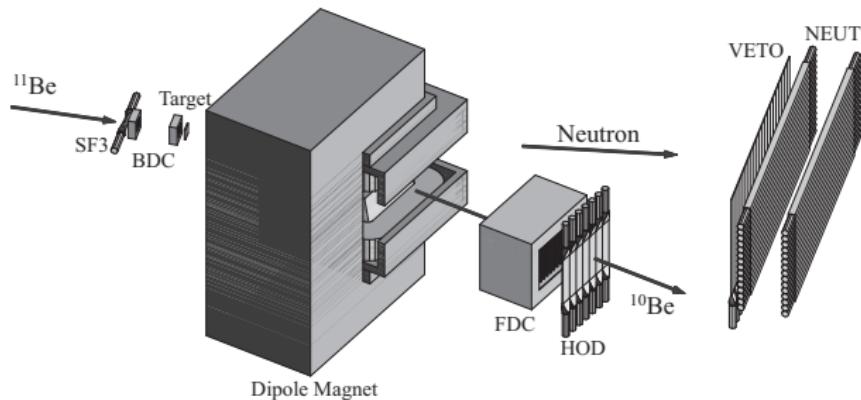
Particle-Rotor Model



Continuum resonances are also well described by the THO basis

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

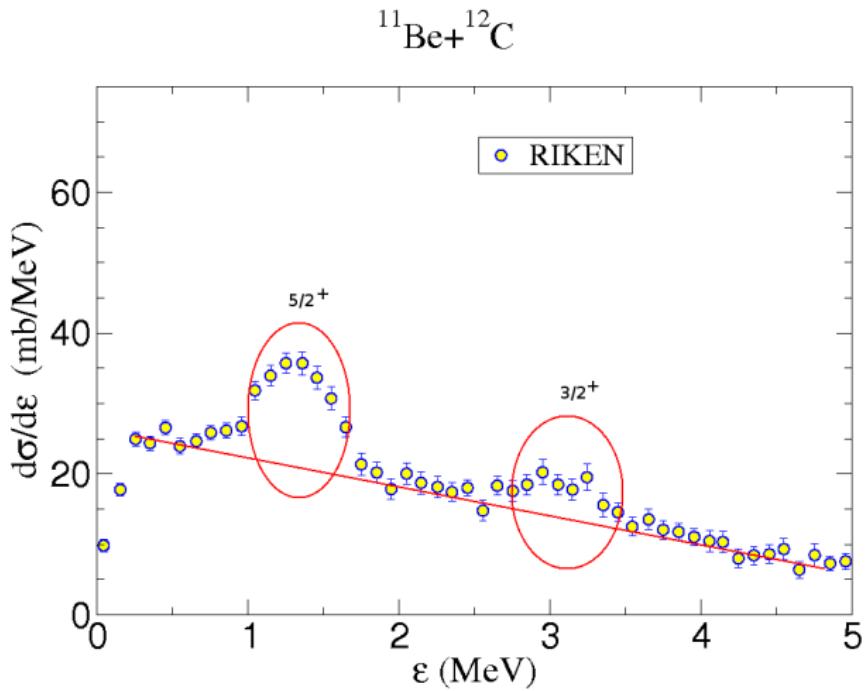
RIKEN: N. Fukuda *et al.*, Phys. Rev. C70, 054606 (2004)



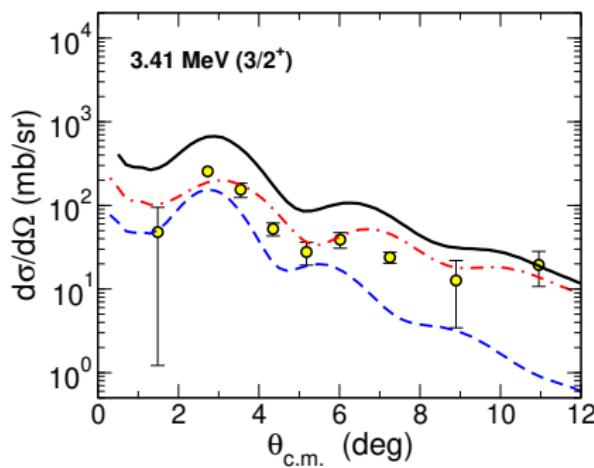
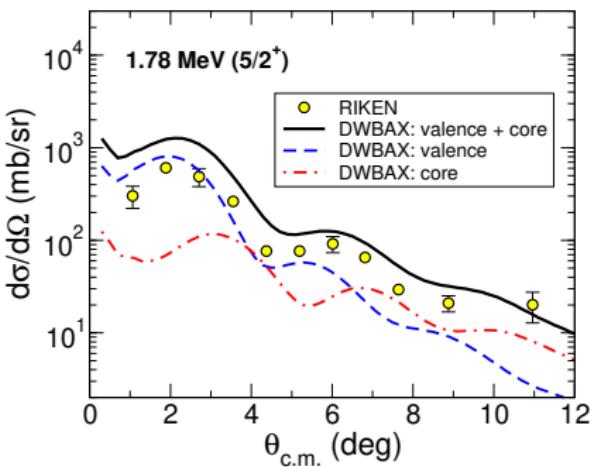
⇒ Measurement of Break up Cross Sections of ^{11}Be on ^{12}C and ^{208}Pb

$^{11}\text{Be} + ^{12}\text{C}$ @ 67 MeV/u

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

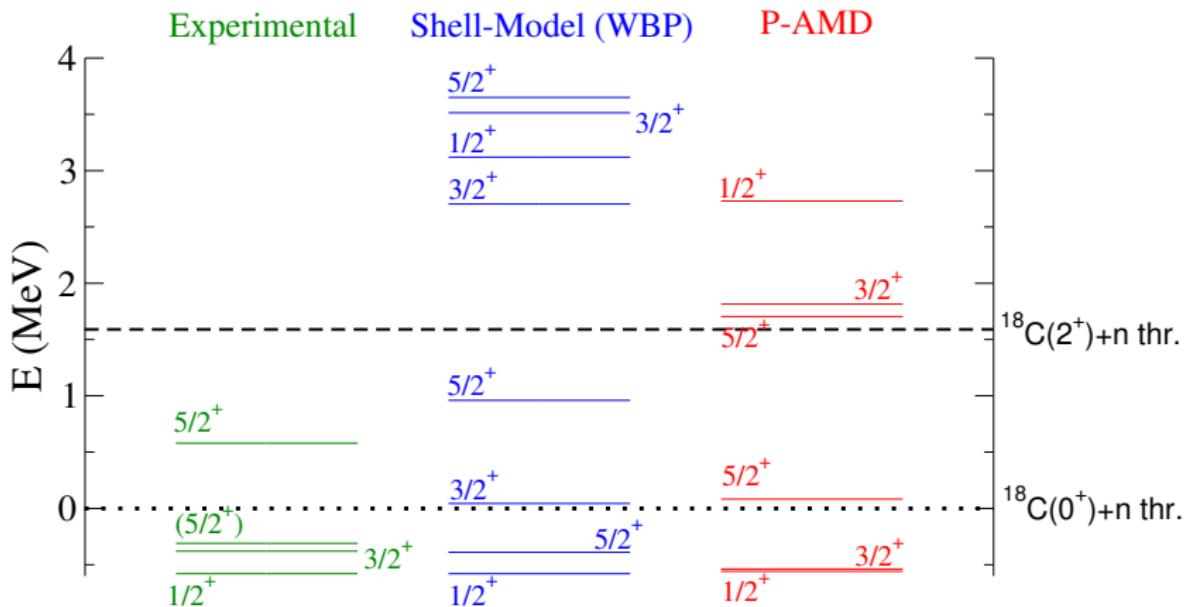


$^{11}\text{Be} + ^{12}\text{C}$ @ 67 MeV/u



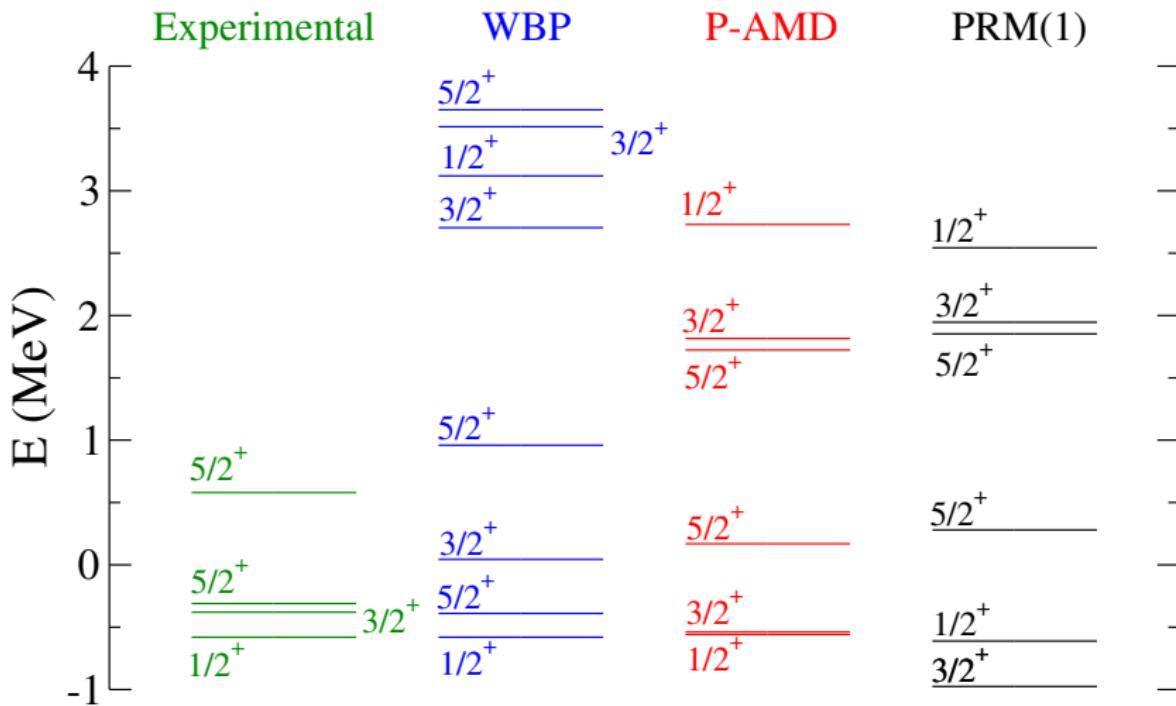
- ⇒ A. M. Moro & J. A. Lay, Phys. Rev. Lett. 109, 232502 (2012)
- ⇒ Fitted spectroscopic factors: EPJ WoC 66, 03053 (2014)

^{19}C Spectrum



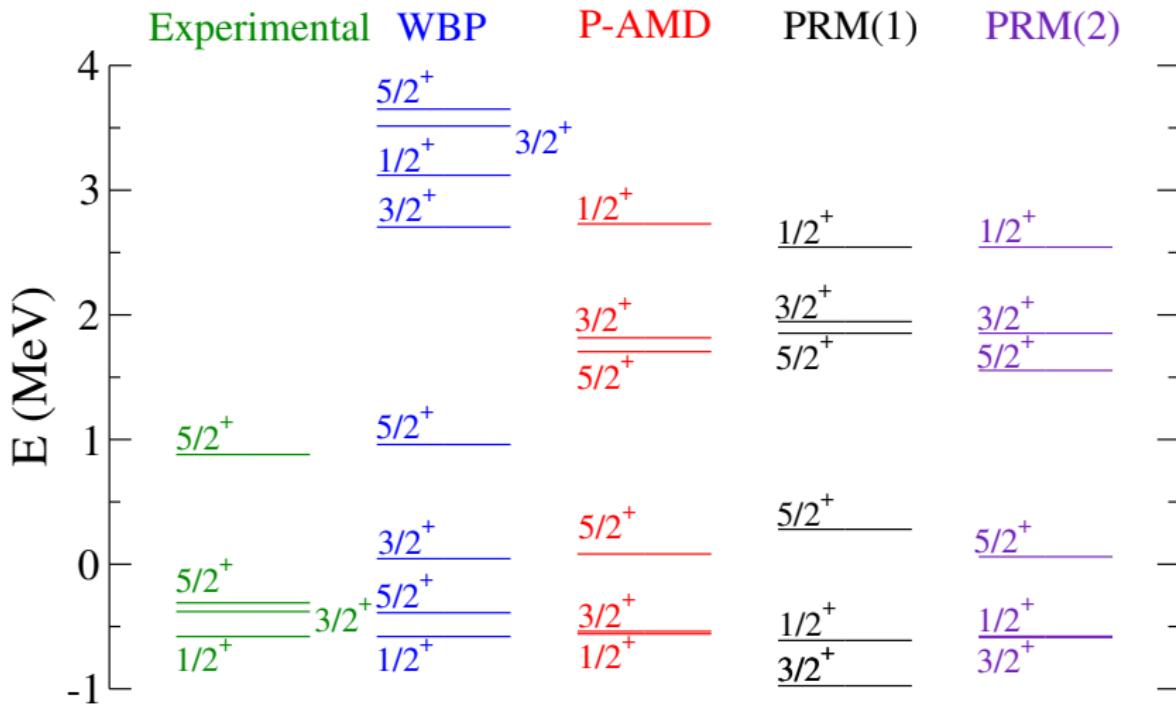
PL B 660, 320 (2008); PL B 614, 174 (2005).

^{19}C Spectrum



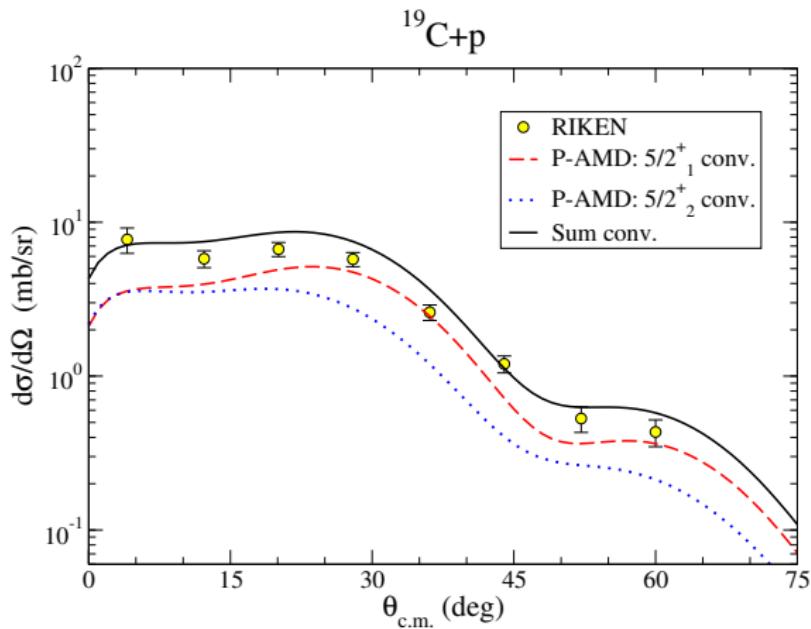
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^{19}C Spectrum



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

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



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$
$1/2^+$	P-AMD	0.849	—	0.031	0.121
	WBT	0.762	—	0.002	0.184
$5/2^+$	P-AMD	0.674	0.189	0.014	0.124
	WBT	0.682	0.177	0.009	0.095
$3/2^+$	P-AMD	0.316	0.565	0.031	0.089
	WBT	0.068	0.534	0.008	0.167