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Linking structure and dynamics in (p, pN) reactions induced by exotic nuclei

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1. Motivation
2. A formalism for (p, pN) reactions
3. Testing the reaction model for binary systems
4. Application to Borromean systems

1 Motivation

2 A formalism for (p, pN) reactions

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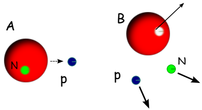
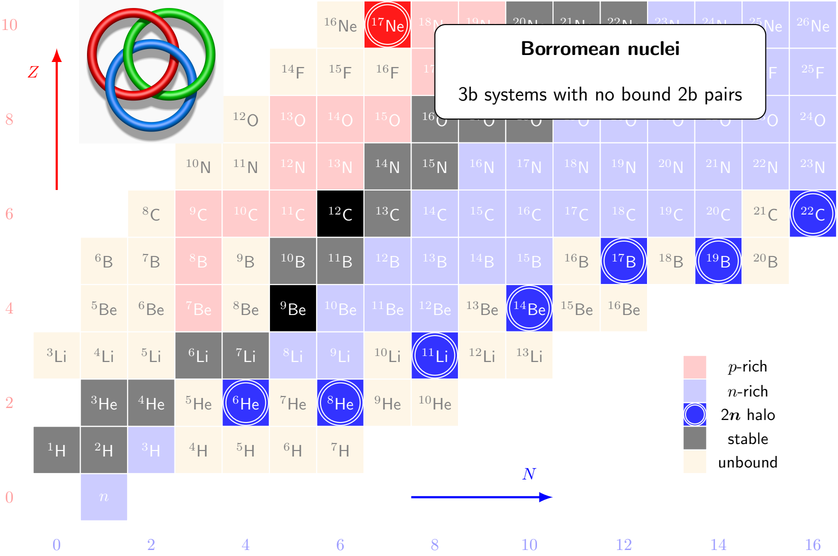
4 Application to Borromean systems





Borromean nuclei

3b systems with no bound 2b pairs

Accessing the structure of Borromean nuclei

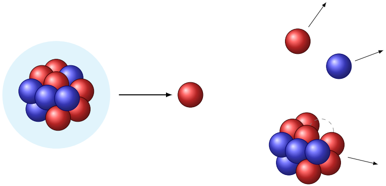
- Understanding the structure of 3-body Borromean nuclei (exotic or not) requires a proper knowledge of the binary sub-systems and excitations/correlations of the core.

- Different reaction observables probe different aspects of these properties. Eg., for ^{11}Li:
  - Exclusive breakup: ^{11}Li $+^{208}$Pb $\rightarrow$ ^{10}Li+n $+^{208}$Pb
  - 1n-transfer: ^{11}Li(p,d)^{10}Li*
  - 2n-transfer: ^{11}Li(p,t)^{9}Li(gs,exc)
  - Knockout: ^{11}Li $+$A $\rightarrow$ ^{10}Li* $+$ X $\rightarrow$ ^{9}Li+n $+$X
  - ...

- In all these reactions, a crucial aspect is how the structure input is linked to the reaction observables

(p, pN) "knockout" reactions in inverse kinematics

- Fast-moving projectile collision with proton target
  One nucleon is removed, leaving the residue in ground or excited state



- High energies to increase mean free path of nucleon inside nucleus
- Structure information inferred from:

Total removal 1N cross sections $\Rightarrow$ spectroscopic factors

Momentum distrib. of residue $\Rightarrow$ orbital ang. momentum

γ and particle decay of residue $\Rightarrow$ exc. states, resonances, virt. states

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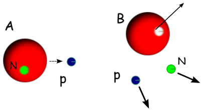
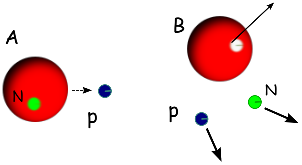


Transfer to the Continuum (TC)

- No IA assumed
- No factorization approximation
- Links dynamics with underlying many-body structure



➢ Assuming a participant/spectator mechanism the (prior-form) T-matrix is:

$$\mathcal{T}_{if} = \left\langle \phi_B(\xi_B)\Psi_f^{(-)}(\vec{r}_p, \vec{r}_N) \middle| V_{pN} + U_{pB} - U_{pA} \middle| \Phi_A(\xi_A)\chi_{pA}^{(+)}(\vec{R}) \right\rangle,$$

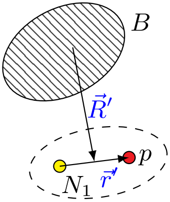
$\Phi_A(\xi_A) \equiv$ g.s. wave function of the projectile A

$\phi_B(\xi_B) \equiv$ continuum wave function of the residual B

$\Psi_f \equiv$ final $(p + N + B$ wave function

$\chi_{pA} \equiv$ distorted p-A wave

Final wave function

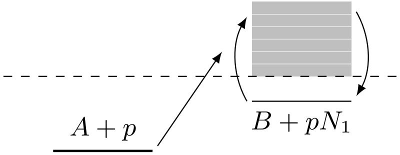


➢ Expanded in proton-nucleon states ($\sim$ CDCC)

$$\boxed{\Psi_f(\vec{r}', \vec{R}') \simeq \sum_{n,j^\pi} \tilde{\phi}_n^{j^\pi}(k_n, \vec{r}')\chi_n^{j^\pi}(\vec{K}', \vec{R}')}$$

➢ Basis of discretized bins

$$\tilde{\phi}_n^{j^\pi}(k_n, \vec{r}') = \sqrt{\frac{2}{\pi N}} \int_{k_{n-1}}^{k_n} \phi_{pN}^{j^\pi}(k, \vec{r}')dk.$$



➢ If we select the (p, d) channel TC reduces to DWBA

$$\boxed{\Psi_f(\vec{r}', \vec{R}') \simeq \phi_d(\vec{r}')\chi_{d\text{-}B}(\vec{R}')}$$

Structure overlaps

- Under the spectator assumption, V_{prior} does not modify B:

$$\boxed{\mathcal{T}_{if} = \left\langle \Psi_f^{(-)}(\vec{r}_p, \vec{r}_N) \middle| V_{pN} + U_{pB} - U_{pA} \middle| \chi_{pA}^{(+)}(\vec{R}) \varphi_{BA}(\vec{r}_N) \right\rangle}$$

with

$$\boxed{\varphi_{BA}(\vec{r}_N) = \langle \phi_A | \phi_B \rangle}$$

- $\langle \phi_A | \phi_B \rangle$ can in principle be evaluated from many-body wave functions of A and B but, most commonly, will be approximated by some simpler forms, such as single-particle form-factors.

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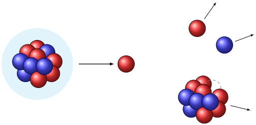


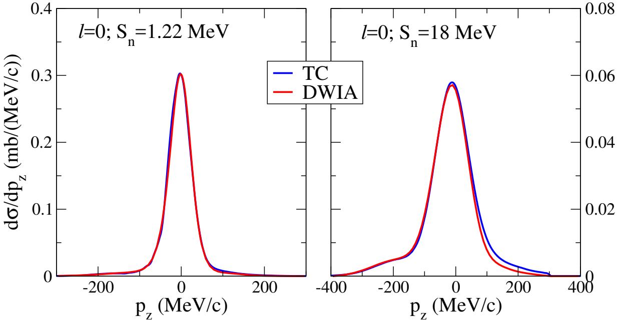
Benchmark with simple SP formfactors

- Assume single-particle overlaps:

$$\boxed{\langle \phi_A | \phi_B \rangle \approx \sqrt{S_{I_c,n\ell j}}\varphi_{n\ell,j}(\vec{r})}$$

- Realistic NN interaction from Reid93.
- N-nucleus potentials from folding (Paris-Hamburg g-matrix) or phenomenological OMP's (KD, Dirac).
- Relativistic corrections included approximately.

Benchmark with DWIA: $^{15}C(p, pn)^{14}C$ @ 420 MeV/A



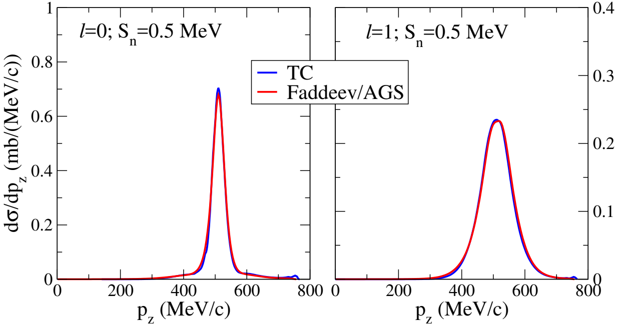
☞ Good agreement with DWIA for weakly-bound and deeply-bound nucleons

[K. Yoshida, M. Gómez-Ramos, K. Ogata, A.M.M., arXiv:1711.04458]

(collaboration with K. Yoshida and K. Ogata)

Benchmark with Faddeev: ^{11}Be$(p, pn)^{10}$Be @ 200 MeV/A

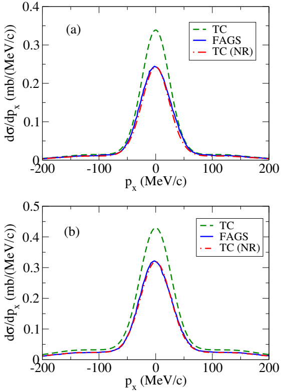
- Neutron removal from $2s_{1/2}$ and (hypothetical) $1p_{1/2}$ orbitals in ^{11}Be
- Simple Gaussian NN interaction



☞ Good agreement, but more realistic benchmarks (eg. realistic NN) needed (in progress).

(collaboration with A. Deltuva)

Benchmark with Faddeev: $^{15}\mathrm{C}(p, pn)^{14}\mathrm{C}$ @ 420 MeV/A



(a) With distorting potentials (KD OMP)
(b) Without distortion potentials

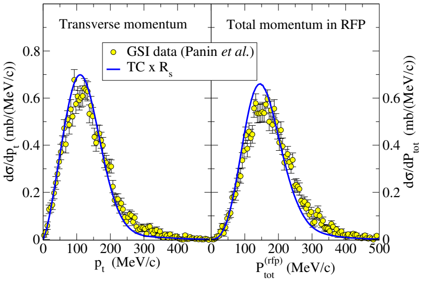
- Good agreement with Faddeev w/o relativistic corrections
- Relativistic kinematics important at these energies!

Faddeev/AGS calculation from E. Cravo et al, PRC93, 054612 (2016)

Comparison with ^{12}C$(p,2p)^{11}$B @ 400 MeV/A

- Exp. data from GSI: Panin *et al.*, PLB753 (2006)204
- Momentum distributions summed over ^{11}B b.s. $(I_c^\pi{=}3/2_1^-, 1/2_1^-, 3/2_2^-)$
- HF-constrained SP overlaps for $\langle ^{12}\mathrm{C}|^{11}\mathrm{B}(I_c^\pi)\rangle \approx \sqrt{S_{I_c,n\ell j}}\varphi_{n\ell,j}(\vec{r})$

$$\boxed{\sigma_{\text{-1n}} = \sum_{I_c,n\ell,j} S_{I_c,n\ell j} \times \sigma_{sp}^{I_c,n\ell j}}$$



σ_{exp} (mb)	$\sigma_{\text{th}}(*)$ (mb)	$R_s(**)$ $(\sigma_{\text{exp}}/\sigma_{\text{th}})$
19.2(18)(12)	27.81	0.69

(*) Shell-model (WBT) SFs
(**) "Quenching" factor.

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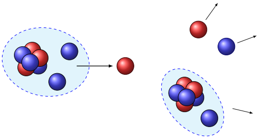
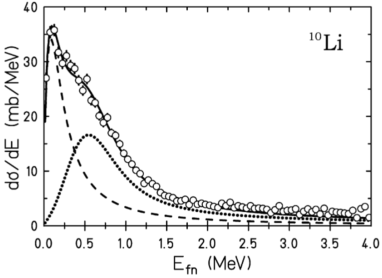


^{11}Li$(p, pn)^{10}$Li in inverse kinematics at 280 MeV/u *

ALADIN-LAND setup at GSI [Aksyutina *et al.*, PLB 666 (2008) 430]



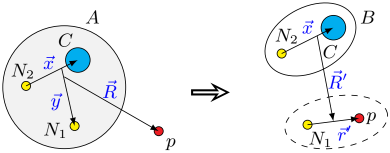
➢ spectroscopic information extracted through fitting with assumed shapes (eg. Breit-Wigner)

➢ reaction dynamics not considered

*More recent data from RIKEN is coming

TC for 3-body projectiles

- 3-body structure explicitly included
- Participant (N_1) / spectator (B) assumption



➢ Prior-form transition matrix:

$$\mathcal{T}_{if} = \left\langle \varphi_B^{2b}(\vec{q},\vec{x})\Psi_f^{(-)}(\vec{r}\,',\vec{R}') \middle| V_{pN_1} + U_{pB} - U_{pA} \middle| \Phi_A^{3b}(\vec{x},\vec{y})\chi_{pA}^{(+)}(\vec{R}) \right\rangle ,$$

where

$$\varphi_B^{2b}(\vec{q},\vec{x}) \equiv \text{continuum wave function of the binary fragment } B$$

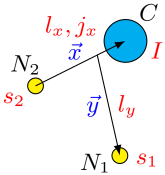
$$\Psi_f \equiv \text{final } p + (N_2+B) \text{ relative wave function}$$

$$\Phi_A^{3b} \equiv \text{g.s. wave function of the initial 3b composite } A$$

$$\chi_{pA} \equiv \text{distorted } p\text{-}A \text{ wave}$$

[M. Gómez-Ramos, J. Casal, A.M.M., PLB 772 (2017) 115]

3b g.s. wave function of $A \Rightarrow$ HH expansion



$$\beta \equiv \{K, l_x, j_x, j_1, l_y, j_2\}$$

$$\vec{l}_x + \vec{s}_2 = \vec{j}_x, \quad \vec{j}_x + \vec{I} = \vec{j}_1$$
$$\vec{l}_y + \vec{s}_1 = \vec{j}_2, \quad \vec{j}_1 + \vec{j}_2 = \vec{j}$$

Diagonalize $\mathcal{H}_{3b}$ in THO basis using: [*J. Casal et al, PRC 88 (2013) 014327*]

- Binary interactions C-N_i, N_1-N_2
- Three-body force to fine-tune g.s. energy

$$\boxed{\Phi_A^{3b,j\mu}(\vec{x},\vec{y}) = \sum_\beta w_\beta^j(x,y) \left\{ \left[\mathcal{Y}_{l_x s_2 j_x}(\widehat{x}) \otimes \phi_I\right]_{j_1} \otimes \left[Y_{l_y}(\widehat{y}) \otimes \chi_{s_1}\right]_{j_2} \right\}_{j\mu}}$$

➢ 2-body WF φ_B^{2b} consistently computed with the same N-C potential

TC calculations [spin of ^{9}Li ignored, $I^\pi = 0^+$]

- ^{10}Li (^{9}Li $+ n$)

  $2s_{1/2}$ virtual state: $a = -20.9$ fm

  $1p_{1/2}$ resonance at $\sim$ 0.5 MeV

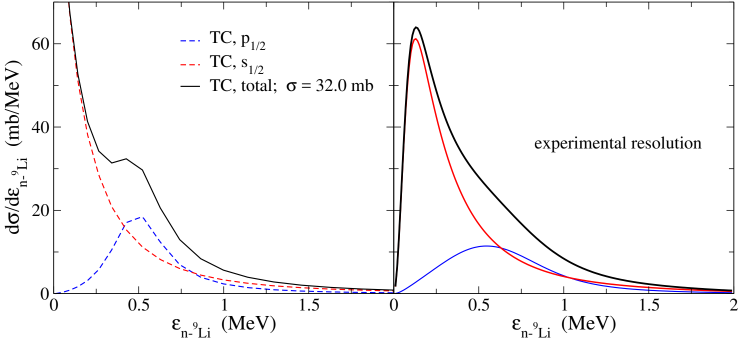
  $1d_{5/2}$ state around 4.5 MeV

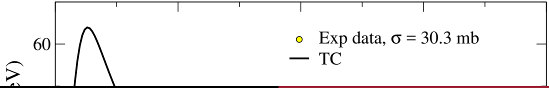
- ^{11}Li (^{9}Li $+ n + n$)

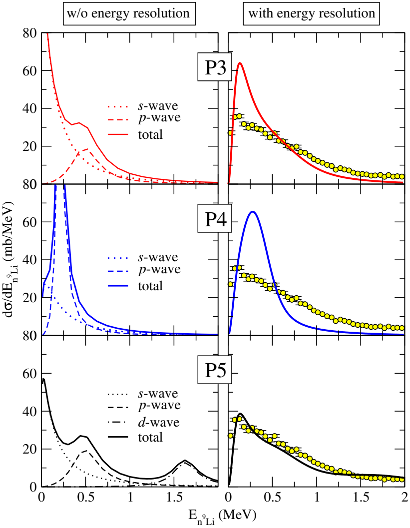
  0^+ g.s. at -0.37 MeV

  $r_{mat} = 3.55$ fm, $r_{ch} = 2.48$ fm

  64% $s_{1/2}$, 30% $p_{1/2}$, 3% $d_{5/2}$







Sensitivity to the structrure model

- P3: reference model
- P4: virtual state at higher E
  p resonance at lower E
- P5: with d resonance ~1.5 MeV

	a (fm)	$E_r[p_{1/2}]$ (MeV)	$E_r[d_{5/2}]$ (MeV)
P3	-29.8	0.50	4.3
P4	-16.2	0.23	4.3
P5	-29.8	0.50	1.5

	$\%s_{1/2}$	$\%p_{1/2}$	$\%d_{5/2}$
P3	64	30	3
P4	27	67	3
P5	39	35	23

☞ P5 consistent with data, but there is no experimental evidence of such a low $d_{5/2}$ resonance

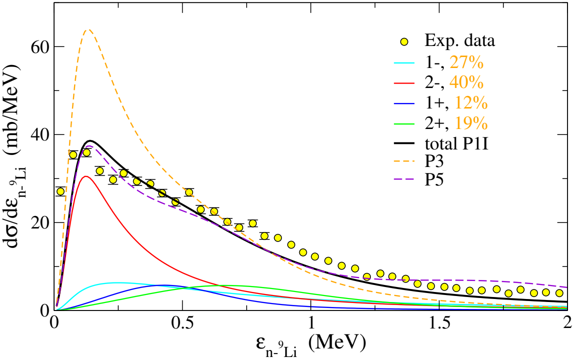
Calculations including ^{9}Li spin; $I^\pi = 3/2^-$

spin-spin splitting:
$s_{1/2} \Rightarrow 1^-, 2^-$
$p_{1/2} \Rightarrow 1^+, 2^+$

Model P1I:

- ^{10}Li:
  $a = -37.9$ fm (2^-)
  res. at 0.37, 0.61 MeV
- ^{11}Li:
  $3/2^-$ g.s. at -0.37 MeV
  $r_{mat} = 3.2$ fm
  $r_{ch} = 2.41$ fm

67% s, 31% p

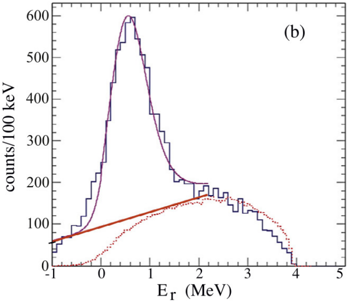


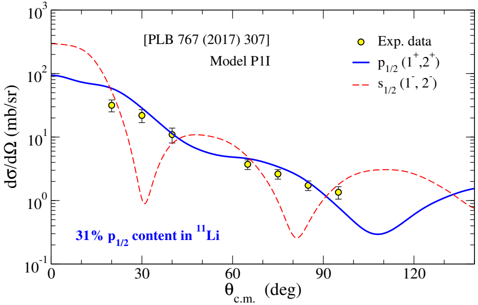
$d_{5/2}$ resonance not required to explain the data

Data from Aksyutina *et al.* [PLB 666 (2008) 430]

Testing the model in $^{11}\mathrm{Li}(p,d)^{10}\mathrm{Li}$ @ 5.7 MeV/u

Data: IRIS at TRIUMF, 5.7 MeV/u, Sanetullaev *et al.* [PLB 755 (2016) 481]

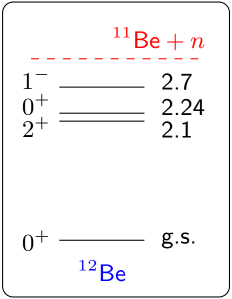




➩ Same model gives good agreement on (p, pn) and (p, d) reactions
➩ weight $p_{1/2}$: 31%

^{14}Be (^{12}Be $+ n + n$)

Ground state $j^\pi = 0^+$, separation energy $S_{2n} \simeq 1.3$ MeV

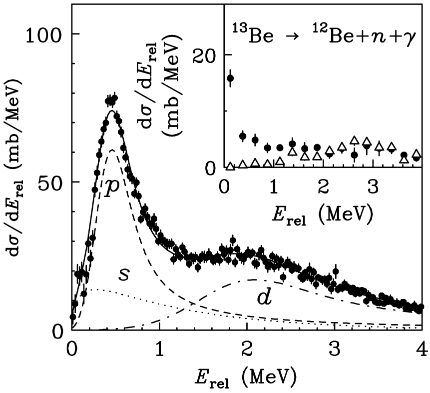


Excited ^{12}Be components in the ground-state wave function of ^{14}Be are essential

Inclusion of core excitations needed !!

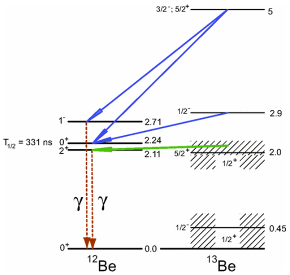
e.g.: rotational model in NPA 733 (2004) 53
by Tarutina *et al.* to couple $0^+_1, 2^+_1$ states

RIKEN data 69 MeV/u (invariant mass + γ coincidences)



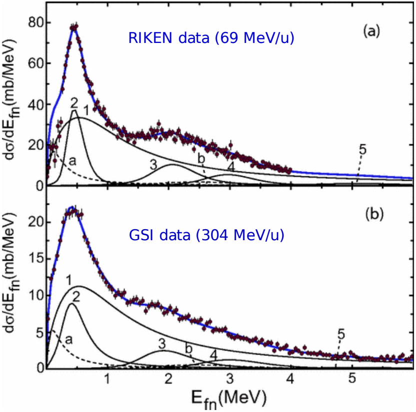
➢ ^{13}Be decay to ^{12}Be excited states observed with γ-coincidences

[Kondo et al., PLB 690 (2010) 245]



☞ Peak dominated by $\ell = 1$ resonance

GSI data (304 MeV/u)



[Aksyutina et al., PRC 87 (2013) 064316]

Simultaneous fit of both sets:

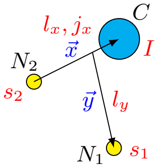
1) $l = 0,\ 1/2^+$
2) $l = 1,\ 1/2^-$
3) $l = 2,\ 5/2^+$
4) $l = 1,\ 1/2^-$
5) $l = 2,\ ?$
a) decay $5/2^+ \rightarrow {}^{12}\text{Be}(2^+)$
b) decay into ${}^{12}\text{Be}(1^-)$

☞ Peak dominated by $\ell = 0$ "resonance"

Structure model for ^{14}Be and ^{13}Be

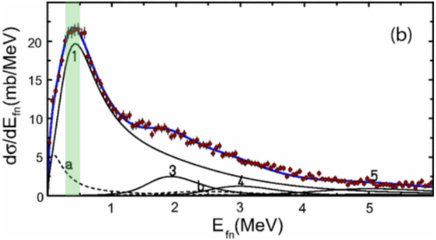
Deformed $^{12}\mathrm{Be} + n$ potential with core couplings in a rotational model

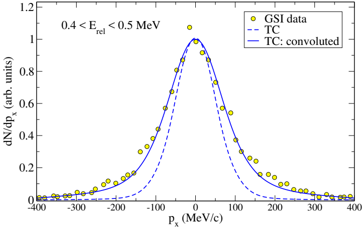
- Only 0^+(g.s.) and 2^+(2.1 MeV) of ^{12}Be included.
  Deformation parameter $\beta_2 = 0.8$ [Tarutina *et al.* NPA 733 (2004) 53]
- $V(l = 0, 2)$ and V_{ls} adjusted to give:
  - **near-threshold $\mathbf{1/2^+}$** virtual state
  - $\mathbf{5/2^+}$ resonance at $\sim$ **2 MeV**
- Shallow $V(l = 1)$ for simplicity



➠ Three-body calculations:
$^{\mathbf{14}}$Be ($^{12}\mathrm{Be} + n + n$) 0^+ g.s. fixed at S_{2n}(exp) $\simeq$ **1.3 MeV**
About **60% of $l_x = 0$** and **35% of $I = 2^+$**

Comparison with GSI's data (304 MeV/u)





- ⇨ Momentum distribution of peak consistent with assumed model and $\ell = 1$ dominance
- ⇨ Not consistent with original interpretation by Aksyutina *et al.*!

- We have developed a new framework (TC) to describe (p, pN) reactions:
  - ➢ Structure information contained in $\langle B|A\rangle$ **overlaps.**
  - ➢ Provides absolute cross sections.
  - ➢ No IA approximation (can be used at low energies).
- Benchmarks with "two-body" projectiles show good agreement with DWIA and Faddeev methods

  Next step: comparison with new R3B systematic data
- Three-body projectiles, with no core excitations:
  - Comparison with ^{11}Li$(p, pn)^{10}$Li GSI's data highlights the importance of the spin of ^{9}Li in the ^{10}Li spectrum.
  - Consistent description of (p, pn) and (p, d) data in completely different energy regimes.
- Three-body projectiles, with core excitations:
  - Comparison with ^{14}Be$(p, pn)^{13}$Be data from GSI and RIKEN suggest dominance of $\ell = 1$ $(1/2^-)$ decay of ^{13}Be (better models required!)
- Future work: other systems (^{8}He, ^{17}B, ^{17}Ne ...) and observables (momentum profiles, angular correlations, ...)

Recent advances and challenges in the description of nuclear reactions at the limit of stability

ECT* Workshop 5-9 March 2018
Trento, Italy

Pierre Capel
José A. Lay
Jesús Casal
Antonio M. Moro