Matsue, June 4-8
Direct Reactions with Exotic Beams (DREB2018)

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

Jesús Casal

ECT*, Trento, Italy

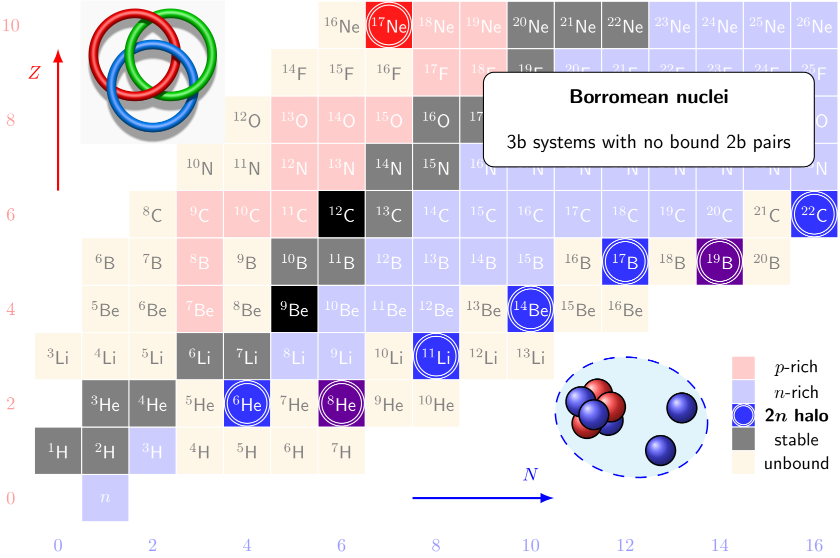
Mario Gómez-Ramos

Antonio M. Moro

Dpto. de Física Atómica, Molecular y Nuclear
Universidad de Sevilla, Spain

Borromean nuclei

3b systems with no bound 2b pairs

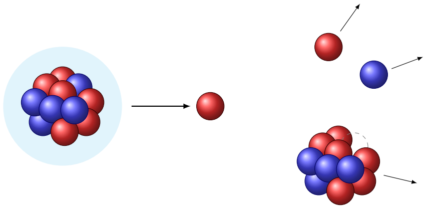


(p, pN) reactions in inverse kinematics

"quasifree" $1N$ removal; p-target knockout

- Fast-moving projectile on a proton target

  One nucleon is removed, leaving the residue in ground or excited state



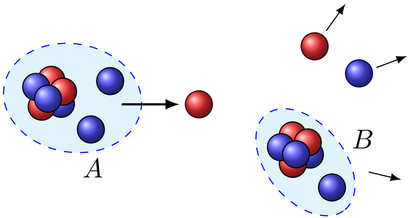
- High energies to increase mean free path of nucleon inside nucleus
- Structure information inferred from total $1N$ removal cross sections, momentum distributions, γ and particle decay of the residue . . .

(p, pN) reactions in inverse kinematics **Borromean**

"quasifree" $1N$ removal; p-target knockout

- Fast-moving projectile on a proton target

  One nucleon is removed, leaving the residue in ground or excited state

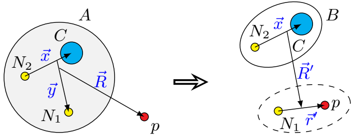


➢ If A is Borromean, the unbound subsystem B will eventually decay

➢ Probe the continuum wave function of the unbound subsystem

Transfer to the Continuum (TC)

- No IA assumed
- No factorization approximation
- 3-body structure explicitly included



➢ Prior-form T-matrix Participant (N_1) / Spectator (B) approach

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

$\varphi_B^{2b} \equiv$ continuum wave function of the binary subsystem B

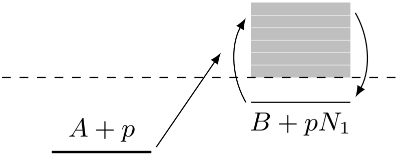
$\Psi_f \equiv$ final $(p+N1)+B$ wave function

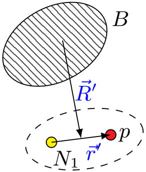
$\Phi_A^{3b} \equiv$ g.s. wave function of the initial 3-body projectile A

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

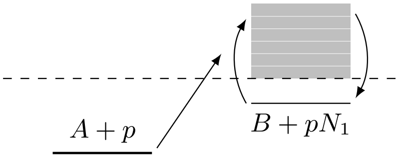
[M. Gómez-Ramos, J.C., A.M. Moro, PLB 772 (2017) 115]

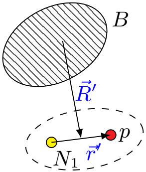
$\Psi_f(\vec{r}', \vec{R}')$ expanded in discretized pN states (CDCC-like)





$\Psi_f(\vec{r}', \vec{R}')$ expanded in discretized pN states (CDCC-like)





➠ Assume $(V_{pN_1} + U_{pB} - U_{pA})$ does not change the state of B

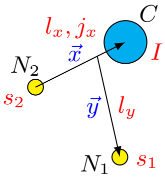
Define **overlaps** $\psi_{LJJ_TM_T}(q, \vec{y}) = \int \varphi^{2b}_{B,LJJ_TM_T}(q, \vec{x}) \Phi^{3b}_A(\vec{x}, \vec{y}) d\vec{x}$

Cross section from auxiliary amplitudes:

$$\mathcal{T}^{LJJ_TM_T}_{if} \equiv \langle \Psi^{(-)}_f(\vec{r}', \vec{R}') | V_{pN_1} + U_{pB} - U_{pA} | \psi_{LJJ_TM_T}(q, \vec{y}) \chi^{(+)}_{pA} \rangle$$

$$\frac{d\sigma^2}{d\Omega_B dq} \propto \sum \left| \mathcal{T}^{LJJ_TM_T}_{if} \right|^2$$

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



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

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

Diagonalize $\mathcal{H}_{3b}$ using: [PRC 88 (2013) 014327]

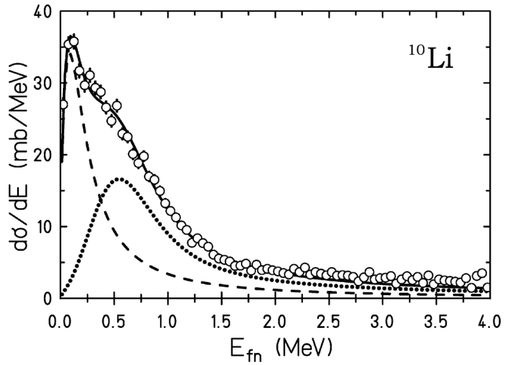
- Binary interactions C-N_i, N_1-N_2
- Three-body force to fine-tune g.s. energy

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

2-body continuum φ_B^{2b} computed with the same C-N potential

^{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]



$l = 0$ virtual state ($s_{1/2}$)
$l = 1$ resonance ($p_{1/2}$)

spectroscopic information extracted through fitting with assumed shapes (e.g.: Breit-Wigner)

reaction dynamics not considered

*More recent data from RIKEN is coming

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

[PLB 772 (2017) 115]

spin-spin splitting:

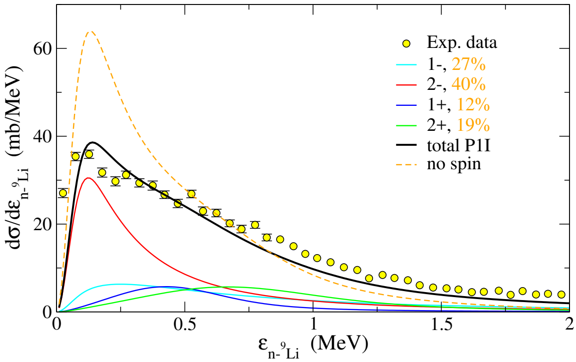
$s_{1/2} \Rightarrow 1^-, 2^-$

$p_{1/2} \Rightarrow 1^+, 2^+$

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

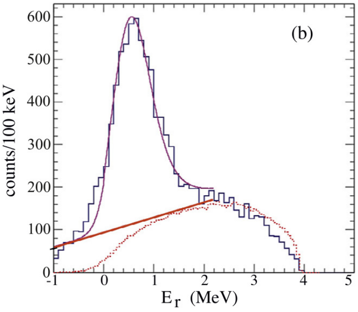
67% s, 31% p

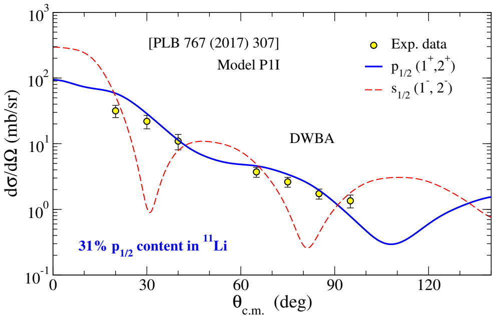


Data from Aksyutina *et al.* [PLB 666 (2008) 430]

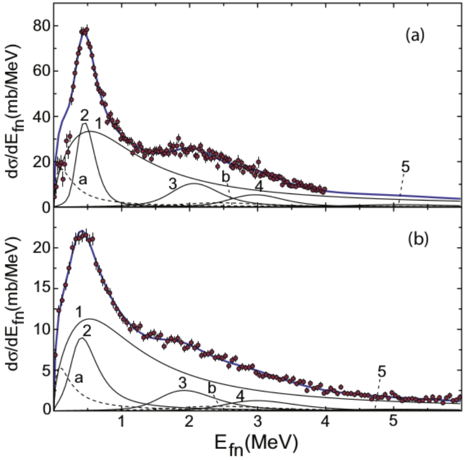
Transfer reaction $^{11}\mathbf{Li}(p,d)^{10}\mathbf{Li}$

IRIS at TRIUMF, 5.7 AMeV Sanetullaev *et al.* [PLB 755 (2016) 481]





➢ Same model gives good agreement on (p,pn) and (p,d) reactions

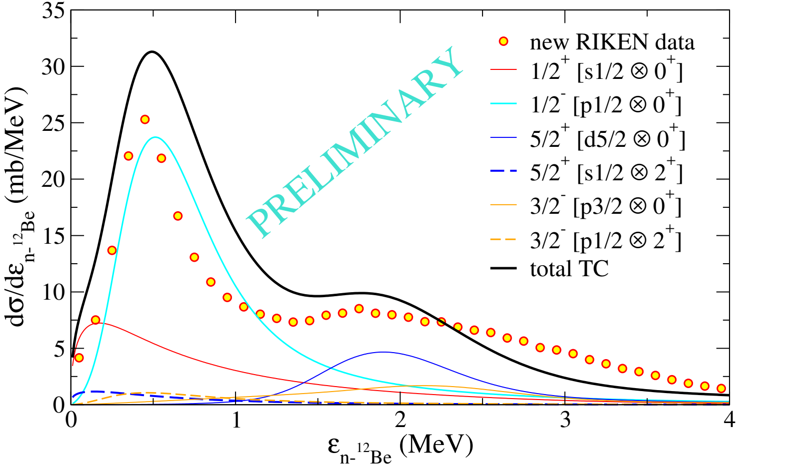


^{14}Be$(p,pn)^{13}$Be

a) Kondo et al. 69 MeV/u
PLB 690 (2010) 245
b) Aksyutina et al. 304 MeV/u
PRC 87 (2013) 064316

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 $5/2^+ \rightarrow {}^{12}Be(2^+)$
b) decay into ^{12}Be(1^-)

^{14}Be$(p,pn)^{13}$Be @ 250 MeV/u new data from RIKEN (A. Corsi)

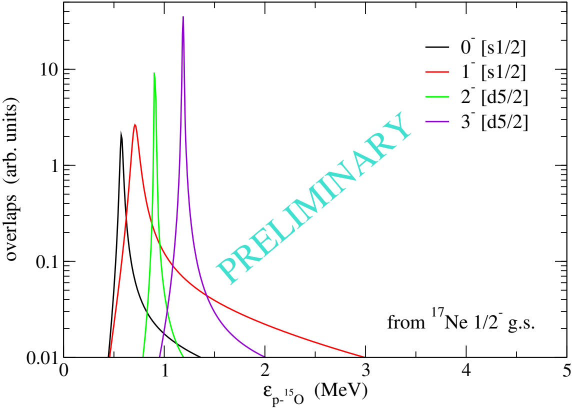


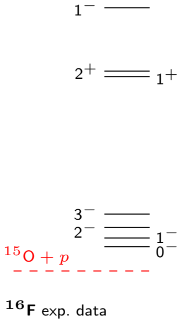
Spectrum governed by low-lying $1/2^-$ resonance

^{17}Ne$(p,2p)^{16}$F

measured at GSI @ 500 MeV/u . . .

^{15}O $+ p + p$ model from [PRC 94 (054622) 2016]: **30% s-wave protons**





- **Transfer to Continuum (TC)**
  To describe (p, pN) reactions induced by 3b projectiles.
  - Structure information contained in $\langle \varphi_{2b}^{q} | \Phi_{3b}^{g.s.} \rangle$ **overlaps.**
  - Provides absolute cross sections.
- **^{11}Li$(p, pn)^{10}$Li**
  - Including the spin of ^{9}Li improves agreement.
  - Same model gives good agreement for ^{11}Li$(p, d)^{10}$Li.
  - Our model: 31% of p-waves in ^{11}Li.
- **^{14}Be$(p, pn)^{13}$Be**
  - Core excited components in a collective model.
  - The analysis is ongoing.

➠ This is a lot of work! ^{14}Be; also ^{17}Ne, ^{8}He, ^{17}B . . .

➠ Other observables: momentum distributions, profile functions, . . .

Project No.

FIS2014-53448-c2-1-P
FIS2017-88410-P

Project No.

P11-FQM-7632

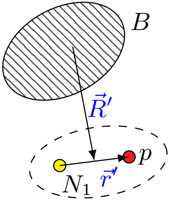
Horizon 2020 No. 654002

- Understanding the structure of 3-body Borromean nuclei requires:
  - A proper knowledge of the corresponding 2-body subsystems
  - Information on excitations/correlations of the core
- Different reaction observables probe different properties
  E.g.: for ^{11}Li:
  - breakup $^{11}\text{Li} + A \to {}^{9}\text{Li} + n + n + A$
  - $1n$ transfer $^{11}\text{Li}(p,d)^{10}\text{Li}^*$
  - $2n$ transfer $^{11}\text{Li}(p,t)^{9}\text{Li}^*$
  - knockout $^{11}\text{Li} + A \to {}^{10}\text{Li}^* + X \to {}^{9}\text{Li} + n + X$
  - $1n$ removal $^{11}\text{Li}(p,pn)^{10}\text{Li}^*$
  - ...
- In all these processes, a crucial aspect is how the structure input is **linked** to the reaction observables

Final wave function

Expanded in proton-nucleon states (CDCC)

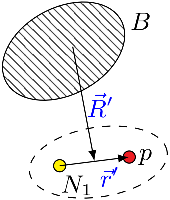
$$\Psi_f(\vec{r}', \vec{R}') \simeq \sum_{n\mathcal{J}\Pi} \phi_n^{\mathcal{J}\Pi}(k_n, \vec{r}')\chi_n^{\mathcal{J}\Pi}(\vec{K}', \vec{R}')$$



Final wave function

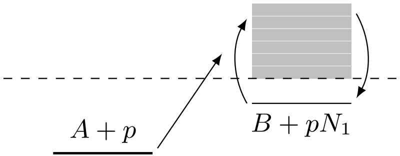
Expanded in proton-nucleon states (CDCC)

$$\Psi_f(\vec{r}', \vec{R}') \simeq \sum_{n\mathcal{J}\Pi} \phi_n^{\mathcal{J}\Pi}(k_n, \vec{r}')\chi_n^{\mathcal{J}\Pi}(\vec{K}', \vec{R}')$$



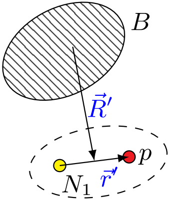
Basis of N discretized bins

$$\phi_n^{\mathcal{J}\Pi}(k_n, \vec{r}') = \sqrt{\frac{2}{\pi N}} \int_{k_{n-1}}^{k_n} \phi_{pN_1}^{\mathcal{J}\Pi}(k, \vec{r}') dk.$$



Final wave function

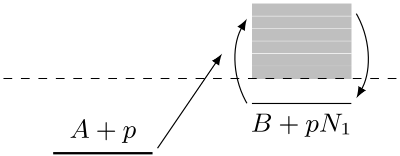
Expanded in proton-nucleon states (CDCC)



$$\Psi_f(\vec{r}', \vec{R}') \simeq \sum_{n\mathcal{J}\Pi} \phi_n^{\mathcal{J}\Pi}(k_n, \vec{r}')\chi_n^{\mathcal{J}\Pi}(\vec{K}', \vec{R}')$$

Basis of N discretized bins

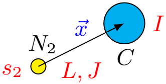
$$\phi_n^{\mathcal{J}\Pi}(k_n, \vec{r}') = \sqrt{\frac{2}{\pi N}} \int_{k_{n-1}}^{k_n} \phi_{pN_1}^{\mathcal{J}\Pi}(k, \vec{r}')dk.$$



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

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

2b continuum state of fragment B



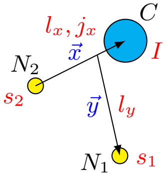
$$\varphi^{(+)}_{\vec{q},\sigma_2,\iota}(\vec{x}) = \frac{4\pi}{qx} \sum_{LJJ_TM_T} i^L Y^*_{LM}(\widehat{q}) \langle LMs_2\sigma_2|JM_J\rangle \times \langle JM_JI\iota|J_TM_T\rangle f^{J_T}_{LJ}(qx) \left[\mathcal{Y}_{Ls_2J}(\widehat{x}) \otimes \kappa_I\right]_{J_TM_T}$$

Coupling order: $\vec{L} + \vec{s}_2 = \vec{J}$, $\quad \vec{J} + \vec{I} = \vec{J}_T$

Obtain solution for each $(L, J)J_T$:

$$f^{J_T}_{LJ}(qx) \longrightarrow \frac{i}{2} e^{i\sigma_L} \left[H^{(-)}_L(qx) - S^{J_T}_{LJ} H^{(+)}_L(qx)\right]$$

3b g.s. wave function of A — Analytical THO method



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

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

$$\vec{l}_y + \vec{s}_1 = \vec{j}_2, \qquad \vec{j}_1 + \vec{j}_2 = \vec{j}$$

Diagonalize $\mathcal{H}_{3b}$ using: [*PRC 88 (2013) 014327*]

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

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

Consistent with 2b wave function: same potential and couplings

- Assume $(V_{pN_1} + U_{pB} - U_{pA})$ does not change the state of B
- Define overlaps $\langle 2b|3b \rangle$:

$$\psi_{LJJ_TM_T}(q,\vec{y}) = \int \frac{f_{LJ}^{J_T}(qx)}{x} \left[\mathcal{Y}_{Ls_2J}(\widehat{x}) \otimes \psi_I\right]_{J_TM_T} \Phi_A^{j\mu}(\vec{x},\vec{y})d\vec{x}$$

- Assume $(V_{pN_1} + U_{pB} - U_{pA})$ does not change the state of B
- Define overlaps $\langle 2b|3b\rangle$:

$$\psi_{LJJ_TM_T}(q,\vec{y}) = \int \frac{f_{LJ}^{J_T}(qx)}{x} \left[\mathcal{Y}_{Ls_2J}(\widehat{x}) \otimes \psi_I\right]_{J_TM_T} \Phi_A^{j\mu}(\vec{x},\vec{y})d\vec{x}$$

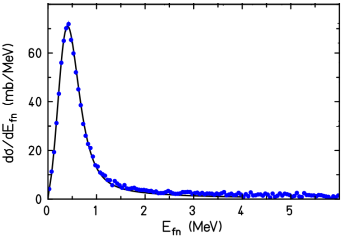
- Auxiliary amplitudes for each 2b configuration $\{(L,s_2)J,I\}J_T$:

$$\boldsymbol{\mathcal{T}_{if}^{LJJ_TM_T}} \equiv \langle \Psi_f^{(-)}(\vec{r}',\vec{R}')|V_{pN_1}+U_{pB}-U_{pA}|\psi_{LJJ_TM_T}(q,\vec{y})\chi_{pA}^{(+)}\rangle$$

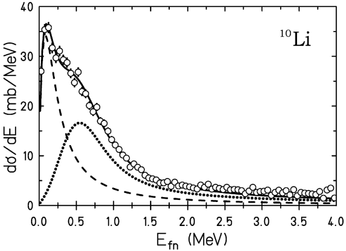
➠ Cross sections

$$\frac{d\sigma_n^2}{d\Omega_B d\varepsilon_x} \propto \sum \left|\mathcal{T}_{if}^{LJJ_TM_T}\right|^2$$

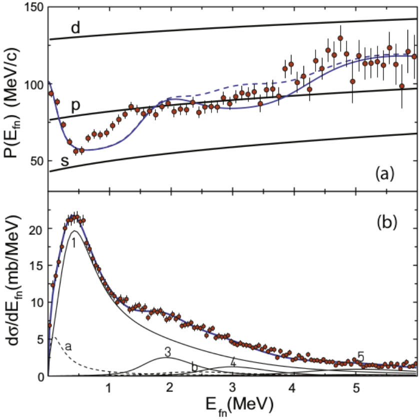
^{8}He$(p,pn)^{7}$He* 240 MeV/u



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



^{14}Be$(p,pn)^{13}$Be* 304 MeV/u



Aksyutina et al. (2008,2009,2013) GSI

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

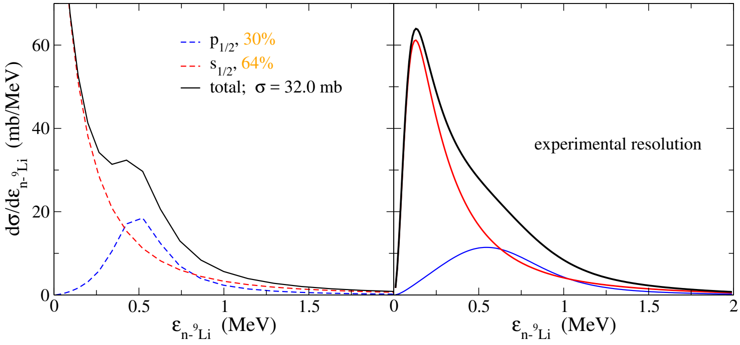
  $1d_{5/2}$ state around 4.5 MeV

- ^{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% $d_{5/2}$



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

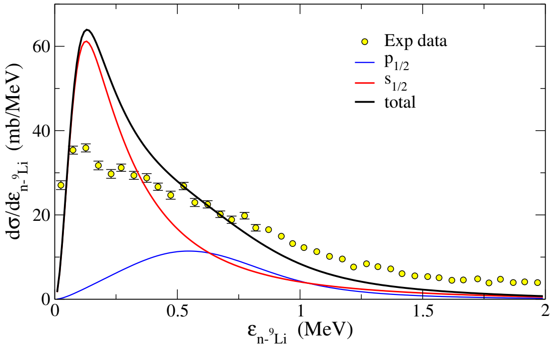
  $1d_{5/2}$ state around 4.5 MeV

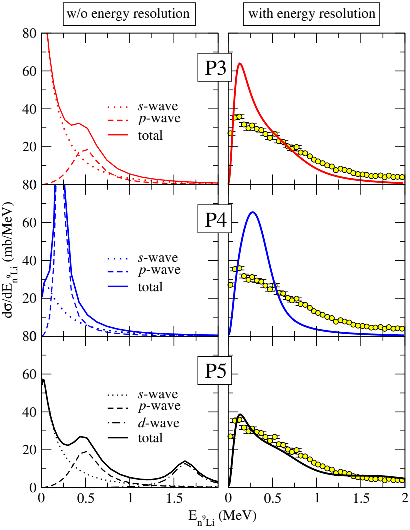
- ^{11}Li (^{9}Li $+ n + n$)

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

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

Factorization of the cross section

$$\frac{d\sigma^{LJJ_T}}{d\varepsilon_x} \simeq \mathcal{C}^{LJJ_T} K(E) \eta^{LJJ_T}(E)$$

Structure form factors (SF):

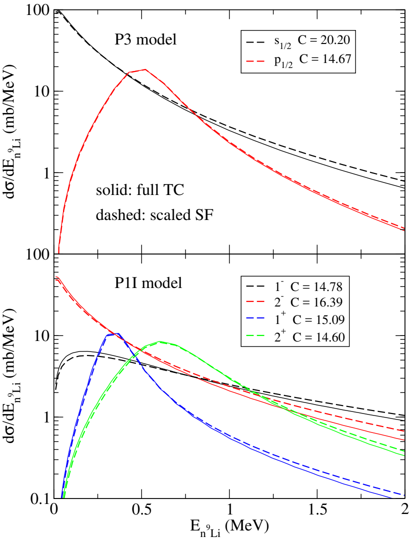
$$\eta^{LJJ_T}(E) \equiv \int d\vec{y} |\psi_{LJJ_TM_T}(E,\vec{y})|^2$$

Correct up to certain extent

BUT!!

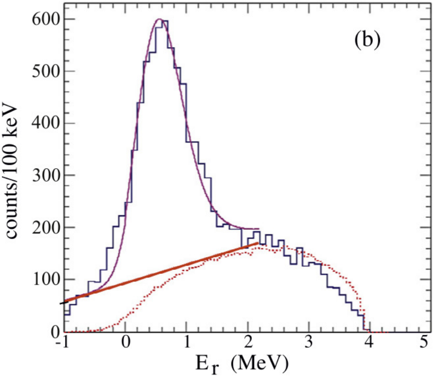
ratio depends on L, J, J_T

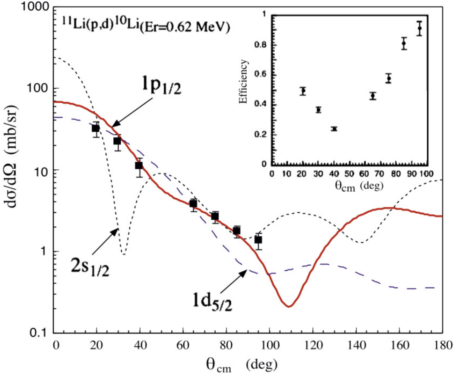
- reaction calc. to obtain relative weights
- less ambiguous than fitting



Transfer reaction $^{11}\mathbf{Li}(p,d)^{10}\mathbf{Li}$

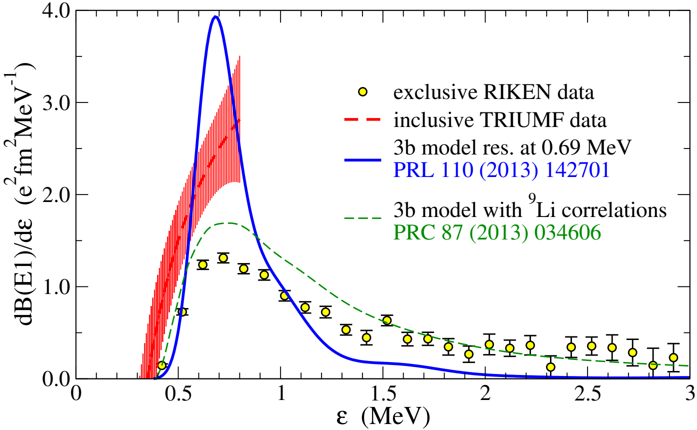
IRIS at TRIUMF, 5.7 AMeV   Sanetullaev *et al.* [PLB 755 (2016) 481]



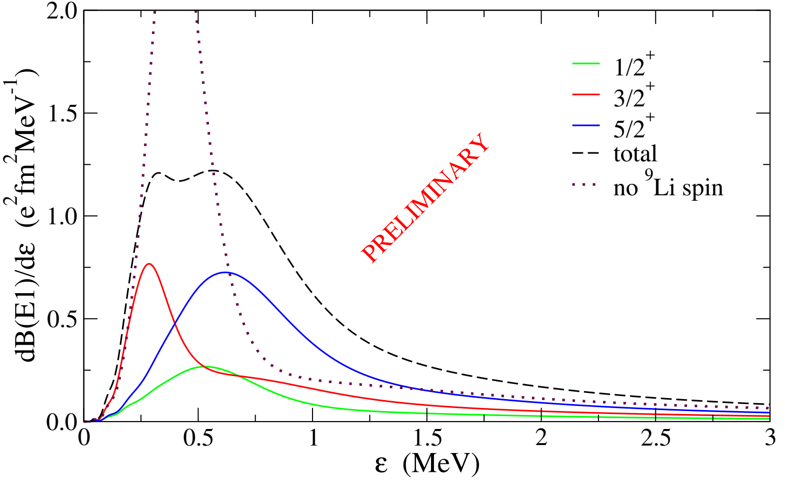


weight $p_{1/2}$: 33%

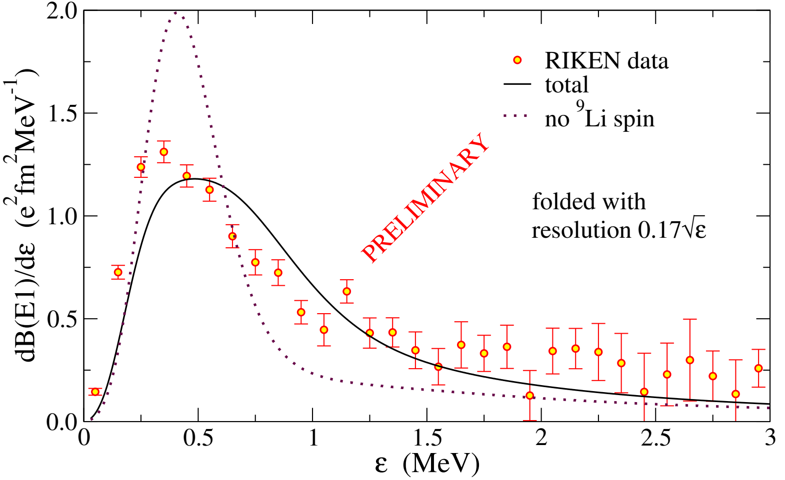
Continuum of ^{11}Li: Dipole response



Large discrepancies between experiments and theory



Again same model P1I seems reasonable

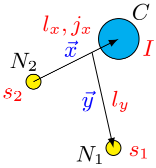


Again same model P1I seems reasonable

Structure model

Deformed ^{12}Be $+ n$ potential with core couplings in a collective 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 $1/2^+$** state
  - **$5/2^+$** resonance at $\sim$ **2 MeV**
- Shallow $V(l = 1)$ for simplicity



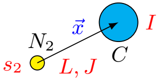
➠ Three-body calculations:

^{14}Be (^{12}Be $+ n + n$) 0^+ g.s. fixed at S_{2n}(exp) $\simeq$ **1.3 MeV**

About **60% of $l_x = 0$** and **35% of $I = 2^+$**

Multichannel problem

Two-body coupling order: $\{\underbrace{(L, s_2)J}_{\text{s.p.}}, I\}J_T \iff \{L_J \otimes I\}J_T$



Example:

^{13}Be$(5/2^+)$: $\{d_{5/2} \otimes 0^+\}$, $\{s_{1/2} \otimes 2^+\}$, $\{d_{3/2} \otimes 2^+\}$, $\{d_{5/2} \otimes 2^+\}$

- So (up to $L_{max} = 2$) we have 4 asymptotic channels
- The w.f. for each channel comprises 4 components
- $\langle$2b$|$3b$\rangle$ overlaps mix them

One contribution to the cross section for each asymptotic channel

Similar for other J_T configurations

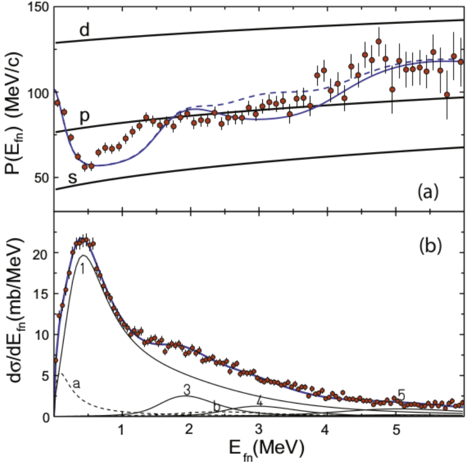
Aksyutina et al.
PRC 87 (2013) 064316

1) using two $1/2^+$ states

No low-energy $1/2^-$ resonance required

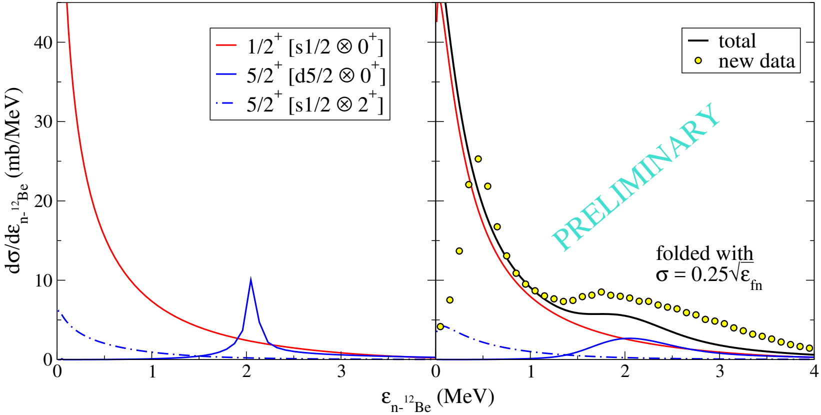
Momentum profile gives an average: mostly $l = 0$, $l = 2$

^{13}Be structure not clear



New data from RIKEN, 250 MeV/u. Anna Corsi *et al.*

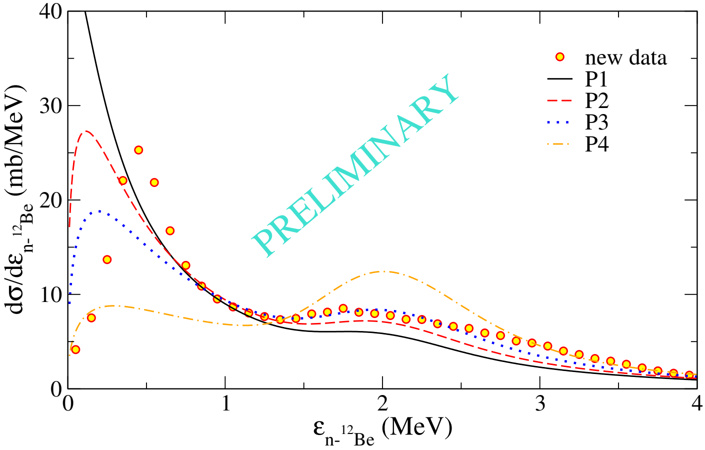
^{14}Be$(p,pn)^{13}$Be @ 250 MeV/u new data from RIKEN (A. Corsi)



Virtual state does not fit - too large scattering length

Missing cross section at high ε

^{14}Be$(p,pn)^{13}$Be @ 250 MeV/u   new data from RIKEN (A. Corsi)



The $1/2^+$ state cannot account for the low-energy peak