Enrico Vigezzi INFN Milano

Inelastic and transfer reactions of light weakly bound nuclei

In collaboration with
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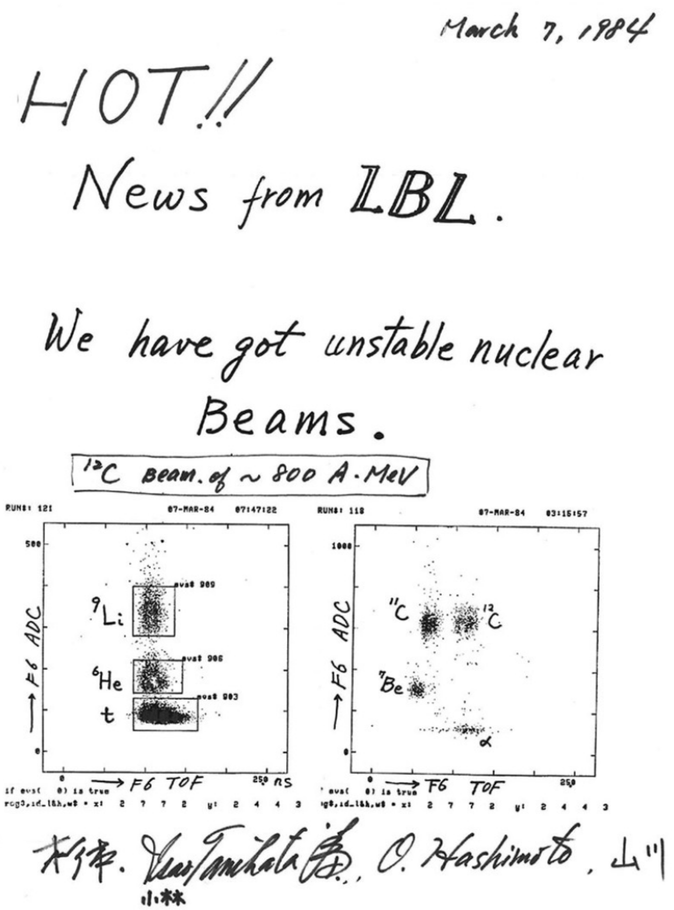
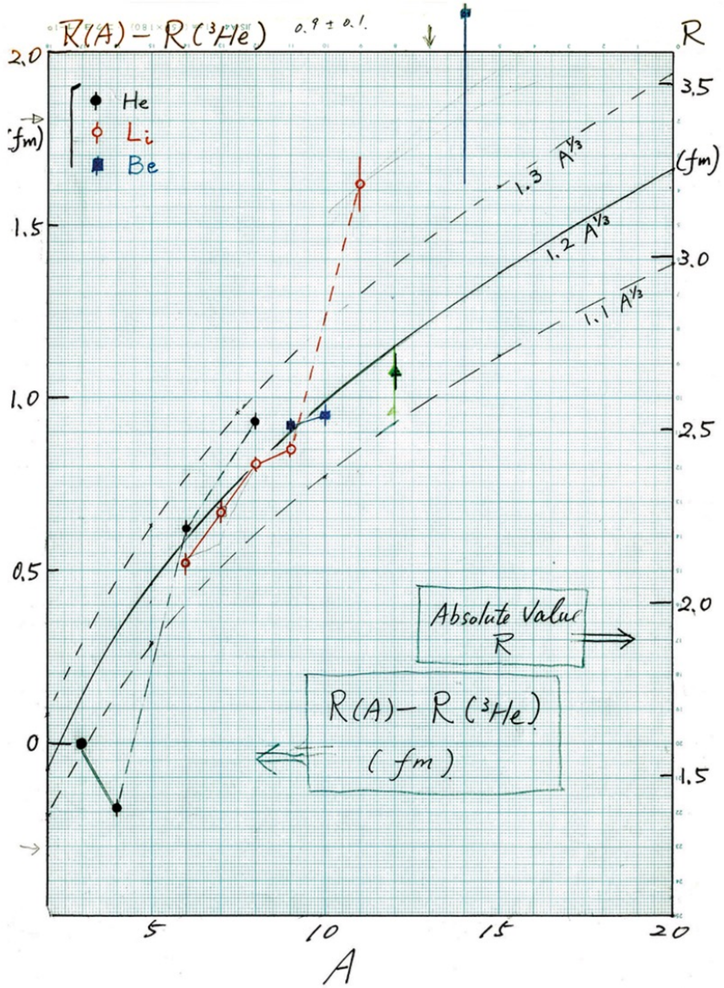
Thanks to
Yassid Ayyad University of Santiago
Jie Chen Southern University of Science and Technology

NUSDAF Meeting , Catania, 22-24 Ottobre 2025

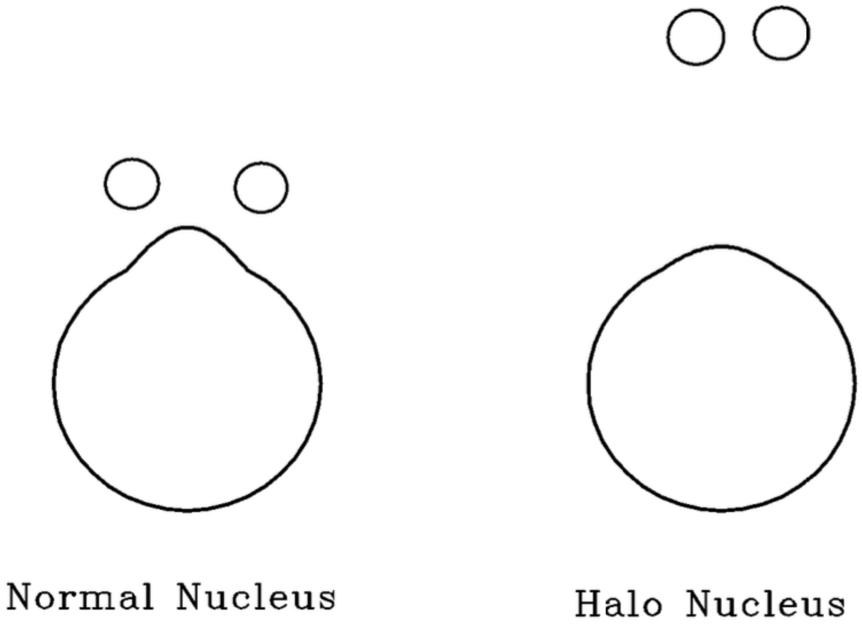

International Symposium
Commemorating the 40th Anniversary of the Halo Nuclei
October 12-18, 2025 | Beijing





I. Tanihata, EPJ Plus 131 (2016) 90

In 1997 Kuo et al predicted that in halo nuclei core polarization would be suppressed, and that the fundamental nucleon-nucleon interaction could be probed in a clearer and more direct way in halo nuclei than in ordinary nuclei….

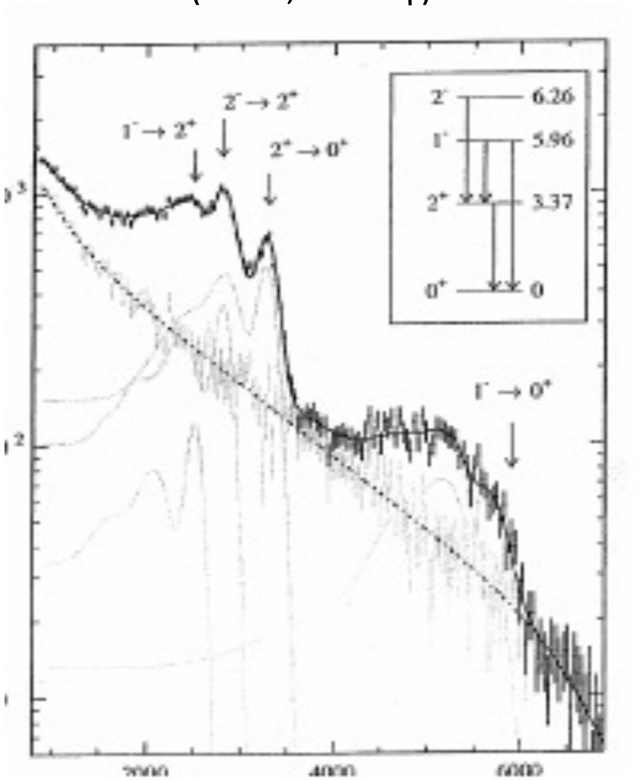


T.T.S. Kuo et al,
PRL 78 (1997) 2708

... But experiments demonstrated that the core dynamics plays an important role...

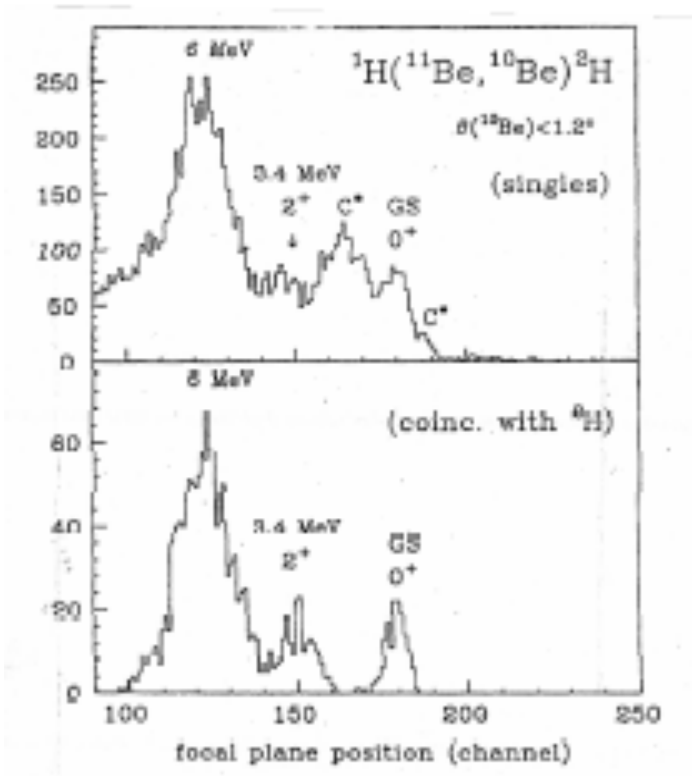
The admixture of $d_{5/2}$ x 2^+ configuration in the $1/2^+$ g.s. of ^{11}Be is about 15%

9Be(11Be,10Be+γ)X

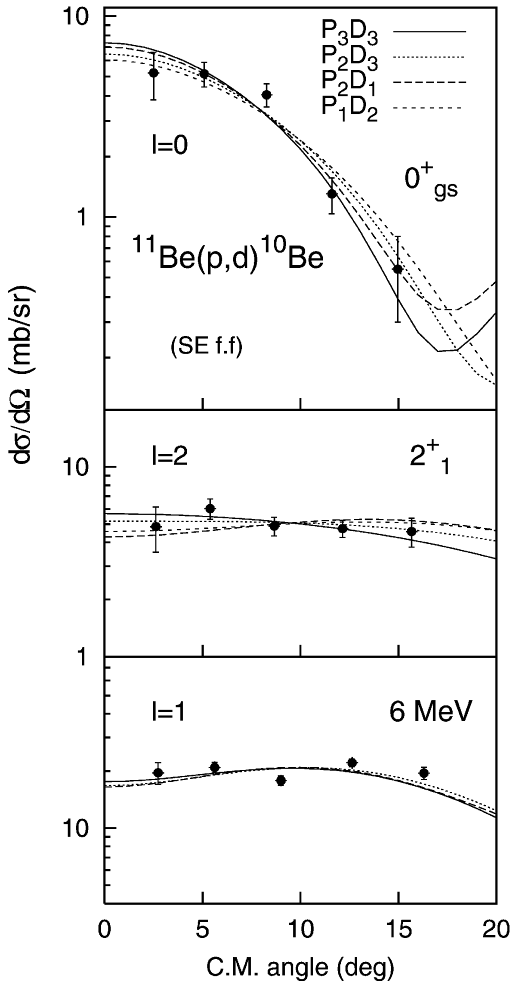


T. Aumann et al. PRL 84 (2000) 35

p(11Be,10Be)d



S. Fortier et al. Phys. Lett. B461 (1999)22
J.S. Winfield et al., Nucl.Phys. A683 (2001)48



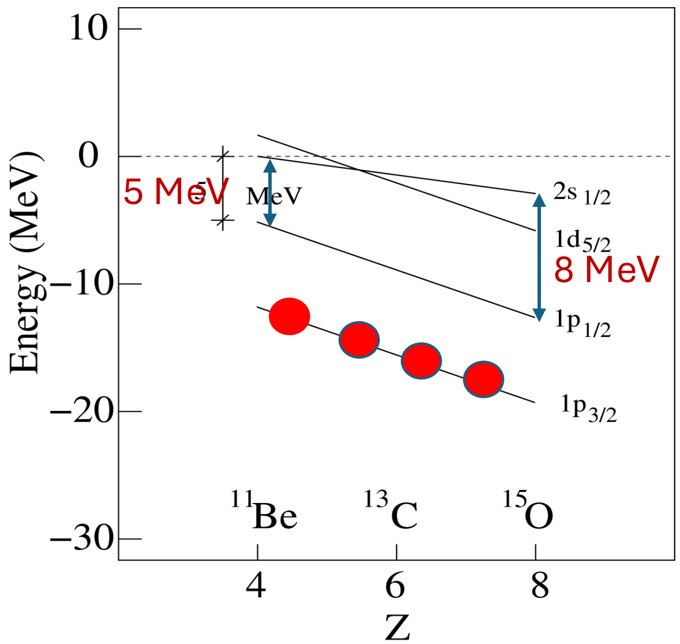
J.S. Winfield et al., Nucl.Phys. A683 (2001)48

A careful analysis of transfer reactions is needed to estimate phonon admixtures in the wavefunctions

$$\left|{}^{11}\mathrm{Be}_{gs}\right\rangle = \alpha\left|{}^{10}\mathrm{Be}(0^+)\otimes 2s\right\rangle + \beta\left|{}^{10}\mathrm{Be}(2^+)\otimes 1\mathrm{d}\right\rangle$$

Good agreement with 2+ cross sections is obtained in DWBA with $\beta^2 = 0.17$ considering the coupling effects on the transfer form factor; using β as a simple spectroscopic factor one finds $\beta^2 = 0.28$

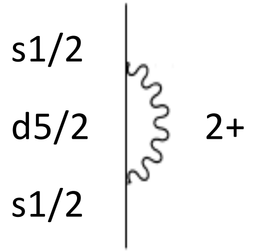
Parity inversion in N=7 isotones is not reproduced by spherical mean field obtained from non relativistic energy density functionals.

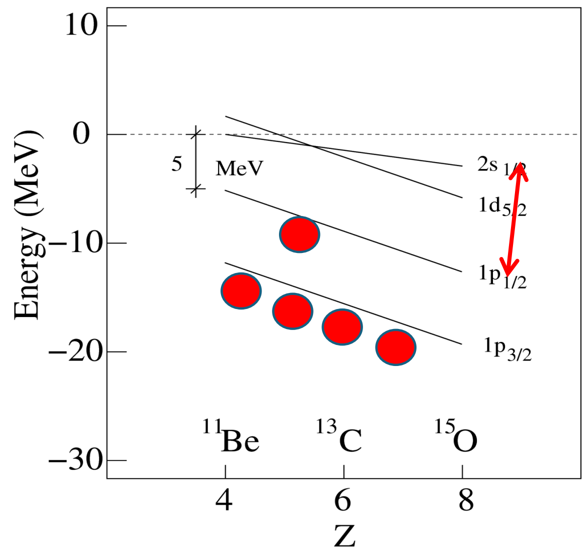


Typical spherical mean-field results with Skyrme forces (Sagawa,Brown,Esbensen PLB 309(93)1)

^{11}Be

Eshift = - 2.5 MeV



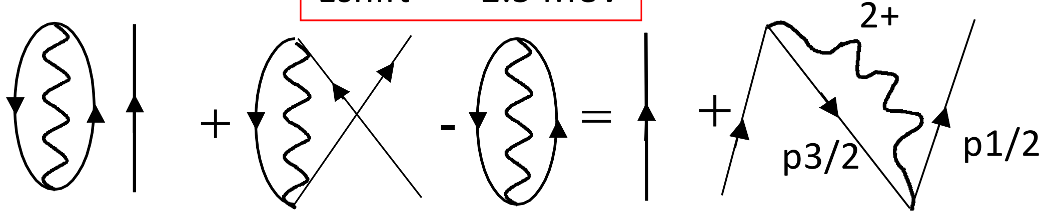


Self-energy

+

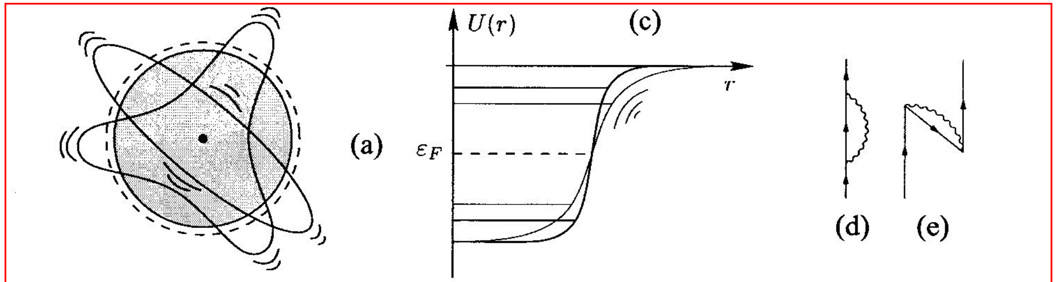
Pauli blocking of core ground state correlations

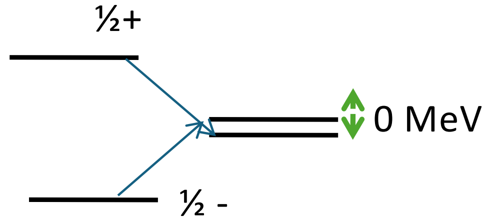
Eshift = + 2.5 MeV



↓

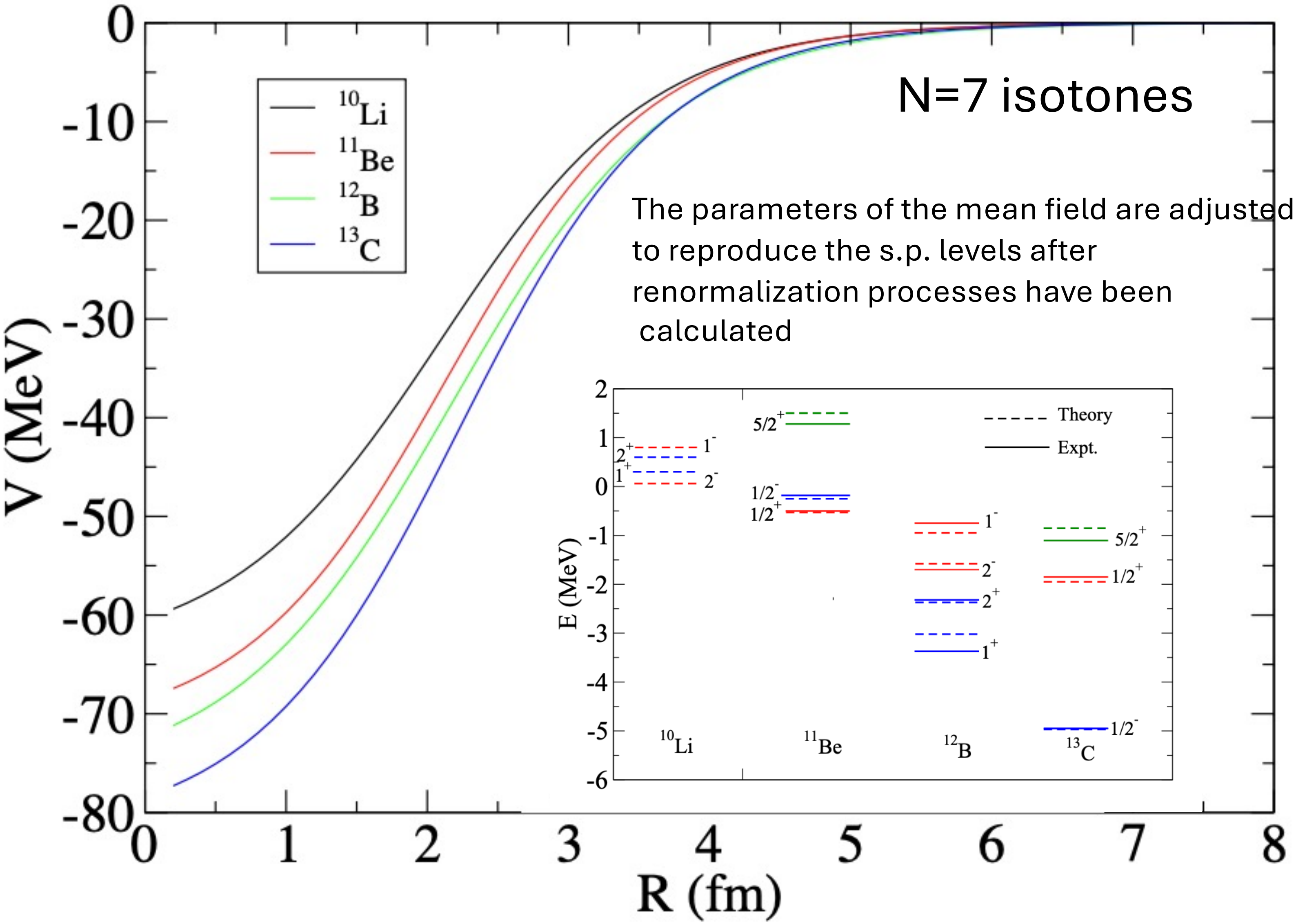
Level inversion





N=7 isotones

The parameters of the mean field are adjusted to reproduce the s.p. levels after renormalization processes have been calculated

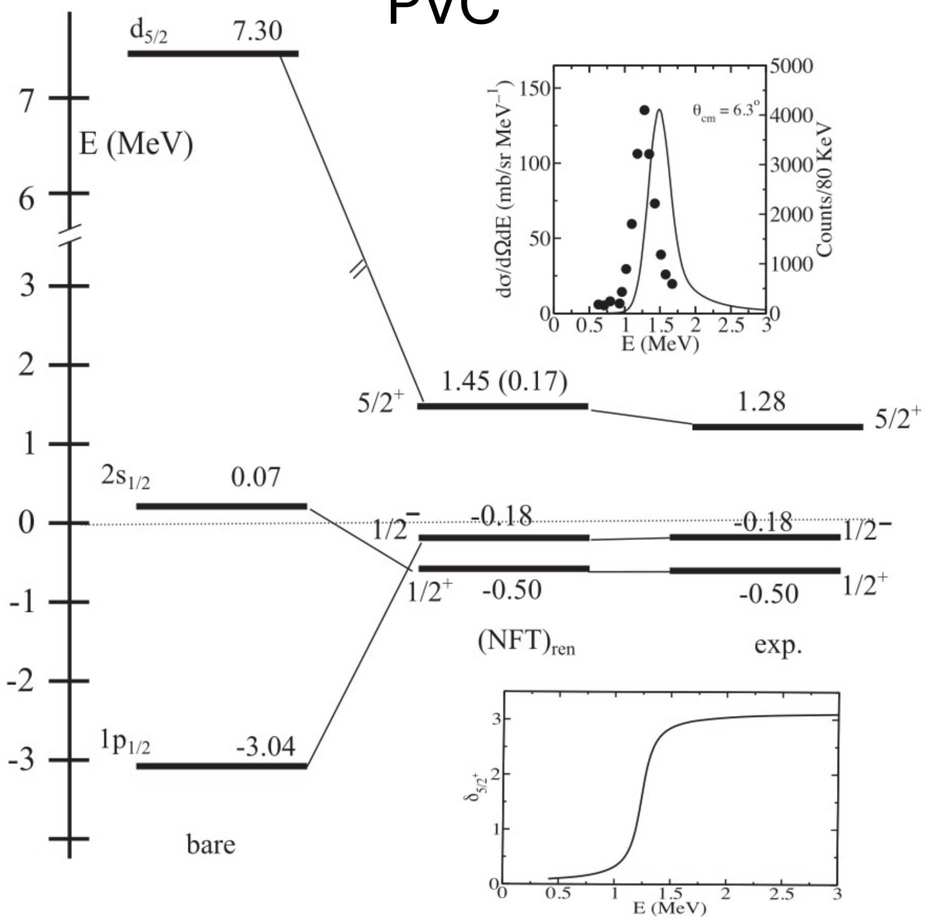


F. Barranco et al.,
PRL 119 (2017) 082501
PRC 101 (2020) 031305(R)

The description of the experimental results from complementary approaches can be of great interest

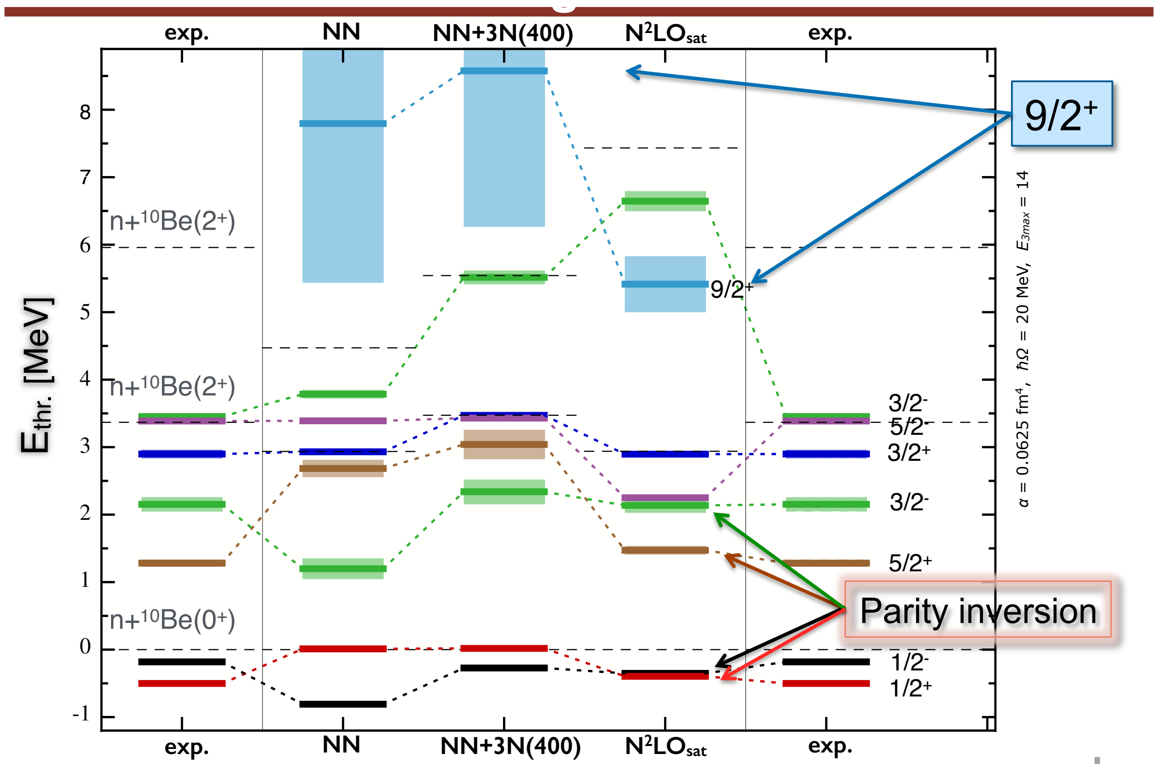
^{11}Be

PVC



F. Barranco et al., PRL 119 (2017) 082501

Ab Initio

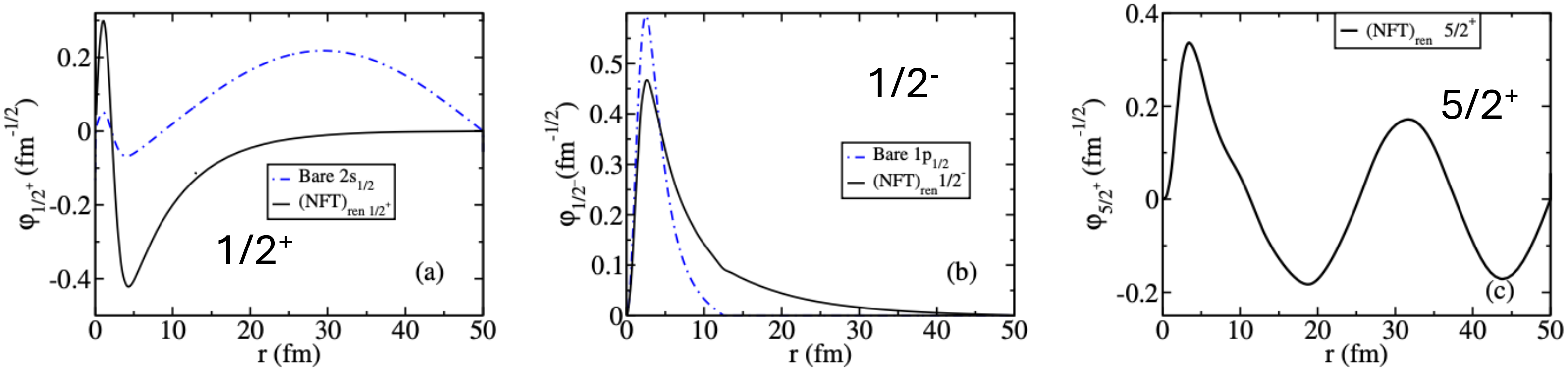


A. Calci, P. Navratil, R. Roth, J. Dohet-Eraly, S. Quaglioni, G. Hupin, PRL 117, 242501 (2016)

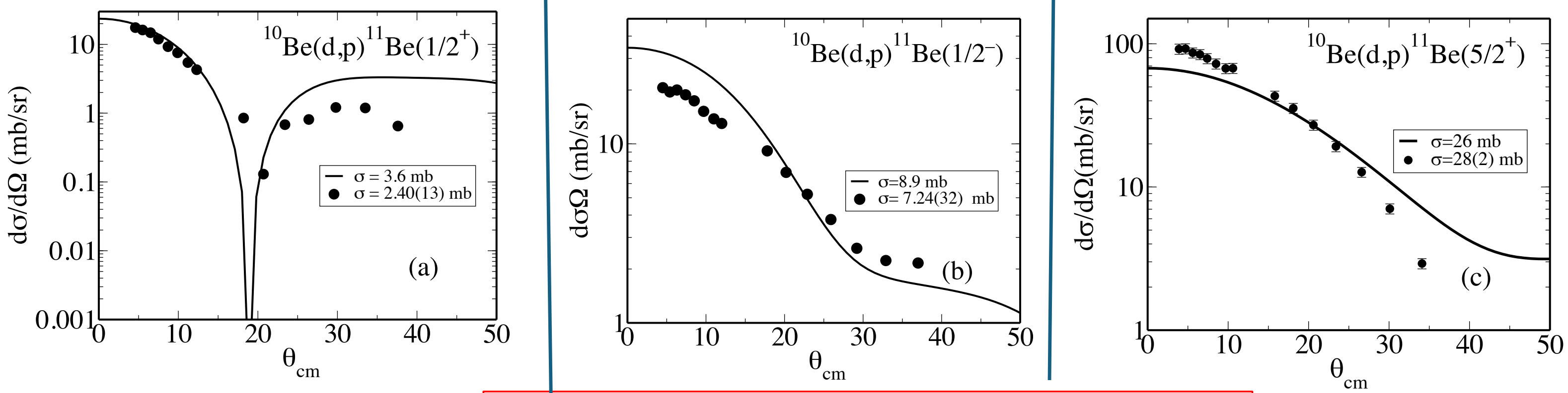
$^{10}Be(d,p)^{11}Be$ at E_d = 21.4 MeV

Test of the single-particle component of the many-body wavefunction

Form factors

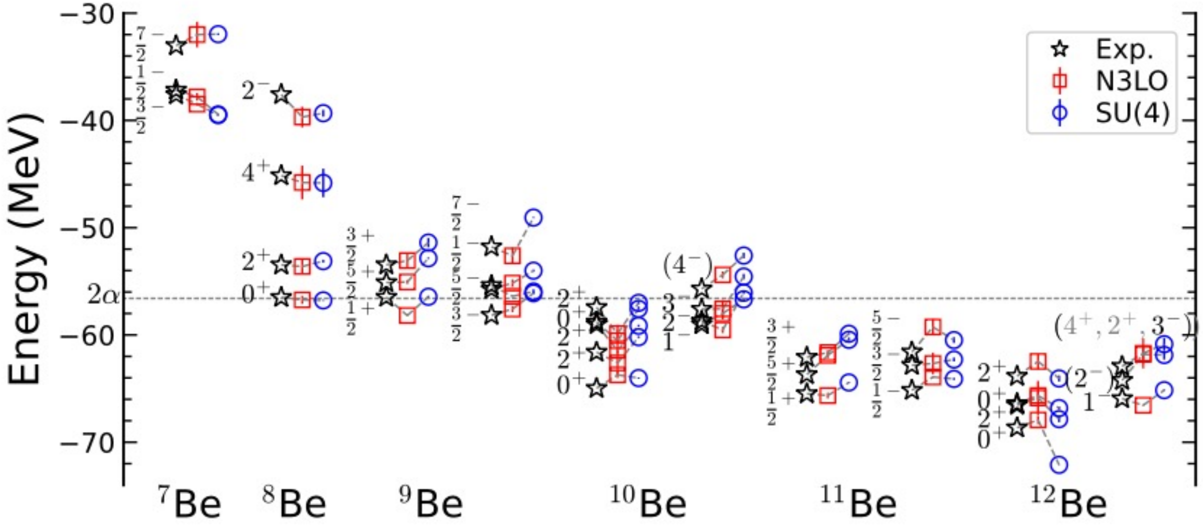


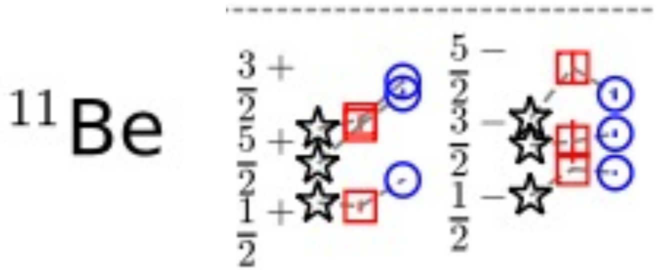
Cross sections



K.T. Schmitt et al., PRC88 (2012) 064612

Lattice Effective field theory

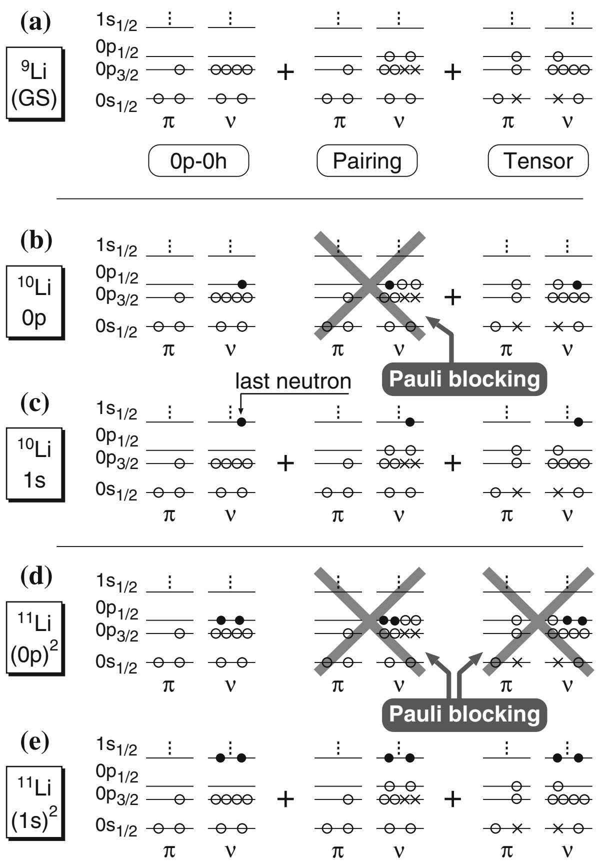




		SU(4)	N^{3}LO	Exp.
^{7}Be	$E2, \frac{3}{2}^- \to \frac{1}{2}^-$	16.0(2)	15.2(5)	26(6)(3) [91]
^{9}Be	$Q(\frac{3}{2}^-)$	7.3(1)	7.4(1.0)	5.29(4) [92]
	$E1, \frac{1}{2}^+ \to \frac{3}{2}^-$	0.131(3)	0.060(15)	0.136(2) [93]
	$E1, \frac{5}{2}^+ \to \frac{3}{2}^-$	0.045(14)	0.049(5)	0.010(8) [67]
	$E2, \frac{5}{2}^- \to \frac{3}{2}^-$	35.7(1.8)	27.8(1.9)	27.1(2.0) [67]
	$E2, \frac{7}{2}^- \to \frac{3}{2}^-$	11.6(2.5)	5.3(8)	9.5(4.1) [67]
^{10}Be	$E1, 3_1^- \to 2_1^+$	0.026(2)	0.004(3)	0.009(1) [67]
	$E2, 2_1^+ \to 0_1^+$	10.6(4)	8.5(9)	9.2(3) [31]
^{11}Be	$E1, \frac{1}{2}^- \to \frac{1}{2}^+$	0.023(3)	0.038(3)	0.102(2) [94]
^{12}Be	$E1, 0_1^+ \to 1_1^-$	0.049(2)	0.056(26)	0.051(13) [95]
	$E2, 2_1^+ \to 0_1^+$	7.8(1.1)	9.0(3.1)	14.2(1.0)(2.0) [6]

S. Shen et al, 134, 162503 (2025)

Comparison with the model by Ikeda, Myo et al.

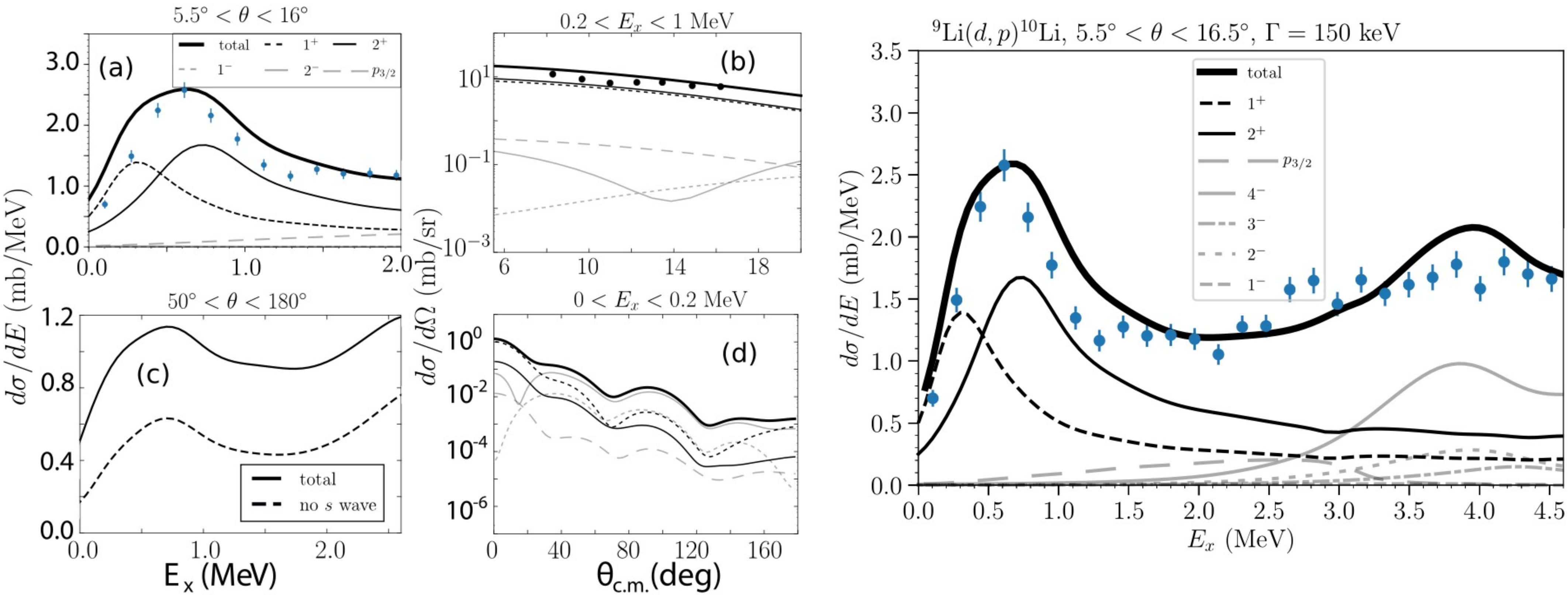


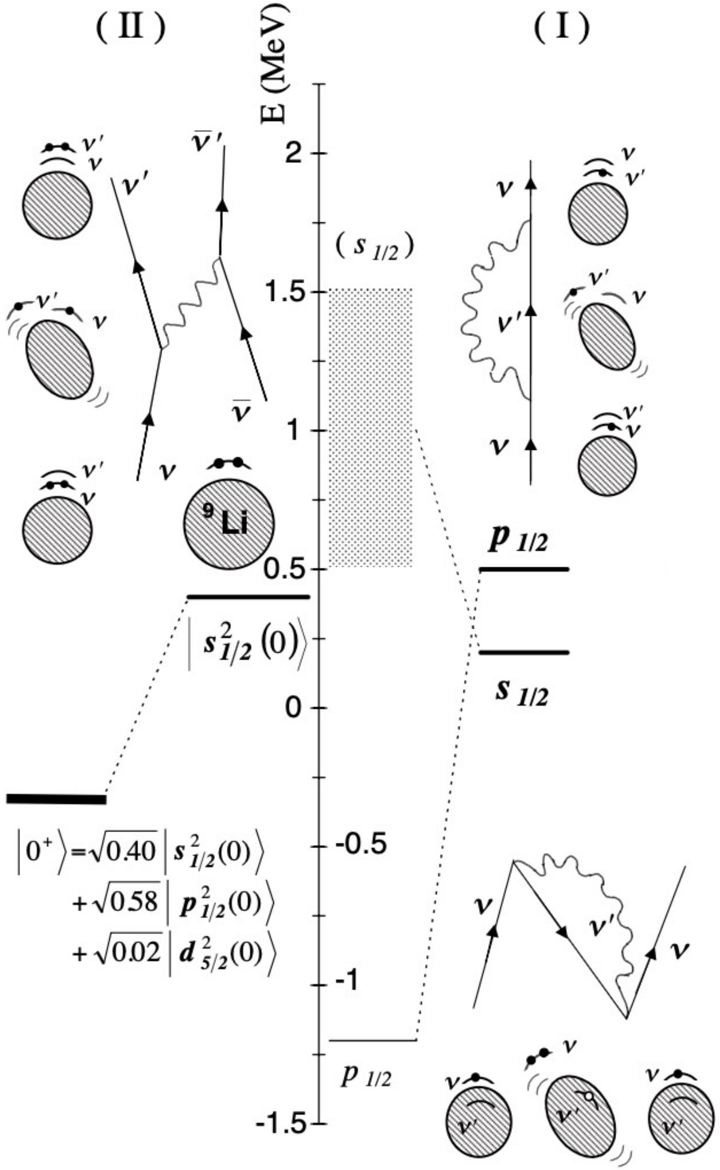
The $p_{1/2}$ orbit is pushed up by pairing correlations and tensor force. Only 3/2- configurations are included: coupling to core vibrations (1/2-) is not considered. Binding energy is given as input. 50%(s^2)-50%(p^2) wavefunction is obtained

K. Ikeda et al,
Lect. Notes in Physics 818 (2010)

^{10}Li and the ^{9}Li(d,p)^{10}Li reaction

F. Barranco et al,
Phys. Rev. C 101 (2020) 031305(R)



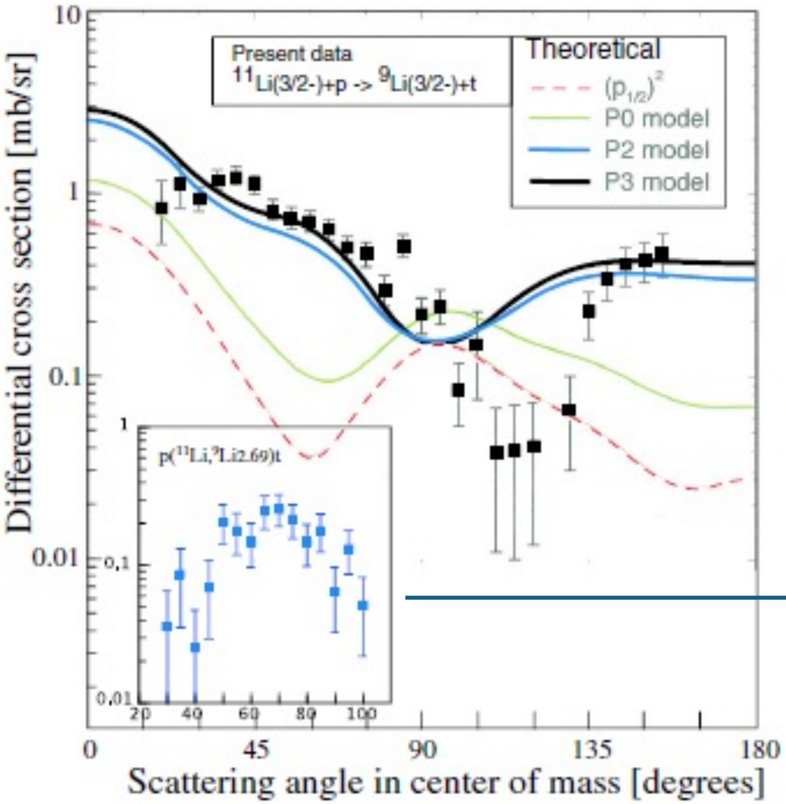


11Li correlated wave function

$$|\tilde{0}\rangle = |0\rangle + 0.7|(ps)_{1^-} \otimes 1^-;0\rangle + 0.1|(sd)_{2^+} \otimes 2^+;0\rangle$$

$$|0\rangle = 0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$

^{11}Li
F. Barranco et al. EPJ A11 (2001) 385



Probing ^{11}Li halo-neutrons correlations via (p,t) reaction

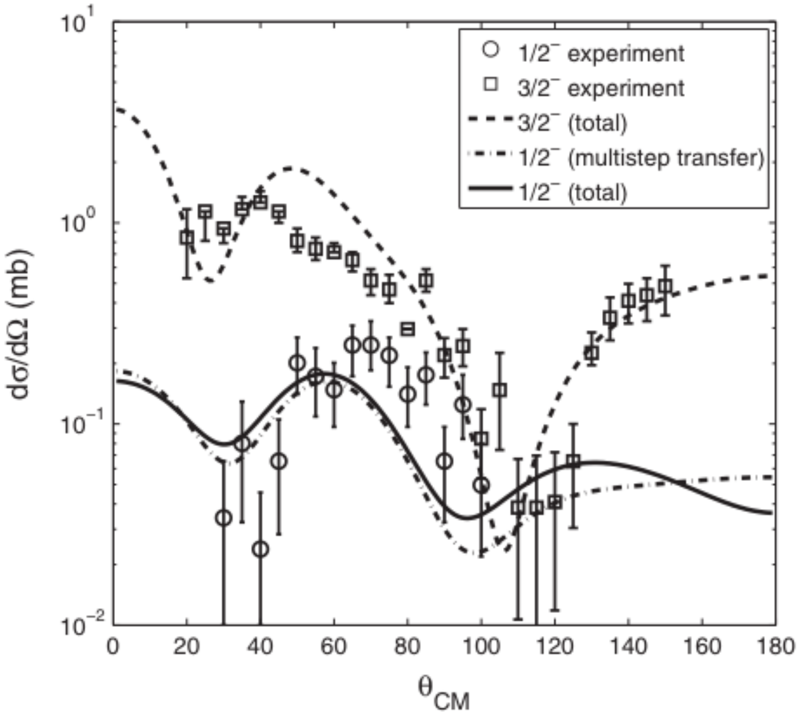
I. Tanihata et al, PRL 100 (2008) 192502

Unique information:
angular distribution associated with the excited state of the ^{9}Li core

TABLE I. Optical potential parameters used for the present calculations.

	V MeV	r_V fm	a_V fm	W MeV	W_D MeV	r_W fm	a_W fm	V_{so} MeV	r_{so} fm	a_{so} fm
$p + {}^{11}$Li [10]	54.06	1.17	0.75	2.37	16.87	1.32	0.82	6.2	1.01	0.75
$d + {}^{10}$Li [11]	85.8	1.17	0.76	1.117	11.863	1.325	0.731	0		
$t + {}^{9}$Li [12]	1.42	1.16	0.78	28.2	0	1.88	0.61	0		

Calculation of absolute two-nucleon transfer cross section by finite-range DWBA calculation



$$|\tilde{0}\rangle = |0\rangle + 0.7|(ps)_{1^-} \otimes 1^-;0\rangle + 0.1|(sd)_{2^+} \otimes 2^+;0\rangle$$

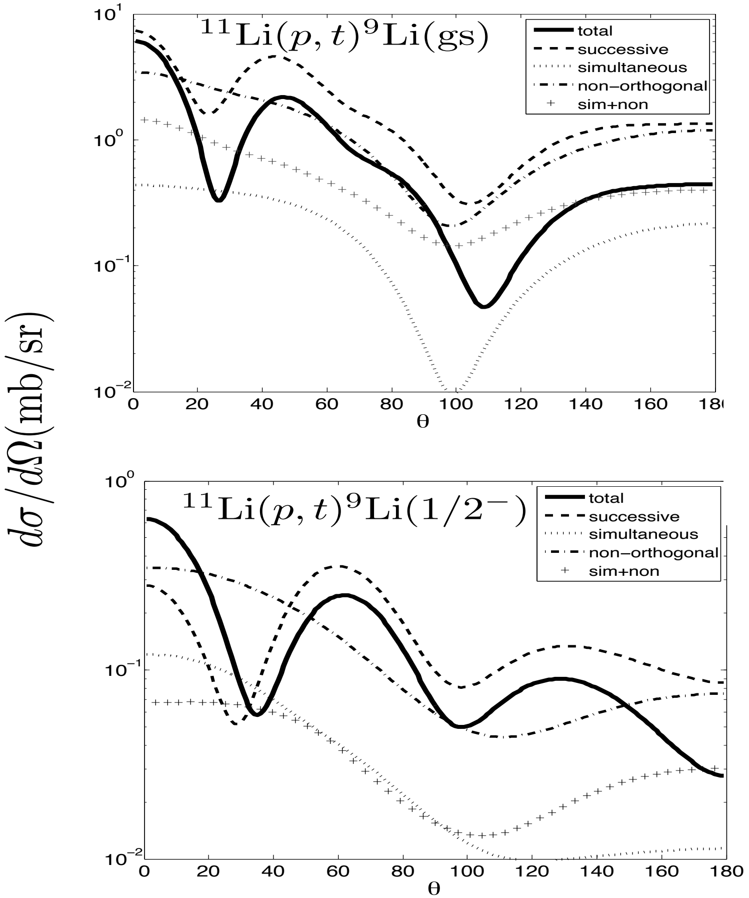
Essential component to populate the excited state of the core

This calculation should be repeated by other groups!

	$\sigma(^{11}\mathrm{Li(gs)} \rightarrow {}^{9}\mathrm{Li\ (i)})$ (mb)		
i	ΔL	Theory	Experiment
gs ($3/2^-$)	0	6.1	5.7 ± 0.9
2.69 MeV ($1/2^-$)	2	0.5	1.0 ± 0.36

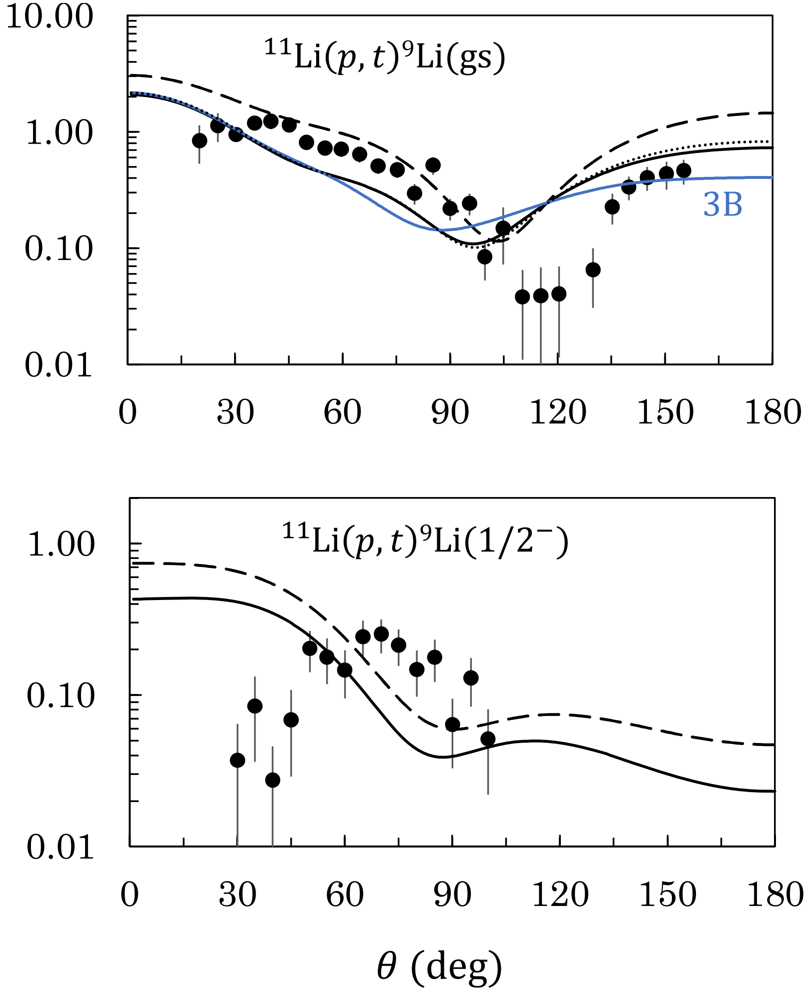
G. Potel et al., PRL 105 (2010) 172502

11Li w.f.: 50% 1- admixture
1% 2+ admixture

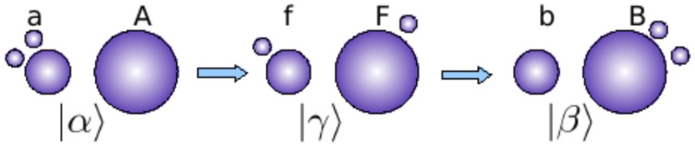


11Li w.f. : 10% 2+ admixture

P. Descouvemont, PLB **862** (2025) 139356



Second order DWBA



Potel *et al.*, PRL **107** 092501 (2011)
Potel *et al.*, PRL **105** 172502 (2010)

$$\sigma \sim |T_{2NT}|^2 = \left| \boxed{\sum_{j_f, j_i} B_{j_f} B_{j_i}} \left(T^{(1)} + T^{(2)}_{succ} + T^{(2)}_{NO} \right) \right|^2 \Rightarrow$$

coherent sum of many terms

structure input:
coefficients of the initial and final wavefunctions (e.g., from a BCS calculation)

Successive transfer

$$\begin{aligned} T^{(2)}_{succ}(j_i, j_f) = 2 \sum_{K,M} \sum_{\substack{\sigma_1\sigma_2 \\ \sigma'_1\sigma'_2}} \int & d\mathbf{r}_{fF} d\mathbf{r}_{b1} d\mathbf{r}_{A2} [\Psi^{j_f}(\mathbf{r}_{A1}, \sigma_1)\Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)]^{0*}_{0} \\ & \times \chi^{(-)*}_{bB}(\mathbf{r}_{bB}) v(\mathbf{r}_{b1}) [\Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)\Psi^{j_i}(\mathbf{r}_{b1}, \sigma_1)]^{K}_{M} \\ & \times \int d\mathbf{r}'_{fF} d\mathbf{r}'_{b1} d\mathbf{r}'_{A2} G(\mathbf{r}_{fF}, \mathbf{r}'_{fF}) [\Psi^{j_f}(\mathbf{r}'_{A2}, \sigma'_2)\Psi^{j_i}(\mathbf{r}'_{b1}, \sigma'_1)]^{K}_{M} \\ & \times \frac{2\mu_{fF}}{\hbar^2} v(\mathbf{r}'_{f2}) [\Psi^{j_i}(\mathbf{r}'_{b2}, \sigma'_2)\Psi^{j_i}(\mathbf{r}'_{b1}, \sigma'_1)]^{0}_{0} \chi^{(+)}_{aA}(\mathbf{r}'_{aA}) \end{aligned}$$

Study of (*p*,*t*) reaction on ^{11}Li at 6 MeV/nucleon

X. Wang,[1,2] J. L. Ferreira,[3] J. Lubian,[3] J. Tanaka,[2] R. Kanungo,[4,5] M. Alcorta,[5] N.Aoi,[2,6] H. Bidaman,[7] C. Burbadge,[7] G. Christian,[5] S. Cruz,[5] B. Davids,[5] A. Diaz Varela,[7] J. Even,[5,8] G. Hackman,[5] J. Henderson,[5] S. Ishimoto,[9] S. Kaur,[4] M. Keefe,[4] R. Krücken,[5,10] K.G. Leach,[5] J. Lighthall,[5] E. Padilla Rodal,[5,11] J. S. Randhawa,[4] P. Ruotsalainen,[5] A. Sanetullaevd,[5] J. K. Smith,[5] O. Workman,[4] and I. Tanihata[1]

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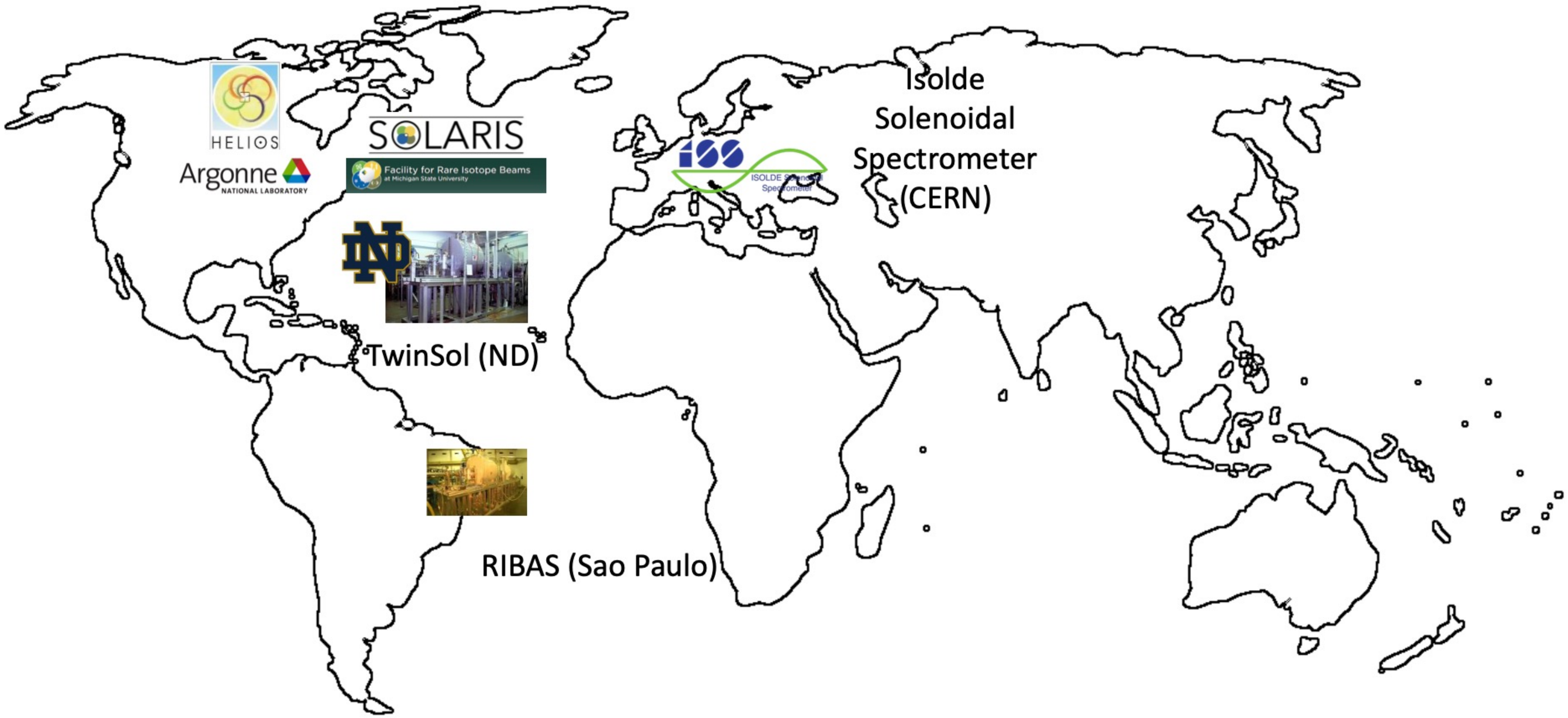
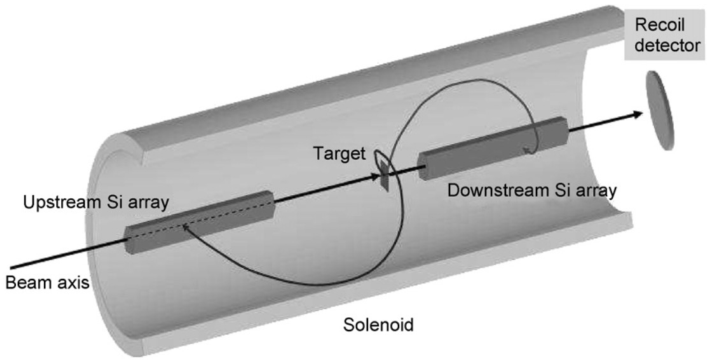
Solenoidal spectrometers around the world

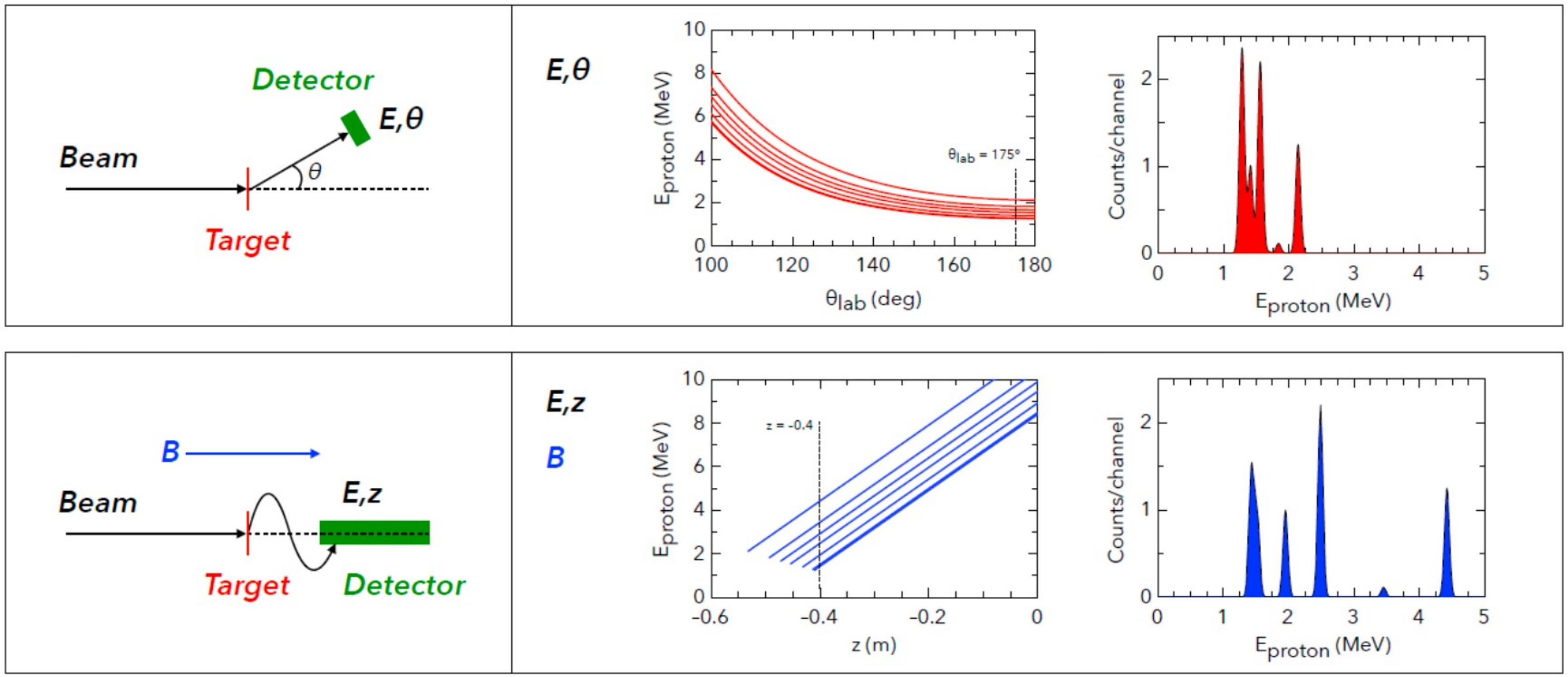




A.H. Wuosmaa et al., NIM A580 (2007) 1280

$$T_{\mathrm{cyc}} = \frac{2\pi r}{v_\perp} = \frac{2\pi}{\mathscr{B}}\frac{m}{qe}.$$

The solenoidal-spectrometer technique



Cluster structure in ^{10}Be and dipole excitations

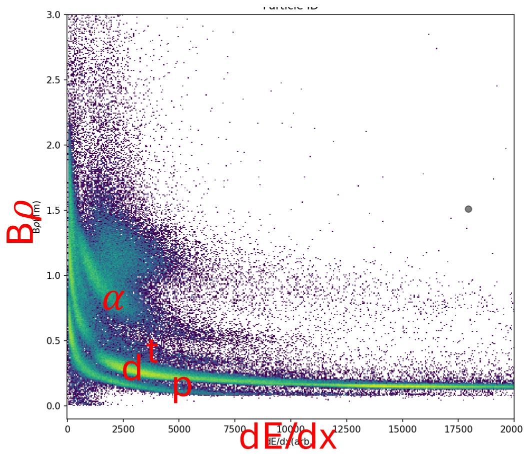
- Cluster structure in ^{10}Be g.s. has been confirmed by cluster knockout reaction.

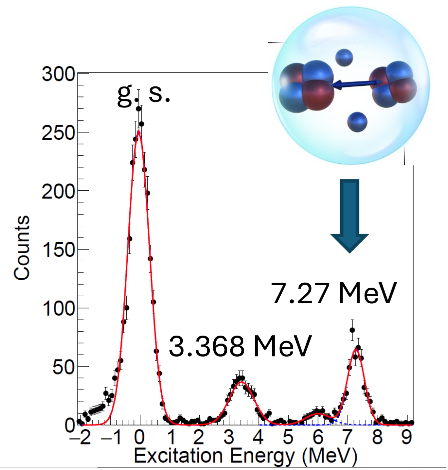
P. J. Li *et al.*, Phys. Rev. Lett. 131, 212501 (2023)

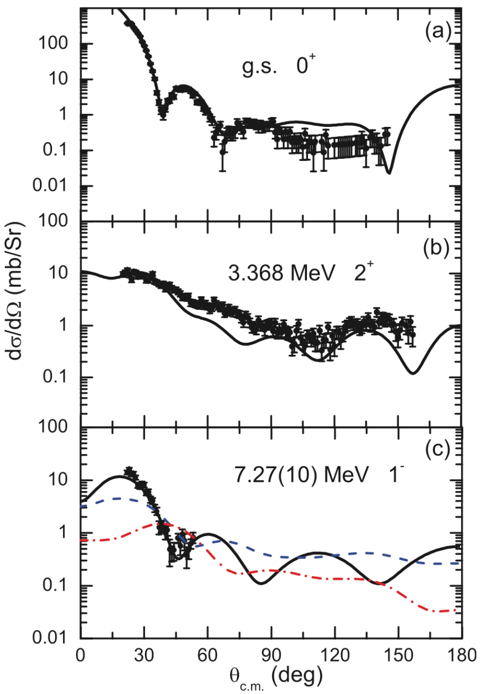
- ^{10}Be(*d,d'*)^{10}Be

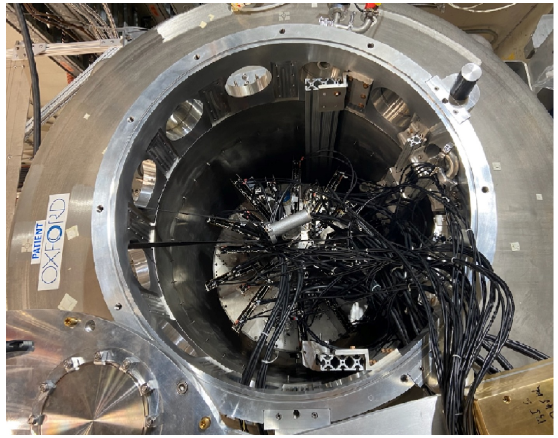
AT-TPC Filled with D_2: 600 Torr
^{10}Be beams @ 9.1 MeV/u
2000 pps
SOLARIS field: B=3 T

α+α+n+n 4-body cluster structure









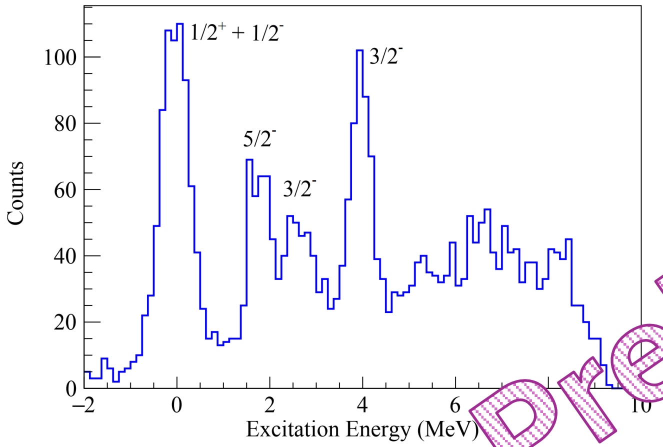
- Energy resolution ~ 700 keV
- Simultaneous measurement of (*d,p*) (*d,t*) and (*d,d'*) reactions with **~100 pps** beam within one week!
- Open wide opportunities in the future with weak exotic beams

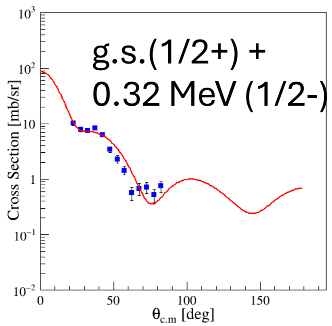
J. Chen, Y, Ayyad *et al*. Phys. Rev. Lett. 134, 012502 (2025).

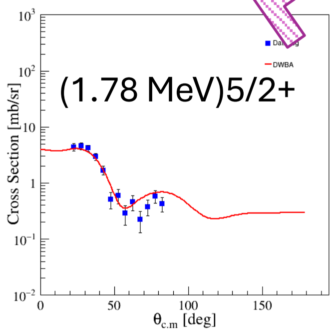
One-neutron removal reaction on ^{12}Be

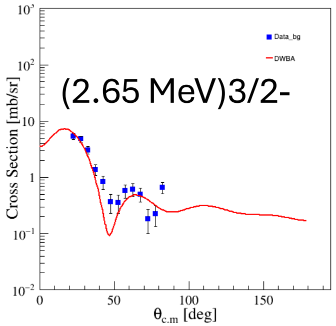
- **^{12}Be(p,d)^{11}Be measurement**
- Configuration mixing in the psd shell
- Occupancy in the $1s_{1/2}, 0p_{1/2}, 0d_{5/2}$ of the ^{12}Be g.s.

Neutron removal reaction ^{12}Be(p,d)^{11}Be

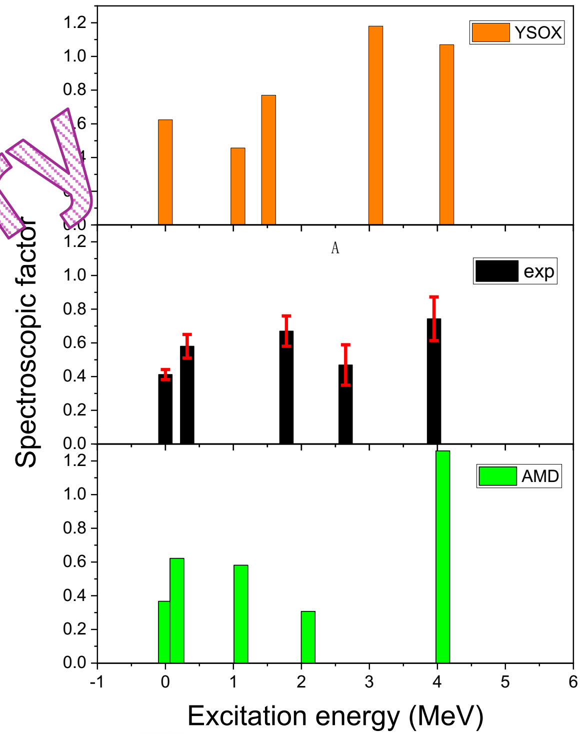








AT-TPC Filled with H_2: 300 Torr
HELIOS @ ATLAS: B=2.5 T



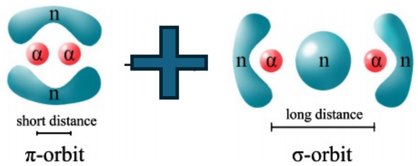
shell model → Single-particle structure

experiment

AMD model → Cluster structure

Courtesy: Qing Zha

34.5%



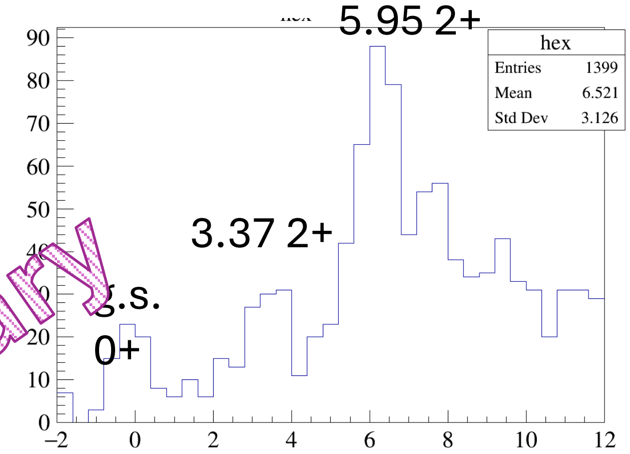
65.5%

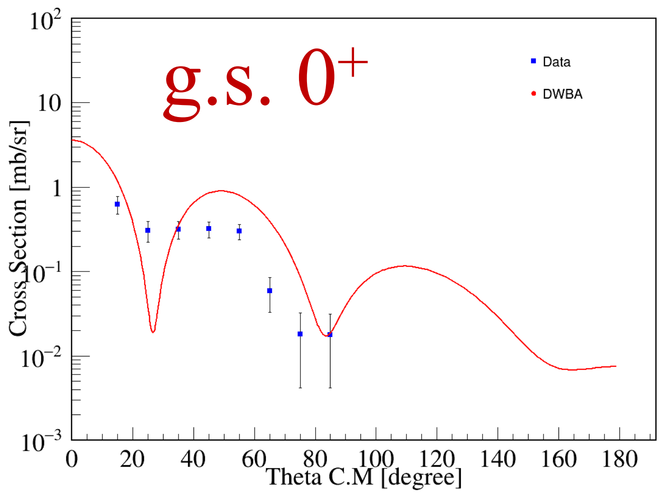
Two-neutron removal reaction on ^{12}Be

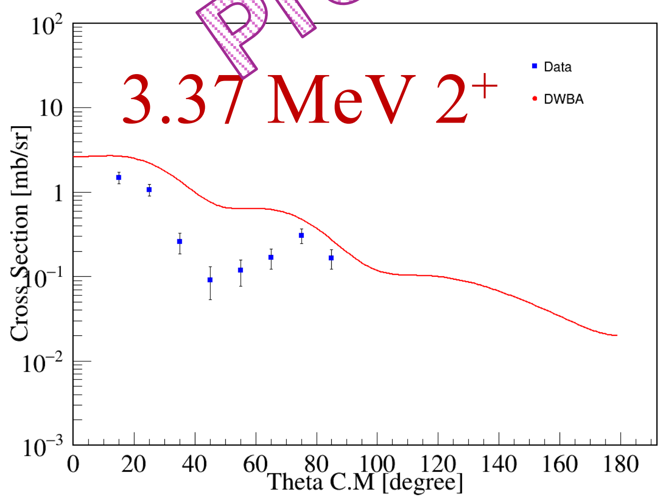
-- How much core excitations in ^{12}Be g.s.?

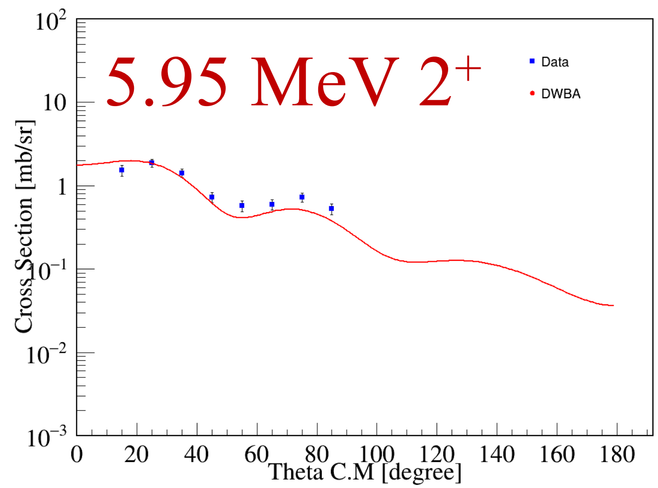
^{12}Be(p.t) excite the g.s. and low-lying state of ^{10}Be.

- ➢ The g.s. and first 2+ state was populated.
- ➢ The second 2+ state at ~6 MeV was strongly populated.





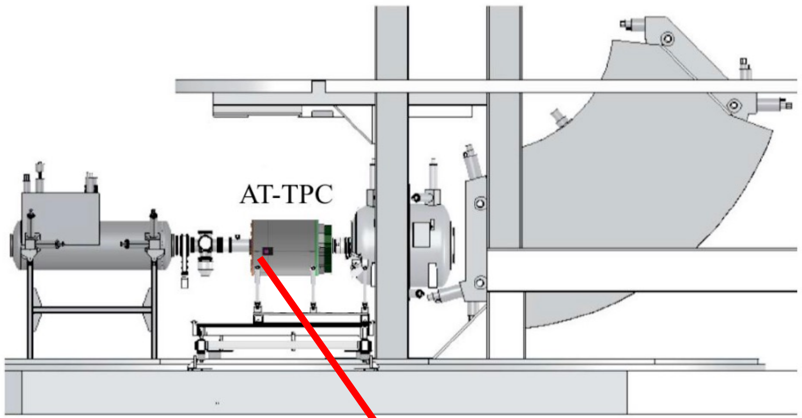




New measurement of dipole resonance of ^{11}Li

-- Proton inelastic scattering of ^{11}Li with AT-TPC+S800

The S800 spectrograph beamline at FRIB



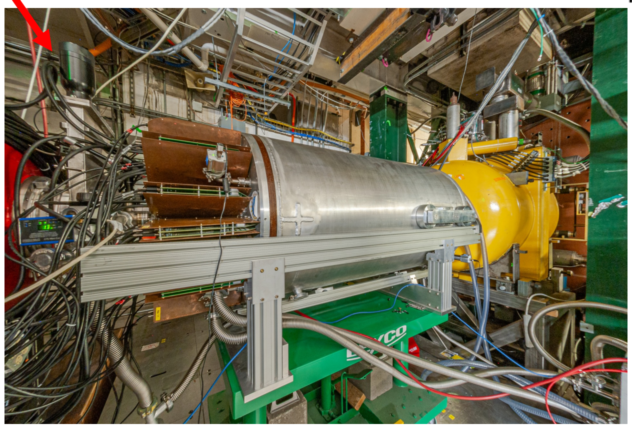
1E+4 pps, ~53.4 MeV/u, ^{11}Li beam

Target: AT-TPC filled with:

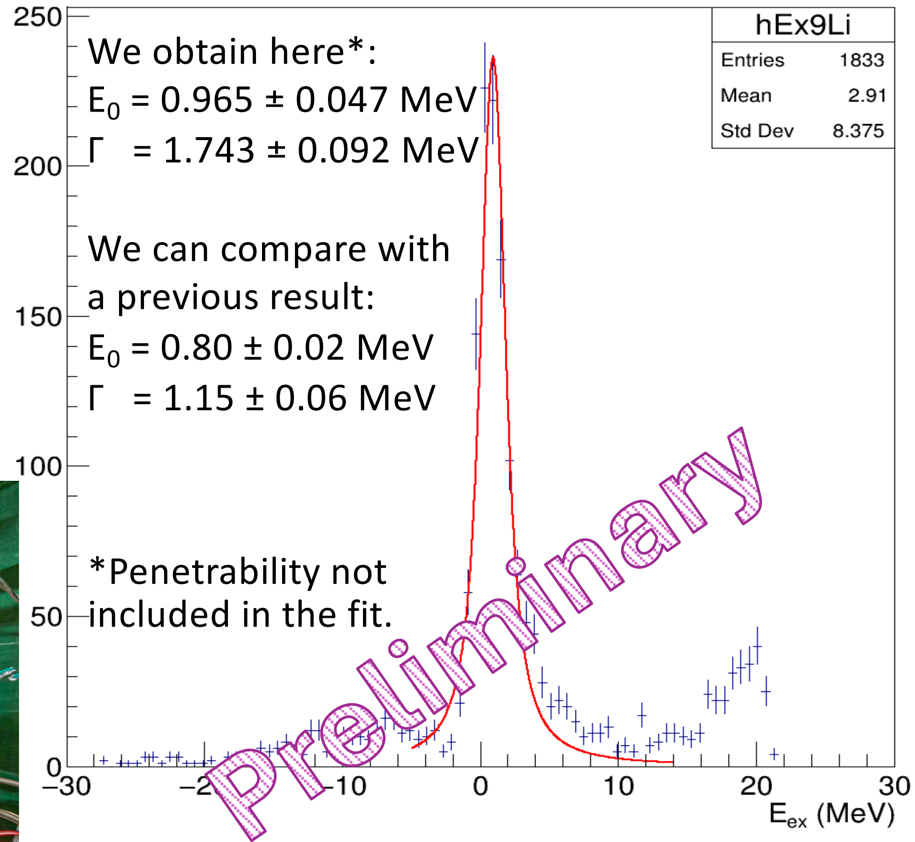
A) H_2@600Torr

B) 90%H_2+10%CF_4@700Torr

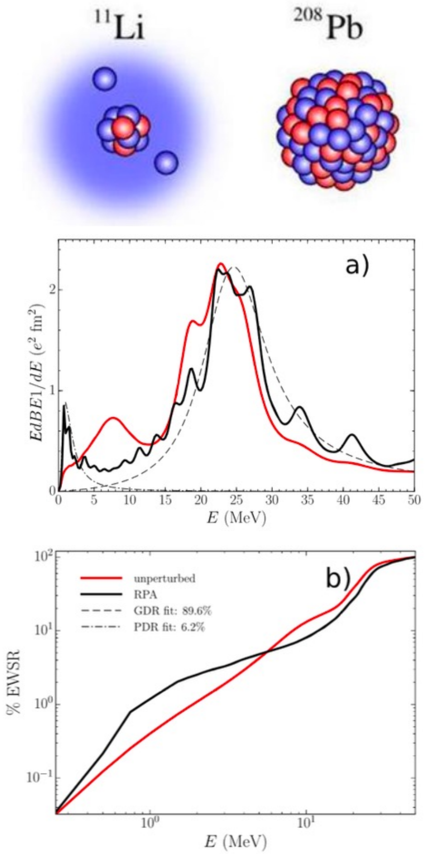
Courtesy: Yassid Ayyad



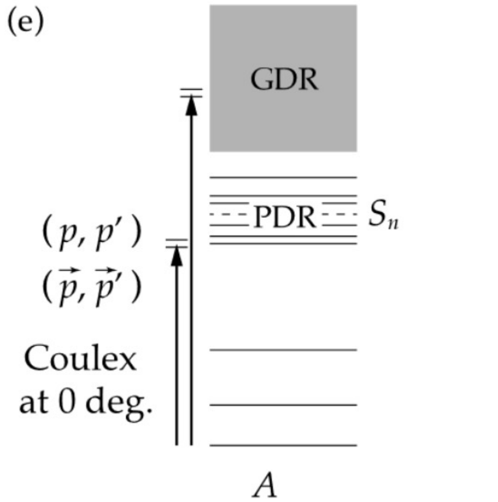
^{11}Li + p → ^{11}Li* + p' → ^{9}Li + 2n + p'



Electromagnetic response of two-neutron halo nucleus ^{11}Li



Phys. Scr. 94 (2019) 114002



proton Coulex at 0 deg.

Progress in Particle and Nuclear Physics 106 (2019) 360–433

- Scattered protons: Inclusive measurement relevant to the full photo-absorption cross section containing all the decay channels.
- Broad excitation energy region.
- Polarization transfer observables measured.
- Absolute photo-absorption cross sections extracted from the measured proton scattering cross section.
- Branching ratios to decaying channels.

Tamii and Kobayashi AAPPS Bulletin (2024) 34:7
A. Tamii et al. Phys. Rev. Lett. 107, 062502 (2011)

Needs for a “novel” TPC design

Increase TPC ‘s rate capabilities and use rare/hazardous gases

One and two nucleon transfer reactions **(t,p)** and **(^{3}He,d) and (^{3}He,p)**

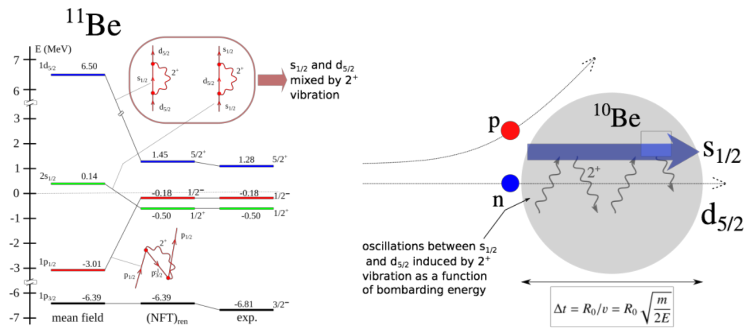
- Isoscalar np pairing
- Giant Pairing Vibrations (GPV)
- Pairing correlations
- Shape co-existence
- Astrophysics

Efficient determination of excitation functions

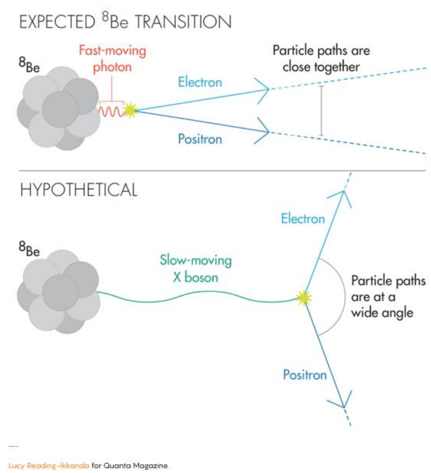
- Resonant scattering
- Transfer reactions as a function of bombarding energy

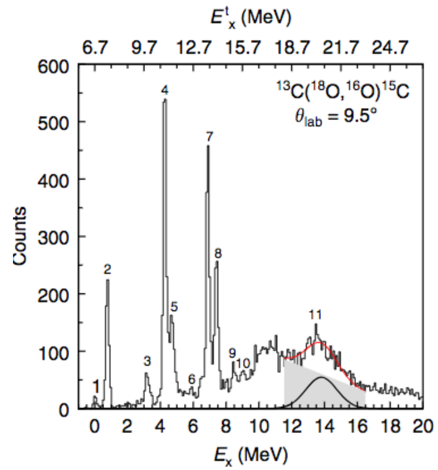
Charge exchange reactions (t,^{3}He)

Search for exotic BSM standard physics.

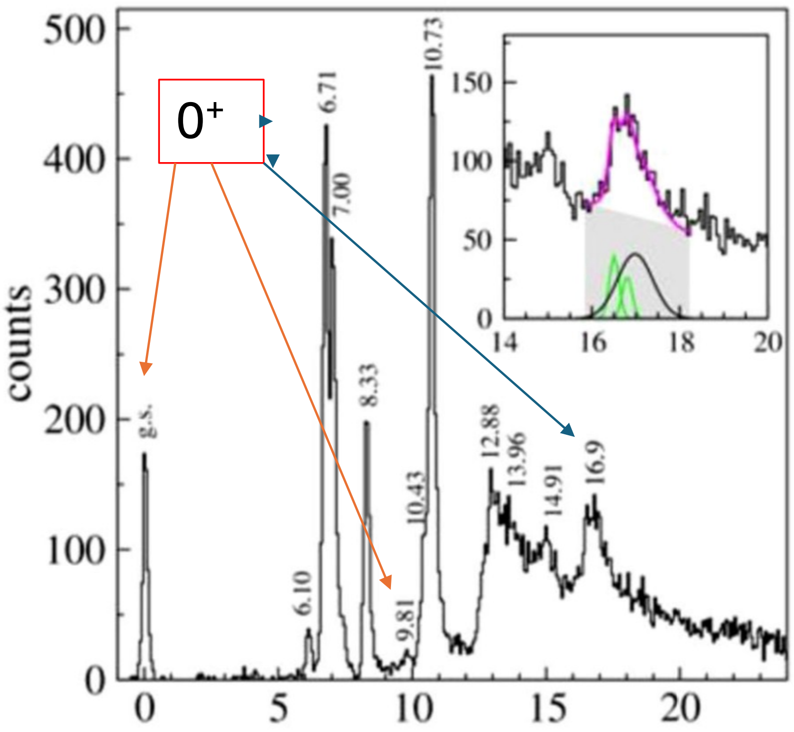


Barranco, GP, Broglia, Vigezzi PRL **119**, 082501 (2017)



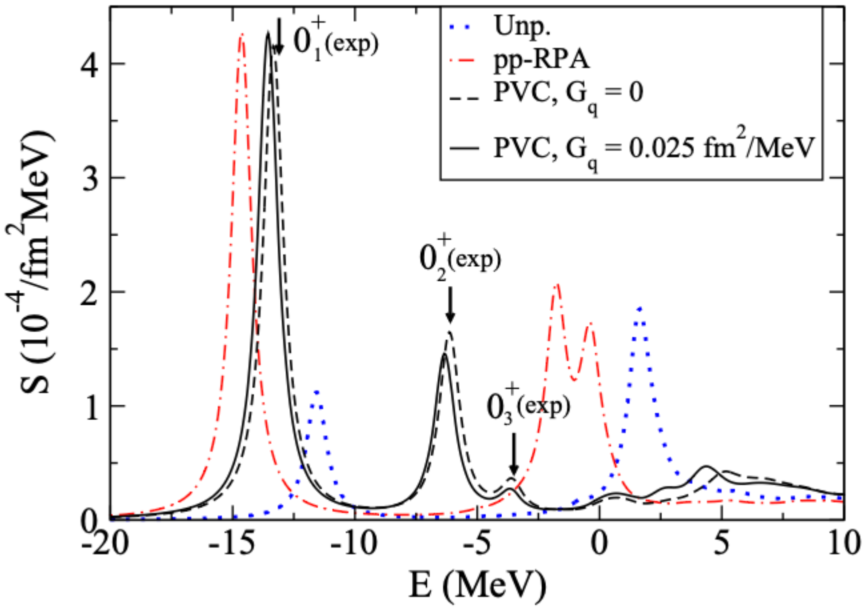


Several unsuccessful experimental searches have been carried out over the years , but recently a bump has been detected at E* ≈ 16 MeV in the reaction $^{12}C(^{18}O,^{16}O)^{14}C$ at E_{lab} = 84 and 275 MeV and interpreted as a signature of GPV



F. Cappuzzello et al., Nat. Comm. 6 (2015) 6743

A new theoretical calculation of the pair strength function (no cross sections yet!)



F. Barranco et al., PRL 134 (2025) 062501

We cannot compute two-neutron transfer cross sections, and for the moment we limit ourselves to pairing strengths

$$S_k(R_{box}) = \Big| \sum_{pp'} X(k)_{pp'} \int dr \psi_p(r) \psi_{p'}(r) 1/V_0 dV/dr(r) < j_p || Y_0 || j_{p'} > + \sum_{hh'} Y(k)_{hh'} \int dr \psi_h(r) \psi_{h'}(r) 1/V_0 dV/dr < j_h || Y_0 || j_{h'} > \Big|^2$$

$$S(E; R_{box}) = \sum_k S_k(R_{box}) \times \mathcal{L}(E - E_k; W)$$

$$S(E) = \frac{\sum_{i=1,N_{box}} S(E; R_{box,i})}{N_{box}}$$