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Spectroscopy of neutron orbitals in ^{16}C: A test for p-sd interactions

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Light Nuclei ESNT workshop

MICHIGAN STATE
UNIVERSITY

U.S. DEPARTMENT OF
ENERGY
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Science

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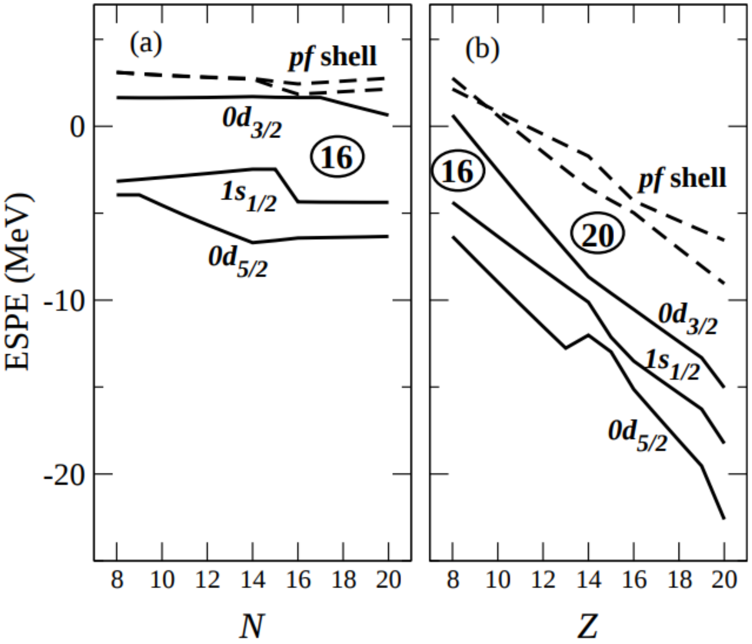
Spectroscopy as a probe of nuclear interactions

O. Sorlin, M.-G. Porquet Prog. Part. and Nuc. Phys 61 (2008) 602–673



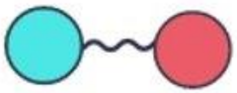
Nuclear Interaction

$$H = \sum_{i=1}^{A} T_i + \sum_{i=1}^{A} \sum_{j \neq i}^{A} V_{ij}$$

Spectroscopy as a probe of nuclear interactions

GAP evolution

nucleon-nucleon interaction



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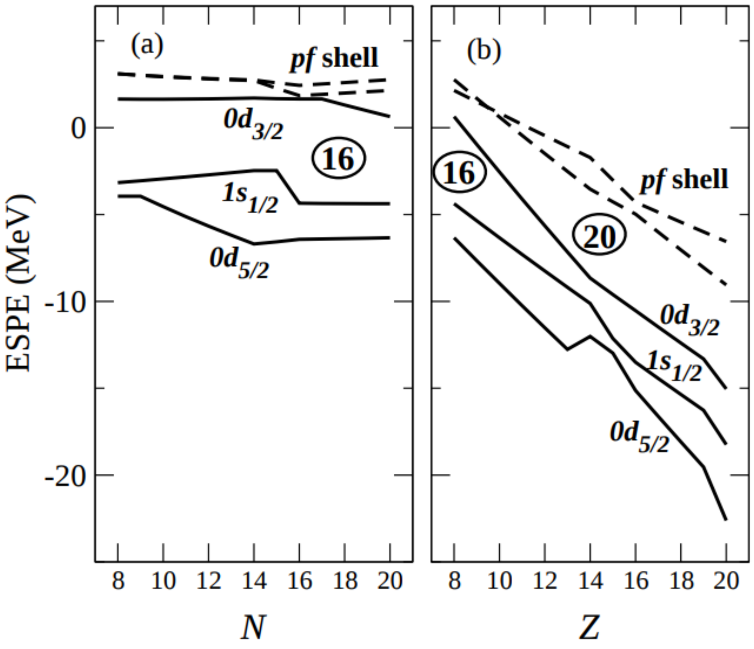
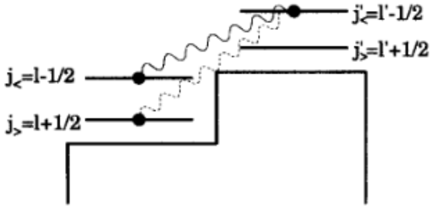


Spectroscopy as a probe of nuclear interactions



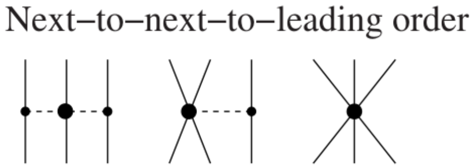
[1] T.Otsuka Nuclear Physics A734 (2004) 365-368

Shell Model + Interaction
SFO-tls in n-rich carbon isotopes [1].

$$\sum_n |\phi_{nj}\rangle\langle\tilde{\phi}_{nj}| + \frac{1}{\pi}\int_{L_+} |\phi_j(k)\rangle\langle\phi_j(k^*)|\, dk = 1$$

[2] N. Michel, W. Nazarewicz, M. Płoszajczak and K. Bennaceur, Phys. Rev. Lett. 89 (2002) 042502.

Gamow Shell Model (GSM)
Explicit consideration of the coupling to the continuum [2].



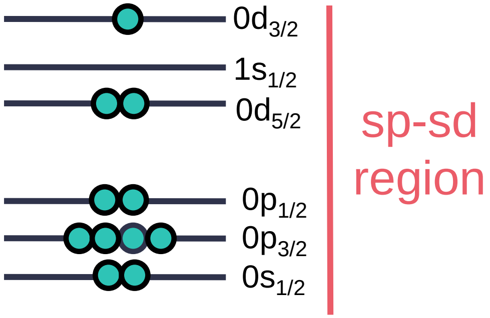
[2] E.Epelbaum, H.W.Hammer, and U.G. MeiBner, Rev. Mod. Phys. 81 (2009) 173.

Ab initio approaches
SCGF with $\mathrm{NNLO_{sat}}$: EFT calculation in medium-mass nuclei [3].

Probing neutron orbitals in ^{16}C

$\mathcal{N}$=8 gap
^{16}C(d,t)^{15}C

$\mathcal{N}$=16 gap
^{16}C(d,p)^{17}C



Use of transfer reactions in the sp-sd region to study the shell evolution and constrain the nucleon-nucleon interaction

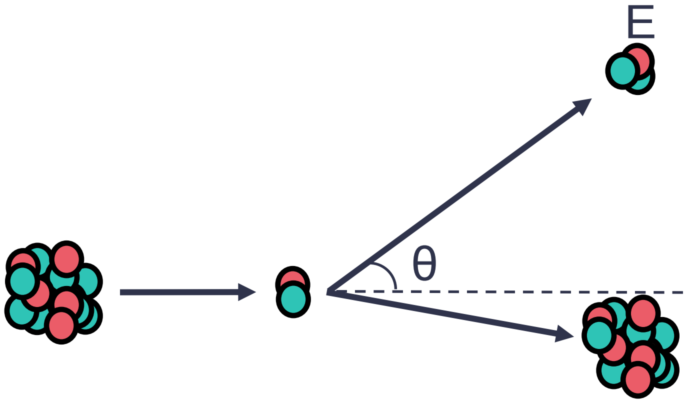
Probing Missing-mass technique

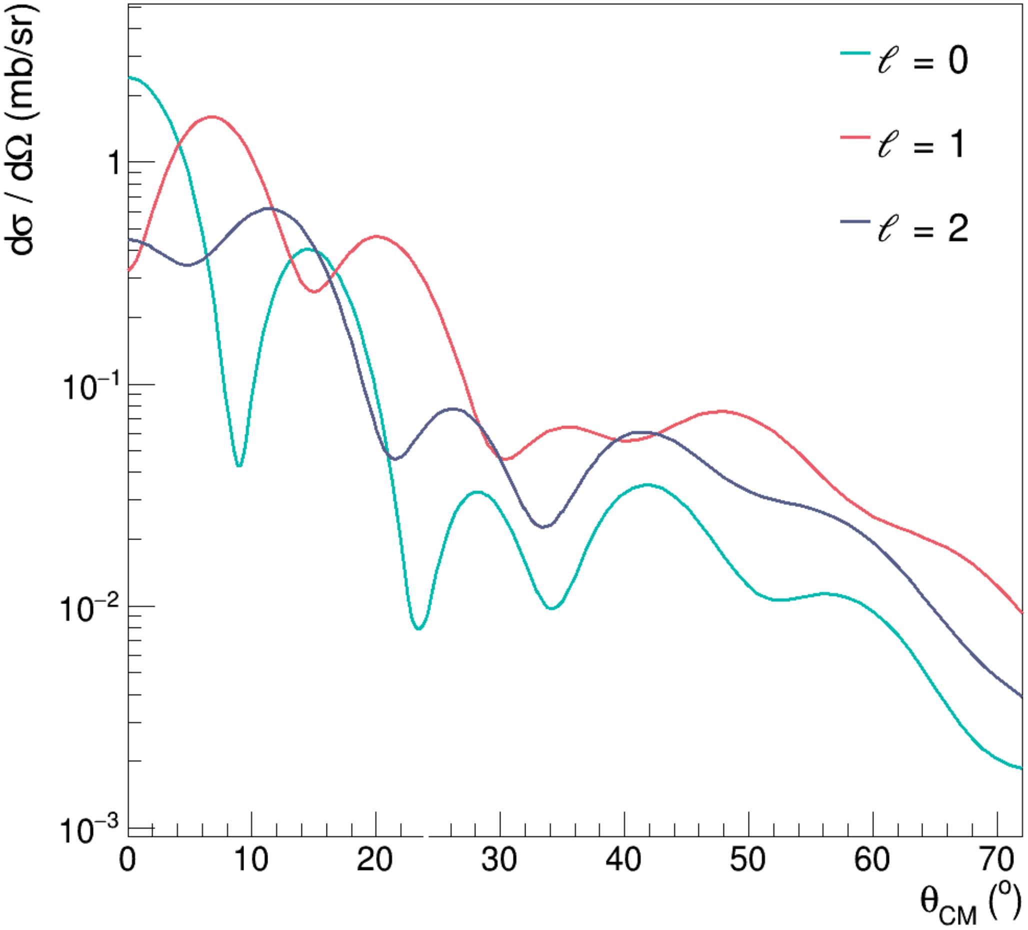
Missing mass technique:

Light Particle:

E,θ ❯ E_x

dσ/dΩ ❯ $\ell + C^2S$

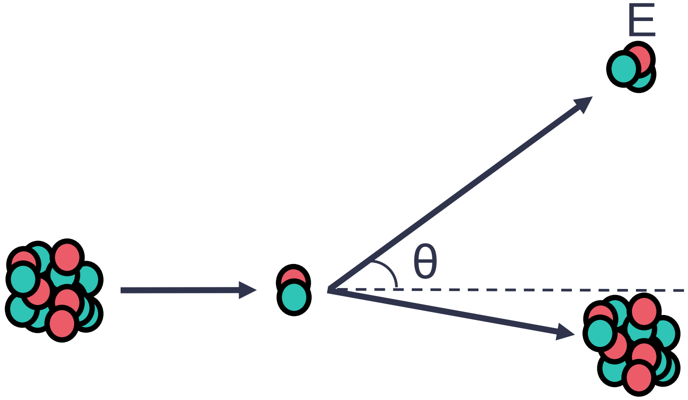


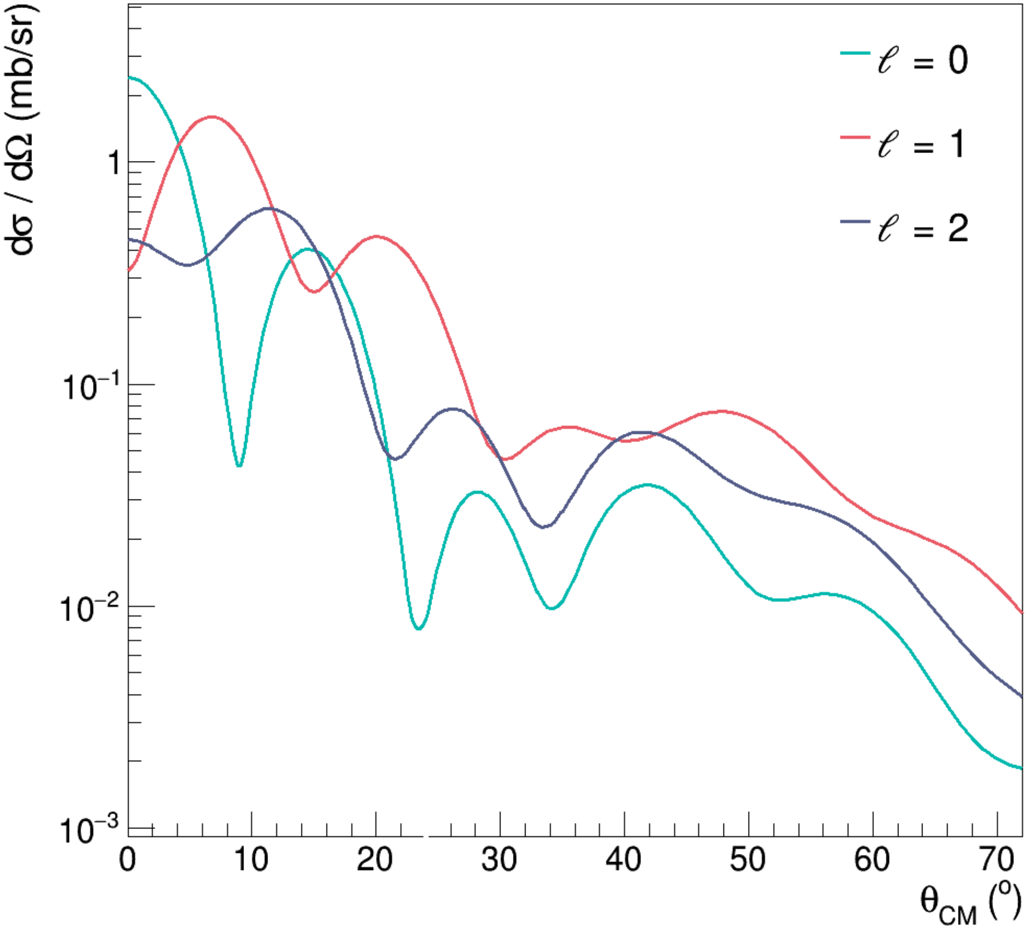


Probing Missing-mass technique

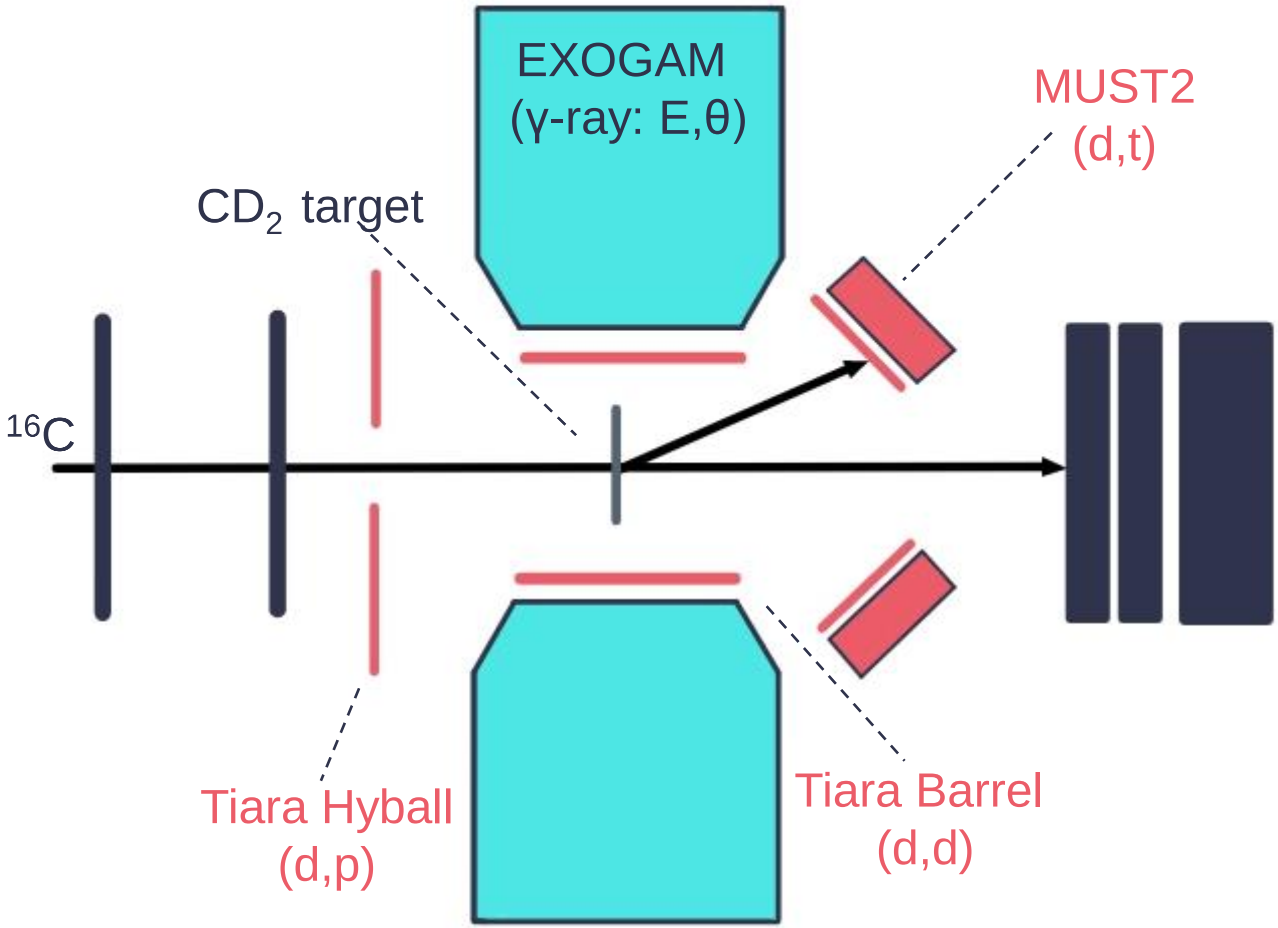
Missing mass technique:

Light Particle:	E,θ dσ/dΩ	❯	E_x ℓ + C^2S





Solid Target setup



EXOGAM
(γ-ray: E,θ)

MUST2
(d,t)

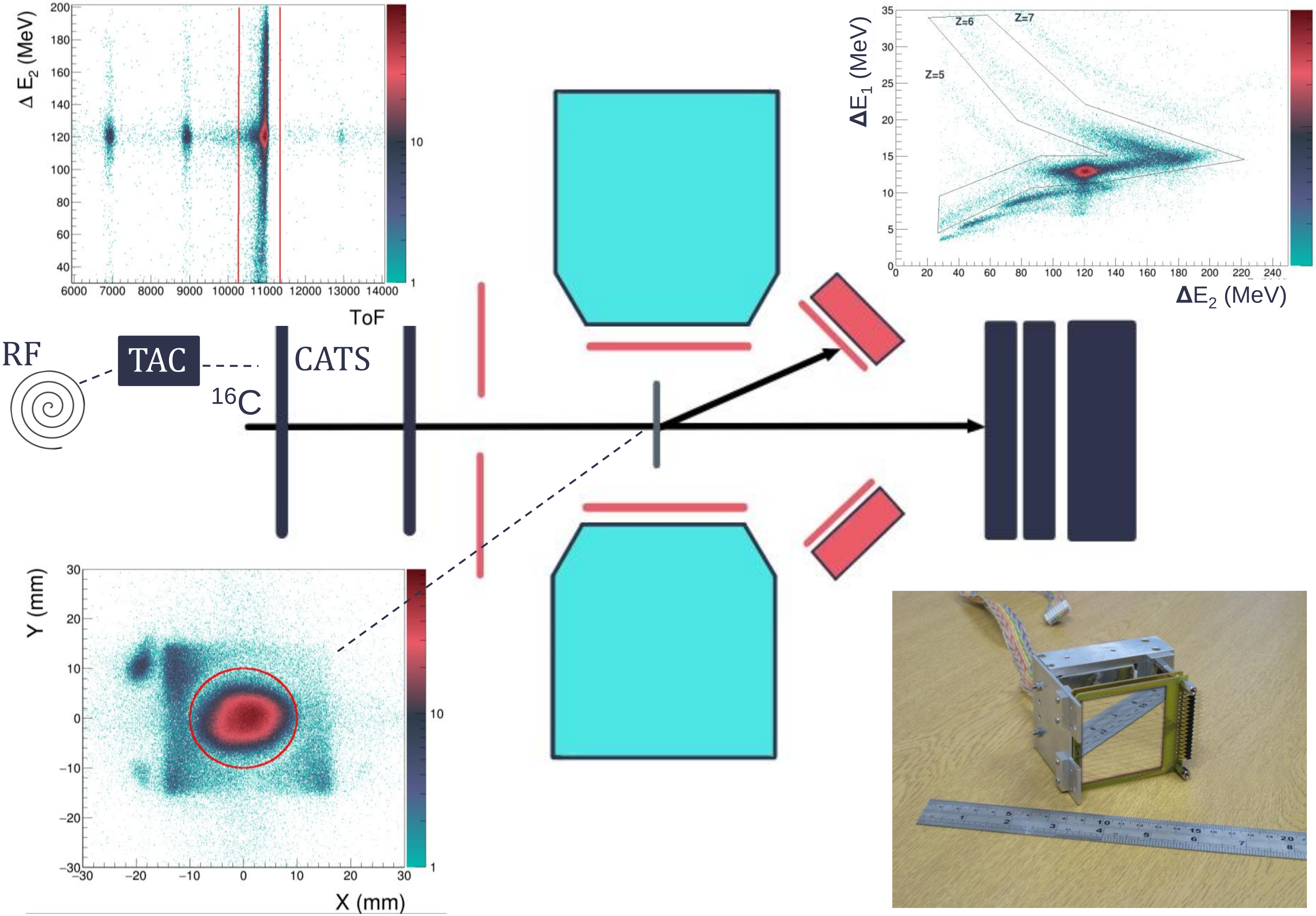
CD_2 target

^{16}C

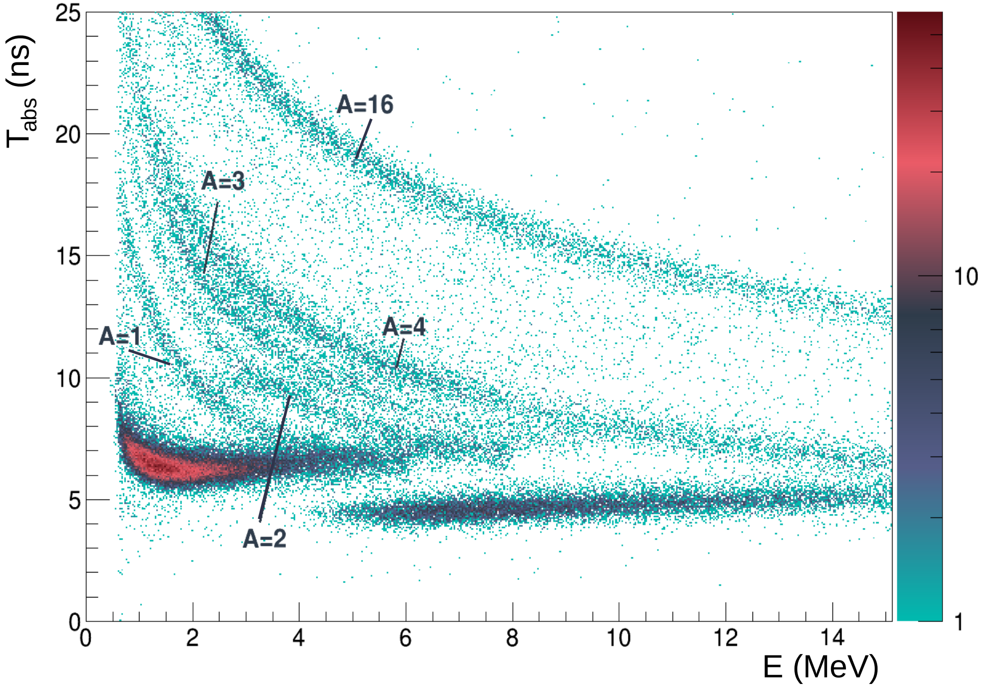
Tiara Hyball
(d,p)

Tiara Barrel
(d,d)

Solid Target setup

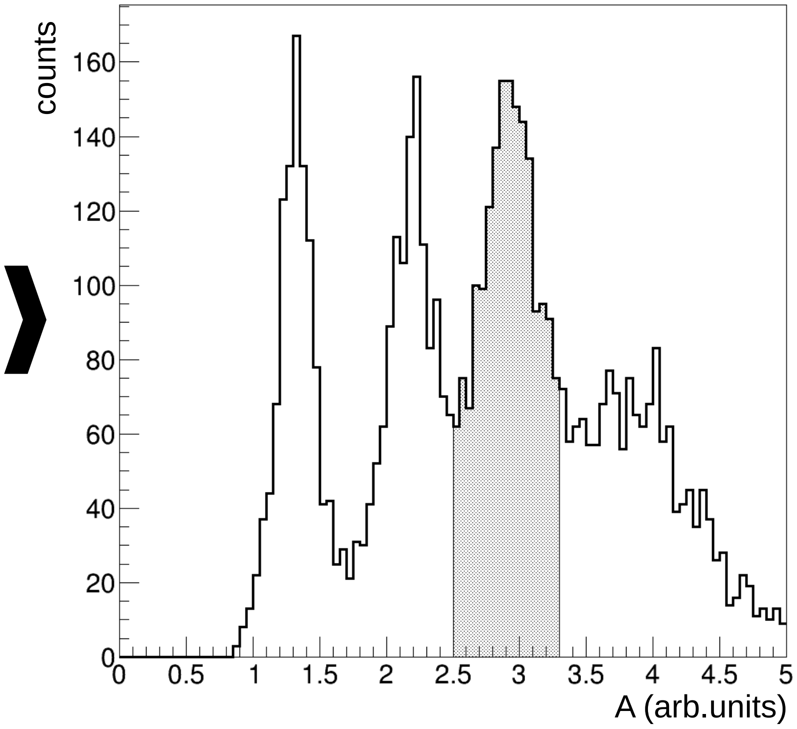


Light Particle PID



❯

A=3 selection gate



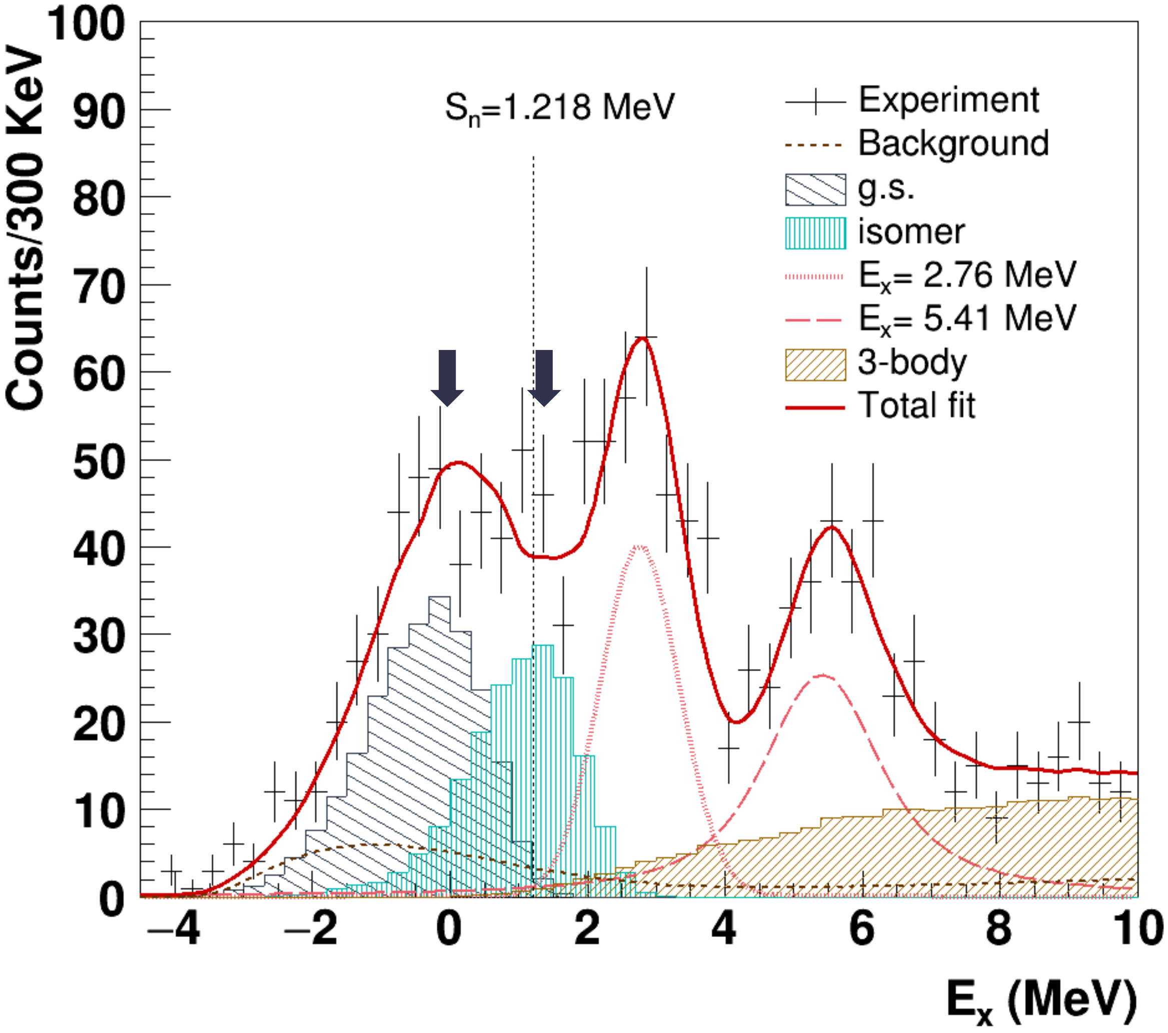
$^{16}C(d,t)^{15}C$: E_x

Bound States

E_x(g.s) = 0 MeV
E_x(i.s) = 0.740 MeV

E_x and C^2S well known!

Experimental resolution obtained with the nptools simulation package.



$^{16}C(d,t)^{15}C$: E_x:Unbound States

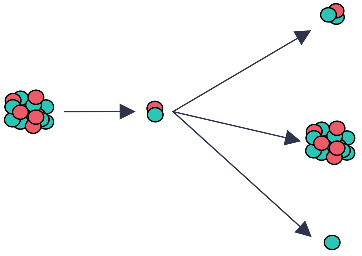
Unbound States

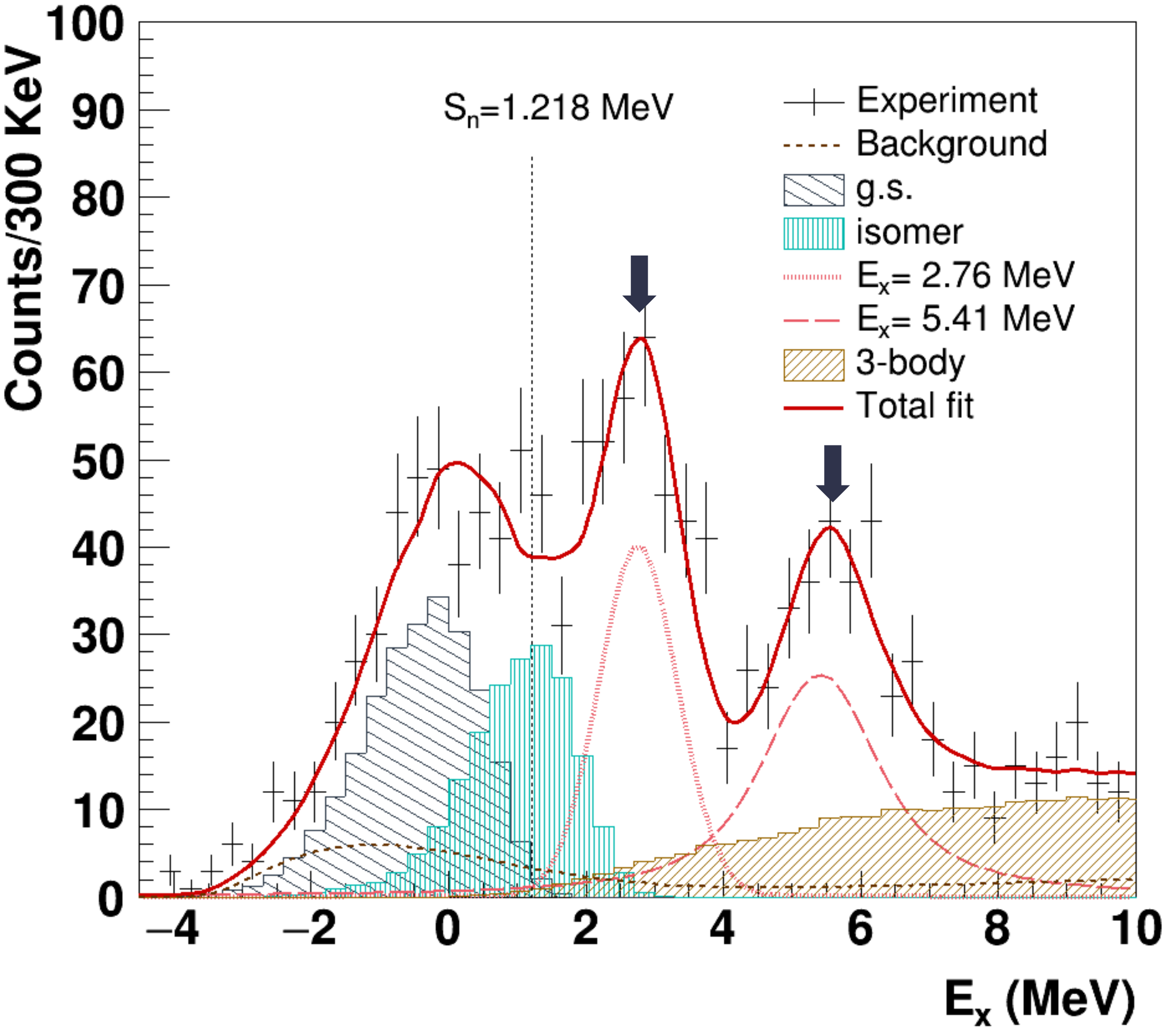
$E(R_1) = 3.1$ MeV
$E(R_2) = 5.41(11)$ MeV

C^2S not known!

BW$\otimes$ σ_{exp}-> lineshape

PS: $^{16}C+d \rightarrow\, ^{14}C+t+n$

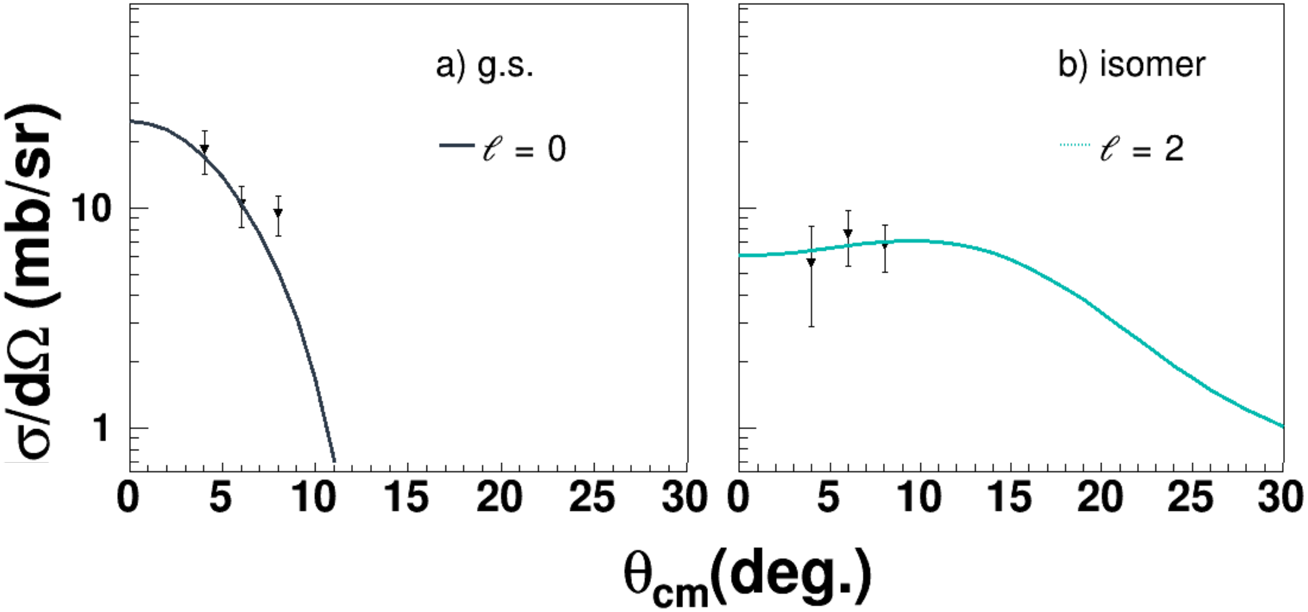




$^{16}C(d,t)^{15}C$: $d\sigma/d\Omega$

DWBA:
FRESCO

- Entrance channel: Modified global parametrization of Haixa. [1]
- Exit channel: OMP from Pang et al. [2]
- <d|t> vertex: Ab-initio (QFMC) + realistic n-n and n-n-n potentials. [3]



Consistent with known assignment of **1/2⁺** and **5/2⁺**

$C^2S(gs) = 0.30(4)$

$C^2S(is) = 0.56(9)$

$^{16}C(d,t)^{15}C$: dσ/dΩ

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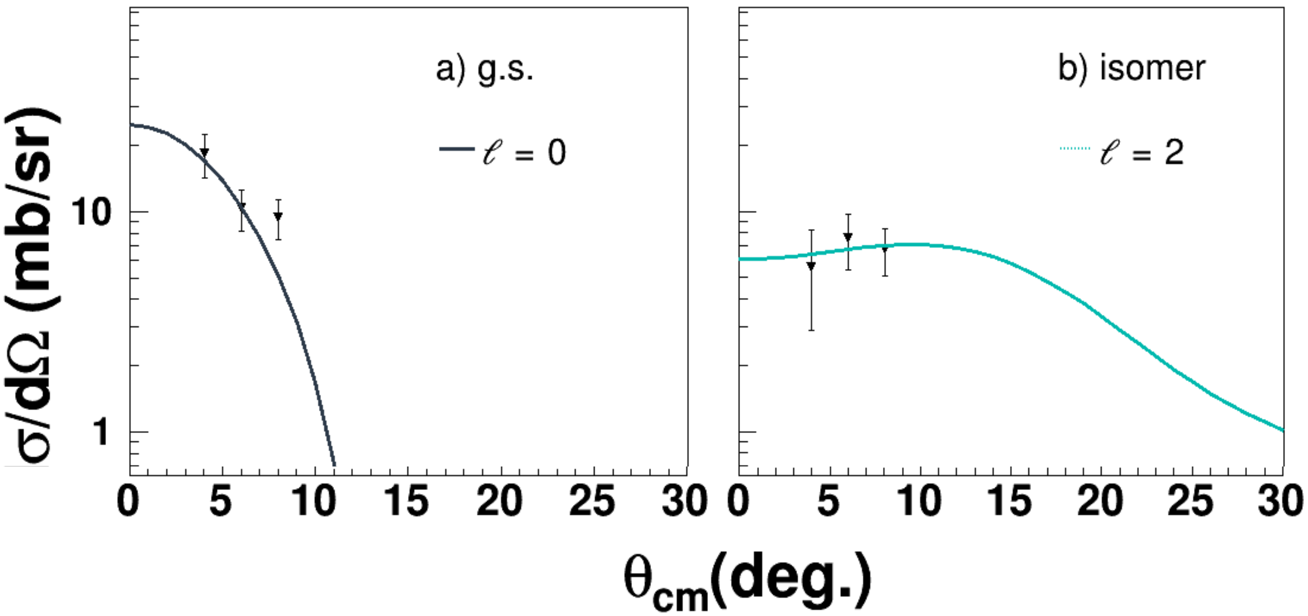


Consistent with known assignment of **1/2$^+$** and **5/2$^+$**

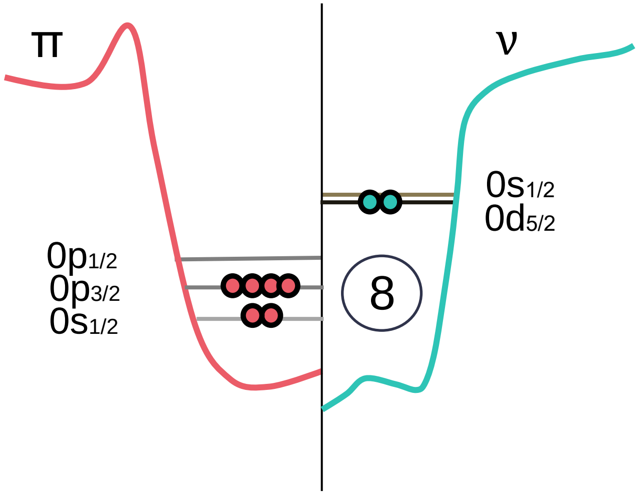
C^2S(gs) = 0.30(4)

C^2S(is) = 0.56(9)

Reduction of the C^2S?

- The observed spectroscopic factors show a clear reduction with the expected values from the IPM.
- This factor agrees well with other RF observed in transfer reactions.
- Our data range is too limited for a detail study of the cross-sections in order to bring more light into this reduction.

$$^{16}C = {}^{14}C \otimes \nu(sd)^2$$

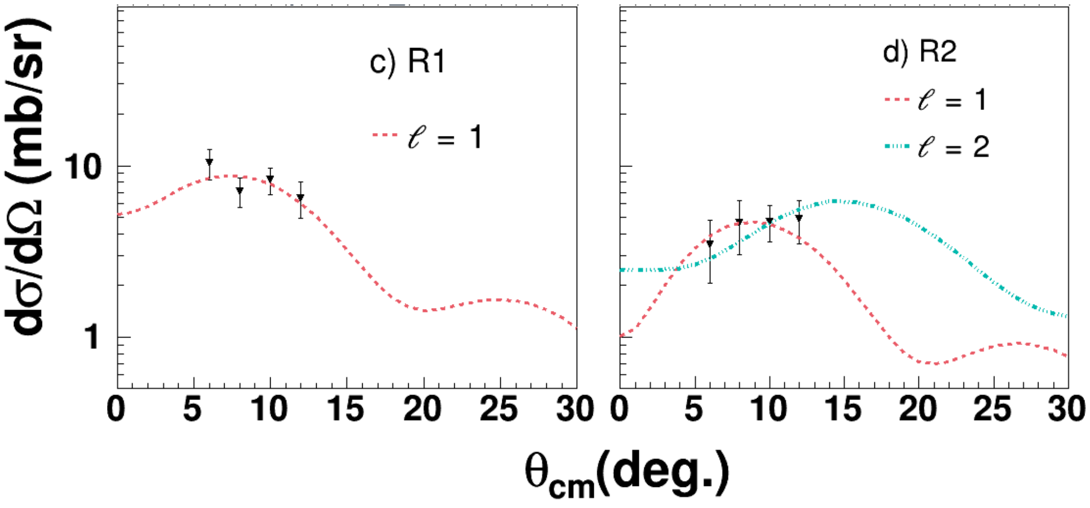


- Previous experiments with ^{12}C and ^{14}C confirmed it as a closed core [1].
- $^{14}C(d,p)^{15}C$ -> Bound States found close to 1[2].

$$\begin{array}{lcl} C^2S(gs) = 0.30(4) & \rangle & C^2S_{norm}(gs) = 0.65(16) \\ C^2S(is) = 0.56(9) & \rangle & C^2S_{norm}(is) = \underline{+\,1.35(32)} \\ & & \qquad\qquad\qquad 2 \end{array}$$

[1] G. Mairle and G.J. Wagner , Nucl. Phys. A 253 (1975) 253
[2] B. Kay et al. Phys. Rev. Lett. 125 (2022), 022301

$^{16}C(d,t)^{15}C$: dσ/dΩ



- Most of the $0d_{5/2}$ is already exahusted by $^{16}C(d,p)^{17}C^{*}$.
- Unphysical occupancy of the $0d_{5/2}$ and $0d_{3/2}$.

Consistent with known assignment of **$1/2^{-}$**

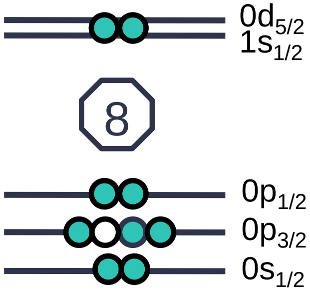
Assigned to be **$3/2^{-}$**

$C^2S_{norm}(R_1) = 1.74(9)$

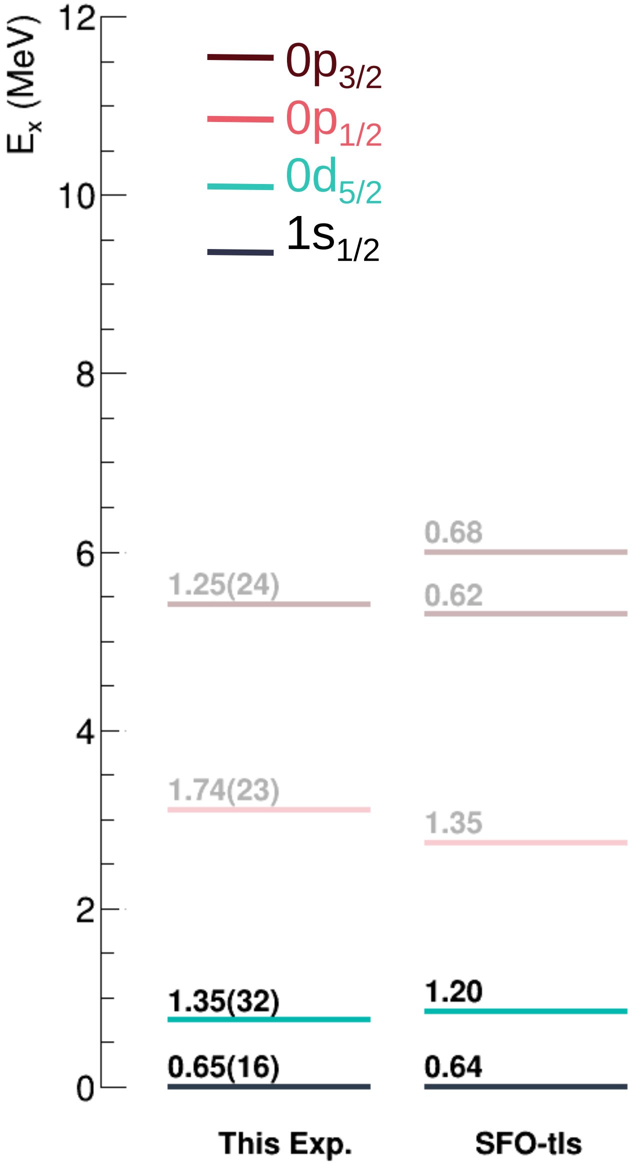
$C^2S_{norm}(R_2) = 1.25(9)$

87% $0p_{1/2}$

31% $0p_{3/2}$



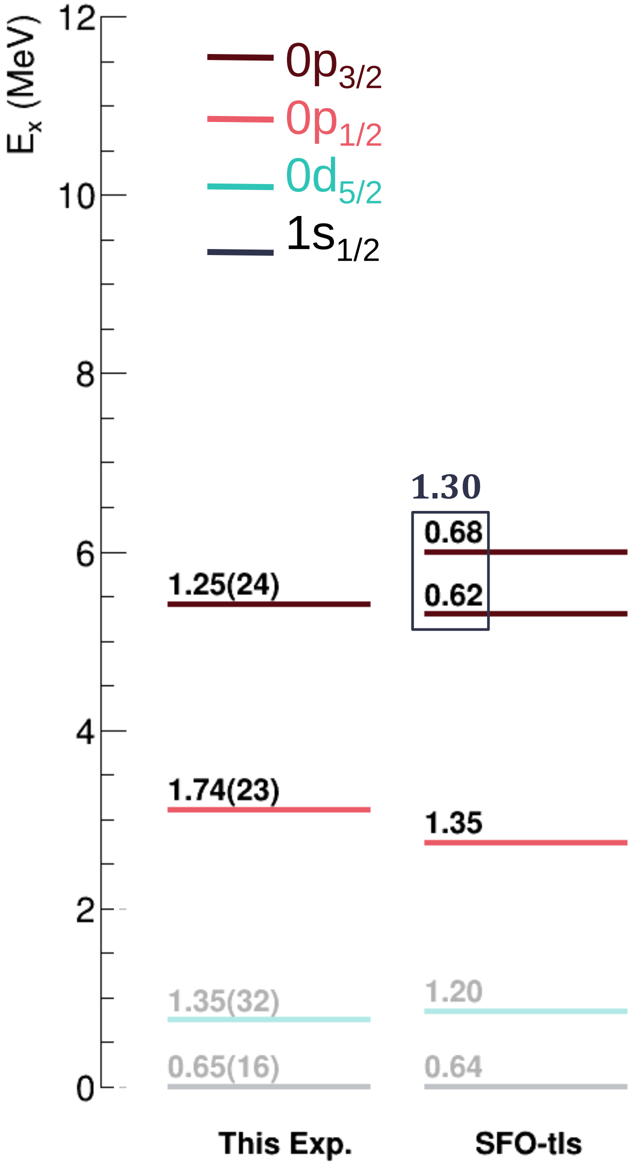
Comparison Shell Model



Bound States

- Good agreement for both energy and C^2S

Comparison Shell Model



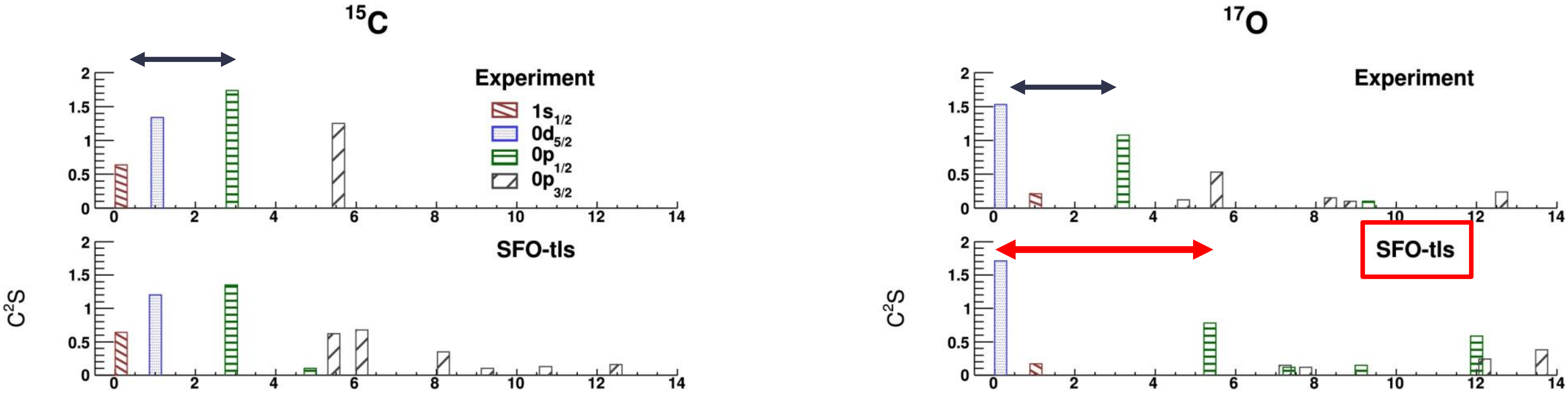
Bound States

- Good agreement for both energy and C^2S

Unbound States

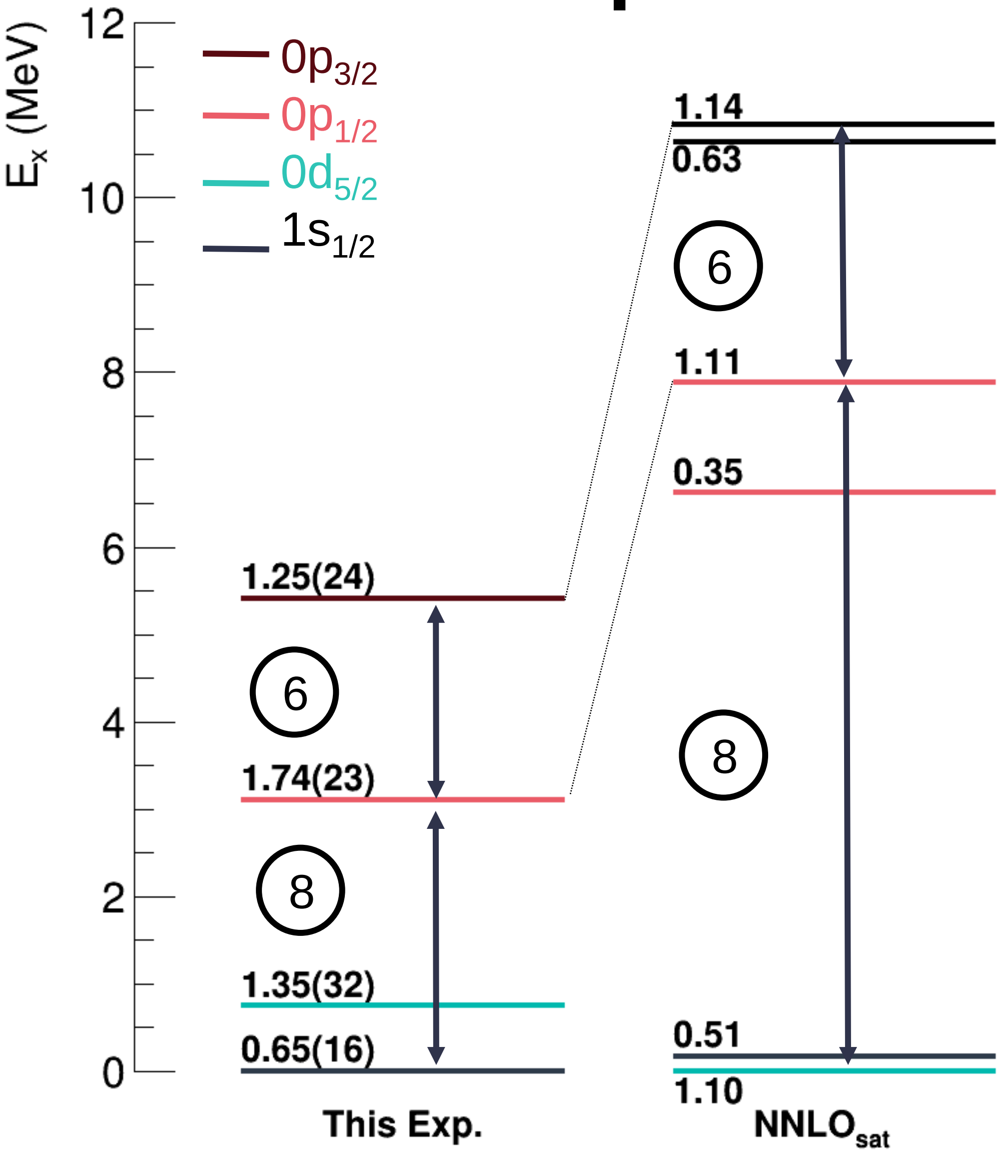
- **1/2⁻**: Good agreement in E and C^2S
- **3/2⁻**: Sum of fragmented strength and part of the strength at higher E.

Comparisons with ^{17}O



- Exp: $E_{1/2-}$ ~ 3 MeV
- SFO_{tls} in ^{17}O: $E_{1/2-}$ ~**4.5 MeV**
- This state 1/2$^-$ can be interpreted as $^{16}O(3^-) \otimes \nu 0d_{5/2}$. which is overestimated by 1.5 MeV already in ^{16}O.
- The Monopole terms of the p−sd and sd−sd matrix elements were made more attractive by 0.375 MeV in the isospin T=0 channel and by 0.125 MeV in the isospin T=1.

Comparison to Ab initio



Bound States

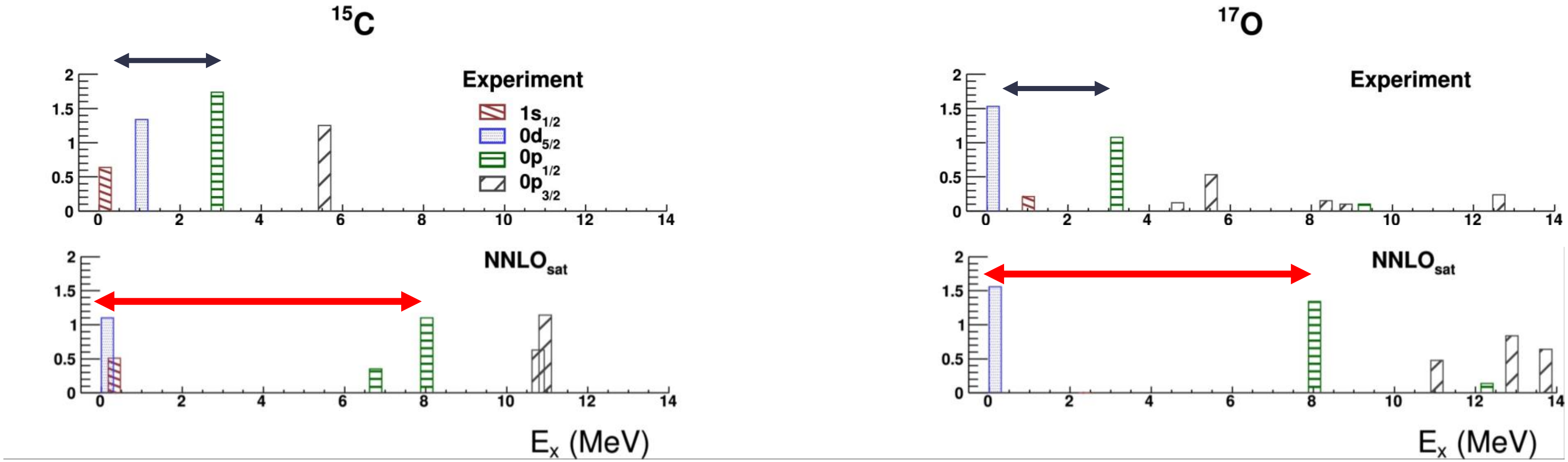
- Quasi degenerated in energy but fairly good reproduction of C^2S

Unbound States

- **$1/2^-$:** Lying too high in
- energy: Overestimation of
- the $\mathcal{N}$ = 8.

- $\mathcal{N}$ =6 well reproduced by the $NNLO_{sat}$ interaction.

Comparisons with ^{17}O



- SCGF with NNLO$_{sat}$: Similar issues both in ^{15}C and ^{16}O.
- Suggests missing 2p-1h correlations in the current approximations and provides motivation for an extension to higher orders.

Study of ^{17}C

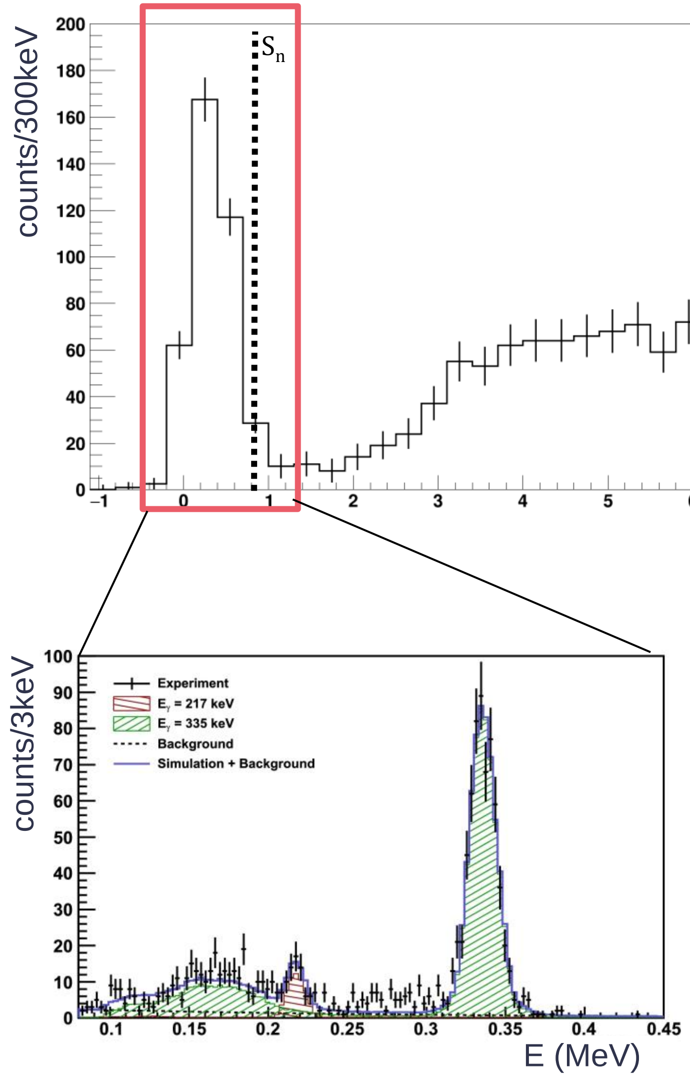
$\mathcal{N}=8$ gap

$^{16}\mathrm{C}(d,t)^{15}\mathrm{C}$

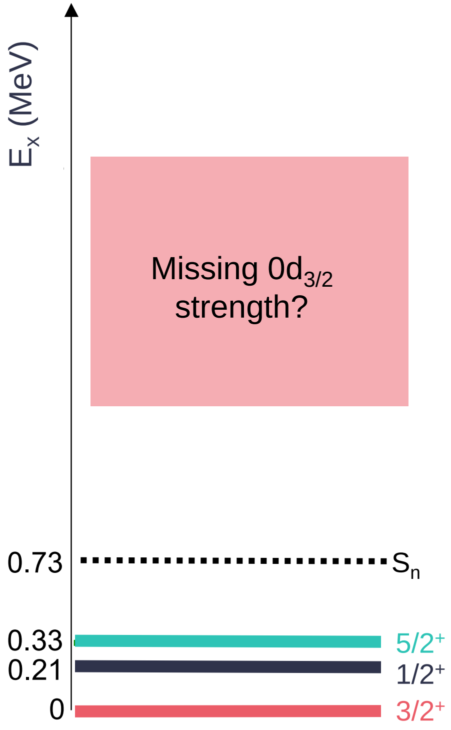
$\mathcal{N}=16$ gap

$^{16}\mathrm{C}(d,p)^{17}\mathrm{C}$

^{17}C Unbound spectroscopy

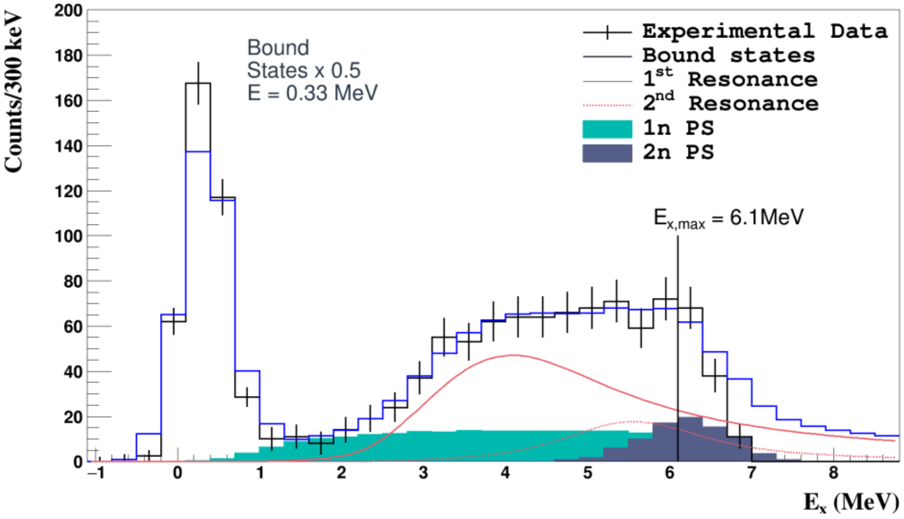


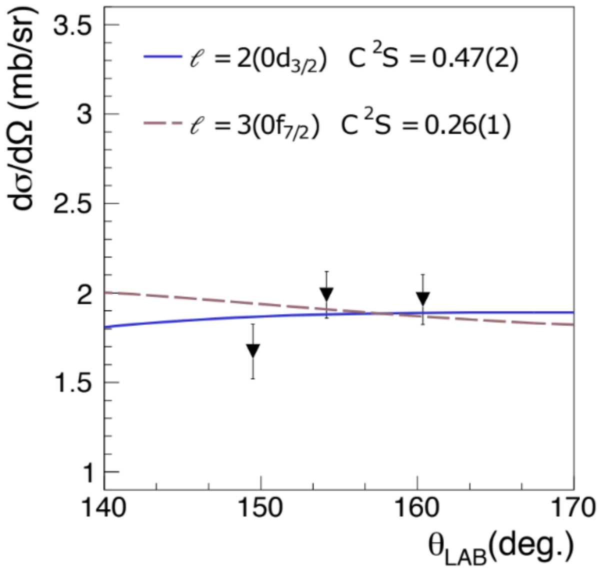
X. Pereira et al. Phys. Lett. B 811 (2020), 135939



Ex (keV)	Jpi	C2S
0	3/2$^+$	0.02(-3/+5)
217	1/2$^+$	0.80(22)
335	5/2$^+$	0.62(13)

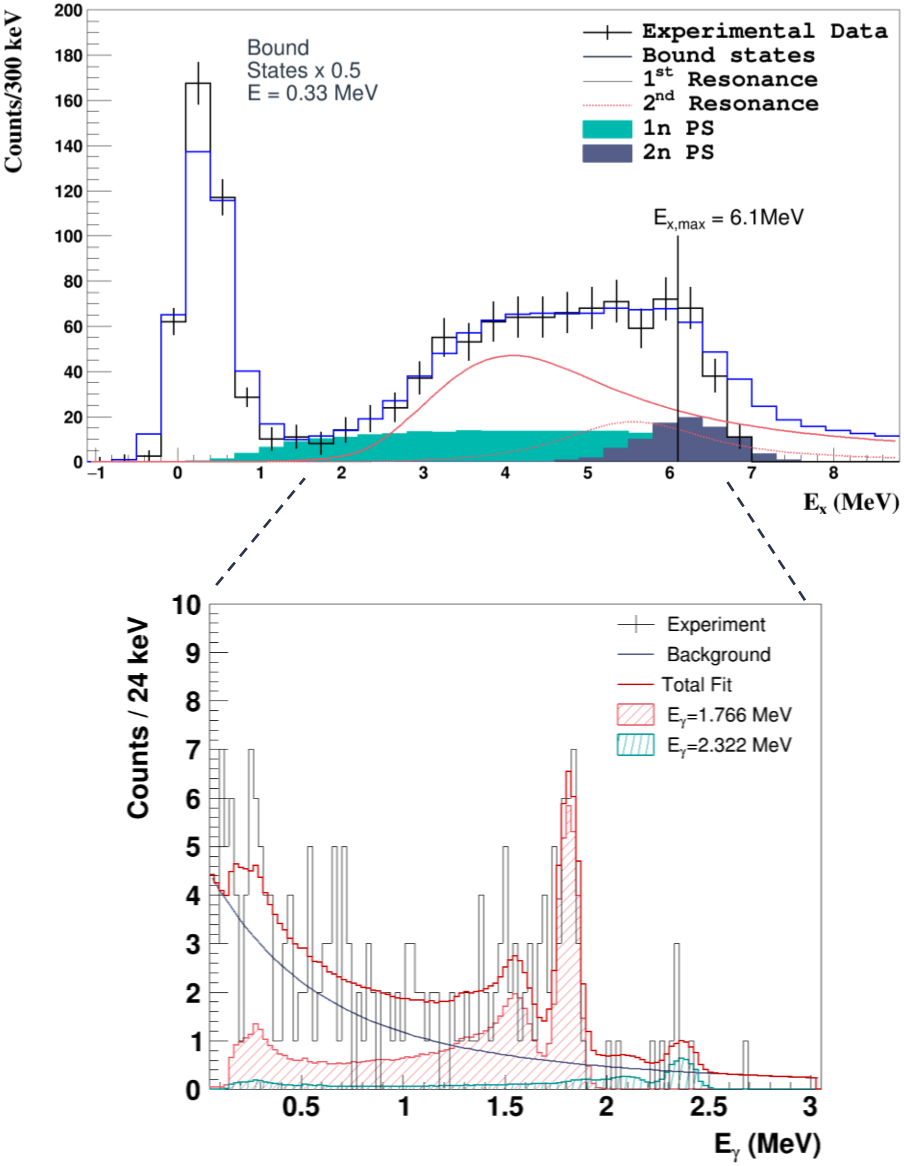
^{17}C Unbound spectroscopy

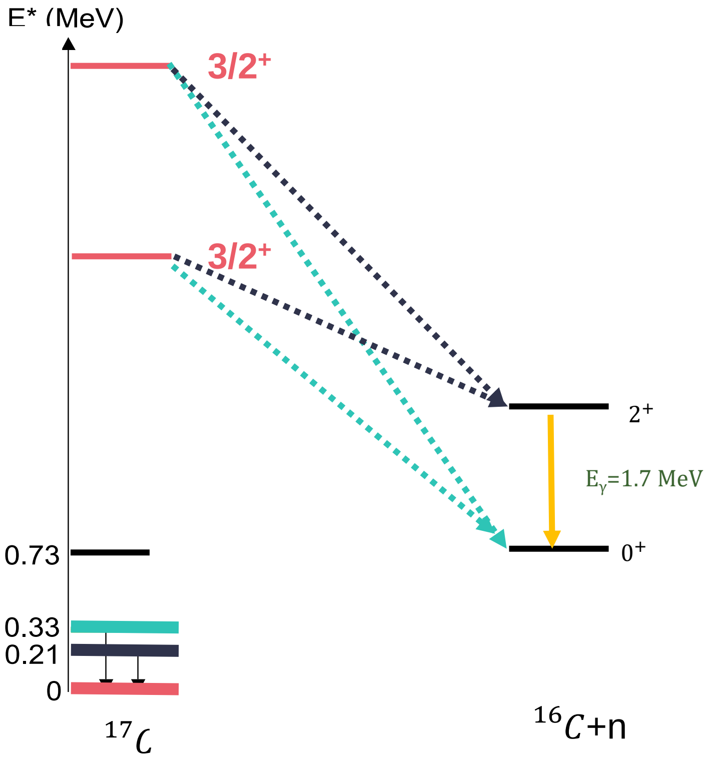




- Unbound states aprox. As single-level R-matrix lineshapes.
- 2R description guided by shell-model calculations. A single broad resonance could also reproduce the shape.
- ADWA calculations KD OMP

^{17}C, Decay information





1st R: BR(0+)=0.34(15)
2nd R: Decay to 2+ dominates

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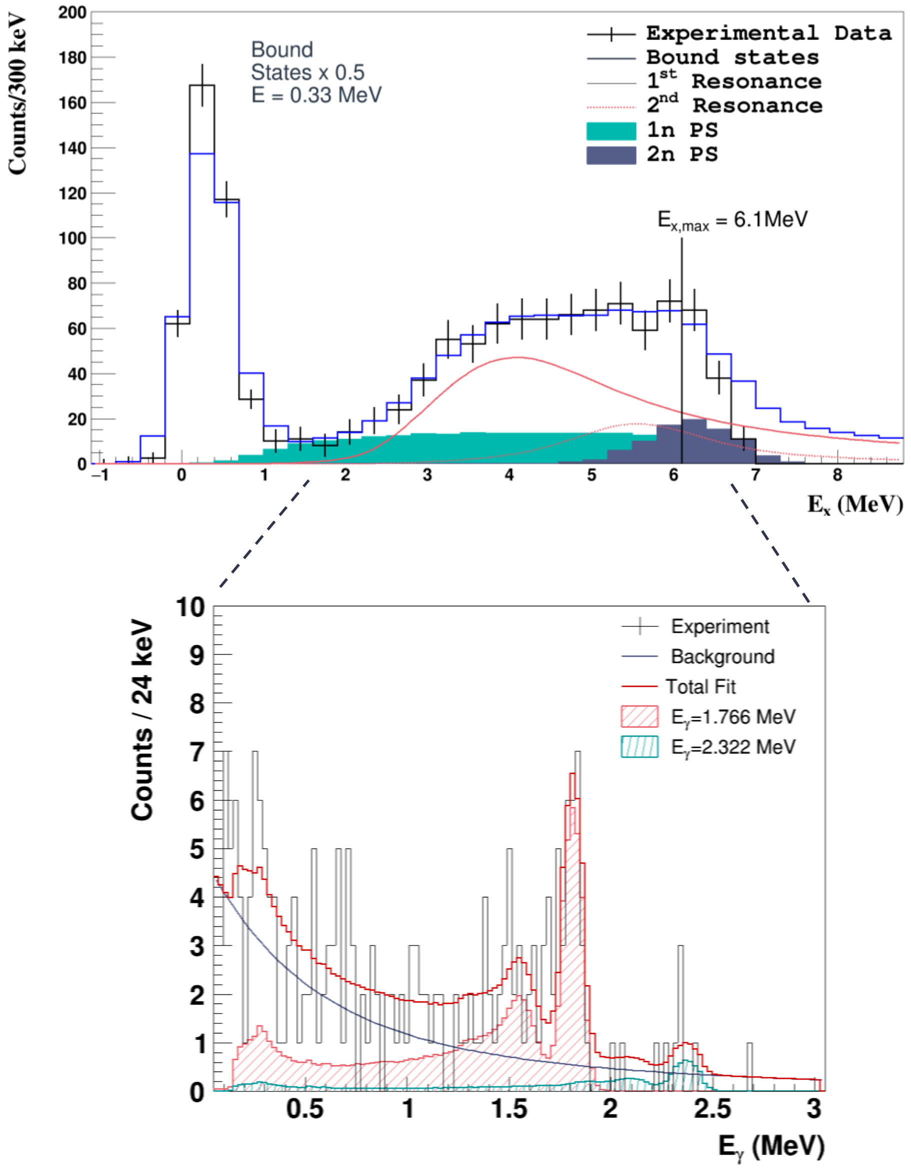
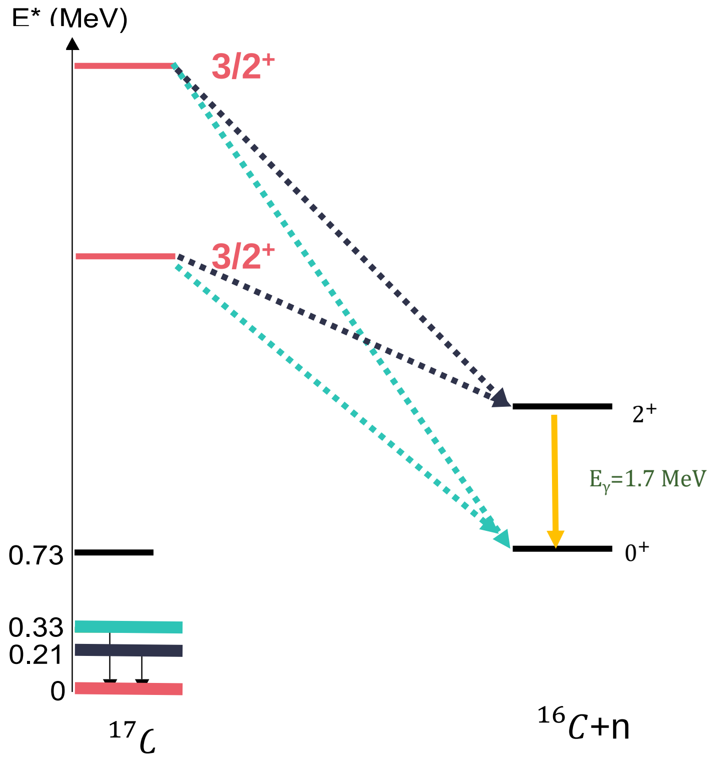
^{17}C, Decay information





Γ_{0+}=BR(0^+)·Γ_{tot}= 1.17(-58/+81) MeV

$C^2S(0^+)$= Γ_{0+}/Γ_{sp}= **0.45(-22/+32)**

$C^2S(0^+)_{norm}$= **0.47(2)**

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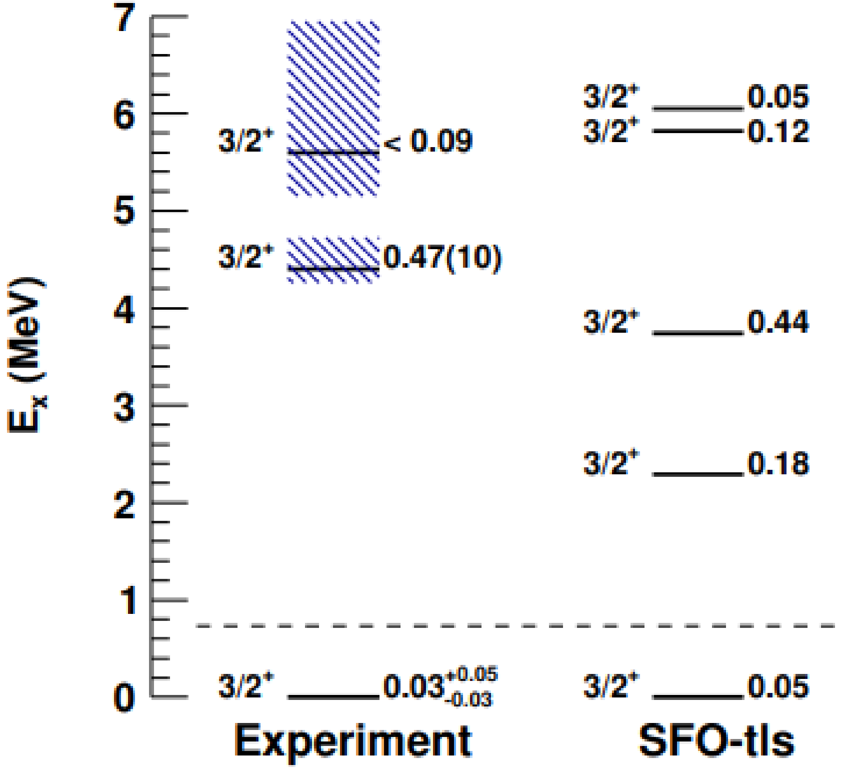
Comparison to SM with SFO$_{tls}$

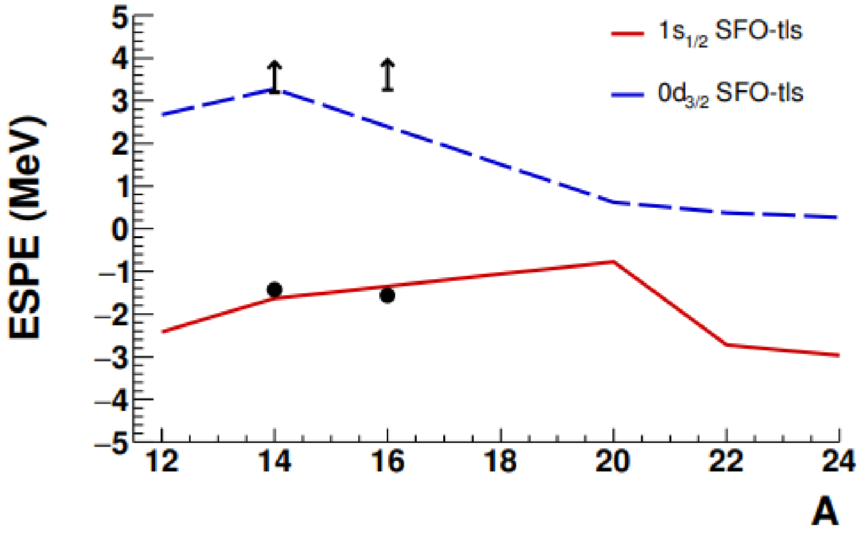


- Main strength well reproduced.

- Lower energy contribution predicted, experimentally out ruled.

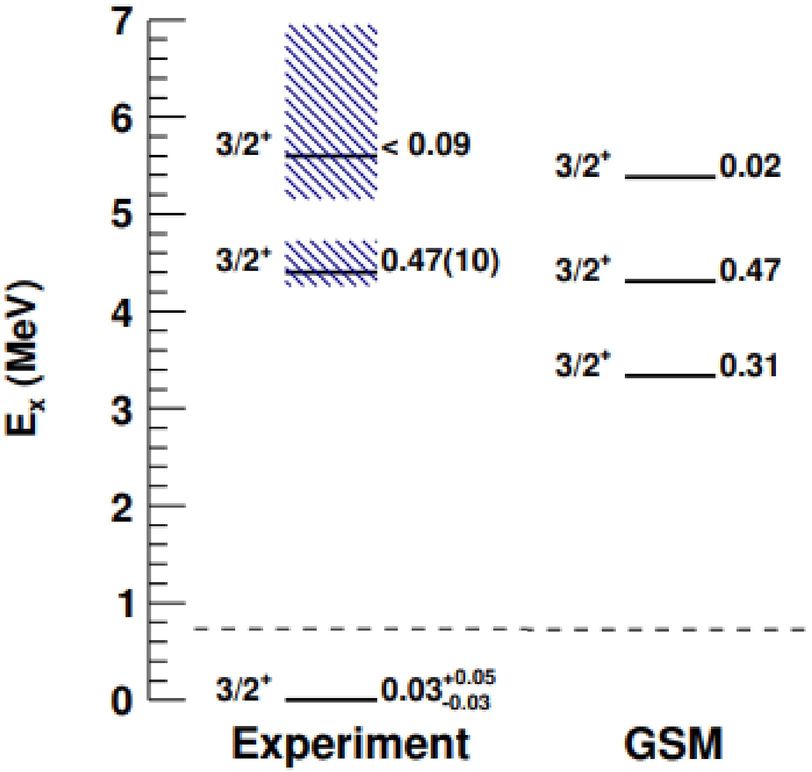
- Missing strength at higher energies.

N=16 Gap and the most n-rich C



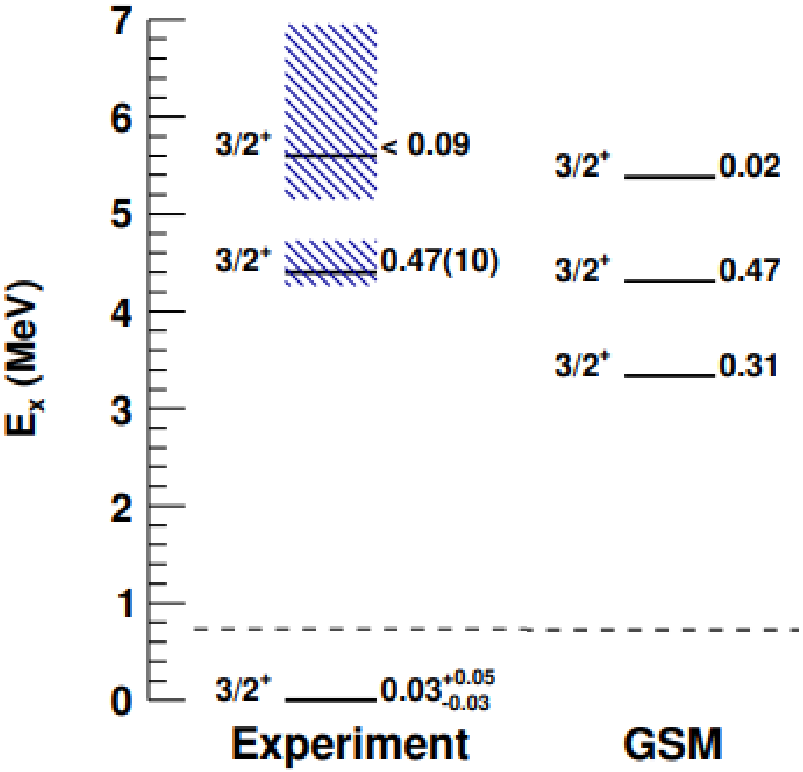
- ESPE_{exp} = 5.08(-0.33/+0.43) MeV
- Constant with respect to ^{14}C.
- SFO-tls predicts an small reduction.
- How can this impact the predictions of the N=16 in close to the drip line?

Comparison to SM with GSM



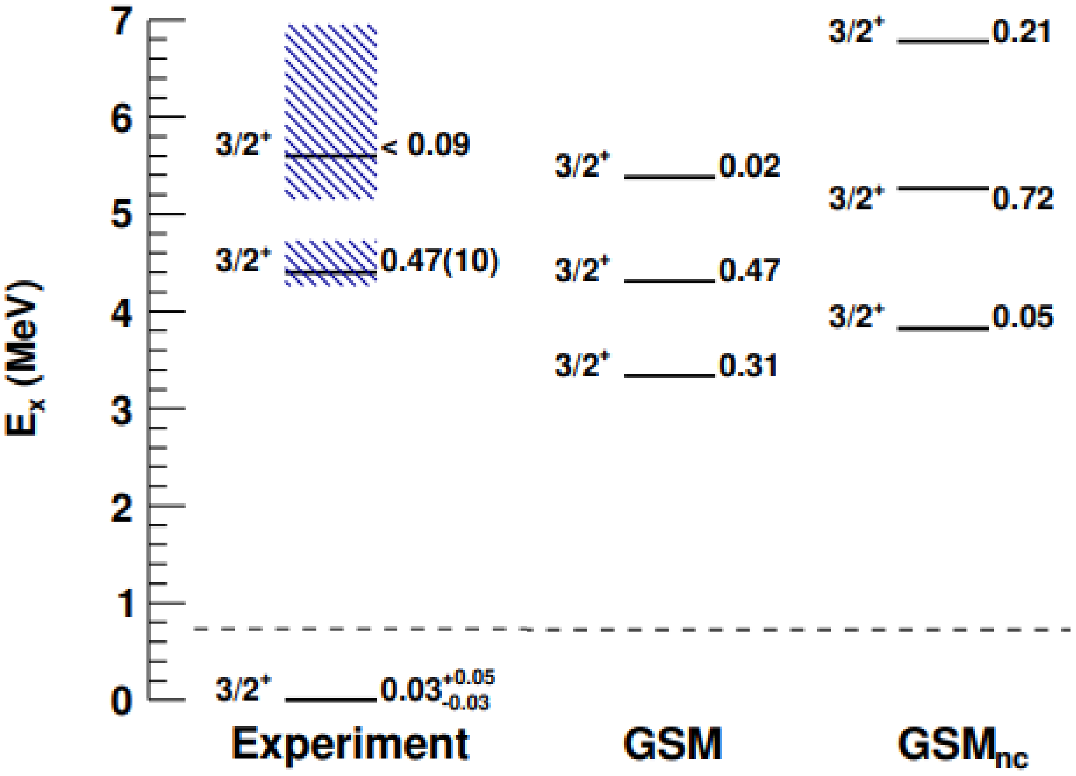
- ^{14}C core.
- FHT interaction.
- Explicit CC and internucleon correlations in a unified description

Comparison to SM with GSM



- Main strength well reproduced.
- Lower energy contribution even more pronounced predicted, experimentally out ruled.

Comparison to SM with GSM



- Main strength well reproduced.
- Lower energy contribution even more pronounced predicted, experimentally out ruled.
- Calculations w/o CC overestimate the strength of the main $3/2^+$.

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Summary

- The p-sd orbitals in ^{16}C were probed using stripping and pickup reactions.

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- The lower limit of the N=16 gap was obtained, showing a larger value that the SFOtls prediction possibly having implications on the drip line nuclei.

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- Ab initio SCGF with NNLO$_{\mathrm{sat}}$ calculations were compared to natural and cross-shell states in ^{15}C and ^{17}O suggesting missing 2p-1h correlations that overestimate the energies of the cross-shell states.
- The lower limit of the N=16 gap was obtained, showing a larger value that the SFOtls prediction possibly having implications on the drip line nuclei.
- The GSM demonstrated to be a powerful method to describe very-unbound states, and it was used to explicitly improve our knowledge of the continuum degrees of freedom.

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