INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS

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$\nu 0p_{1/2} - \nu 0p_{3/2}$ spin-orbit splitting in ^{20}O

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IGFAE-USC, GANIL and LPC-Caen

EuNPC 2025 - Caen

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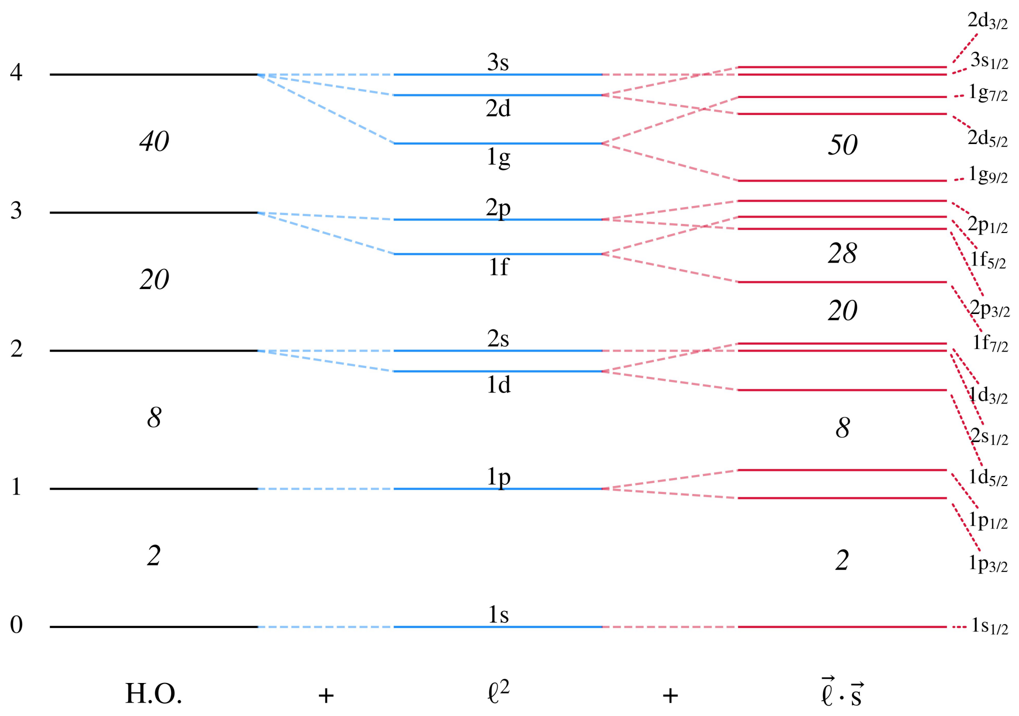
A recap on the SO splitting

Introduced by M. Goeppert-Mayer, reproduces magic numbers for stable nuclei.



SO splitting is mainly a **surface** effect:

$$V_{SO} = -\frac{1}{\hbar^2} V_{so}(\vec{l} \cdot \vec{s}) \left(\frac{1}{r} \frac{dV}{dr} \right)$$

Affected by many phenomena as **drip-lines** are approached

A recap on the SO splitting

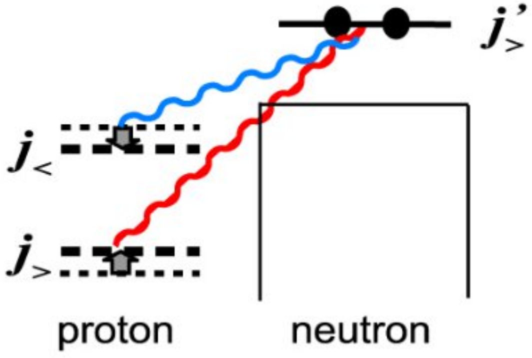
One of the possible causes could be the **tensor force.**

T.Otsuka and Y. Tsunoda, JPG 43 (2016)

Tensor force emerges from the **monopolar** component of the *NN* force:

$$H = H_0 + \mathbf{H_{mono}} + H_{\mathrm{multi}}$$

⇒ Mainly affected by $\pi\nu$ interactions



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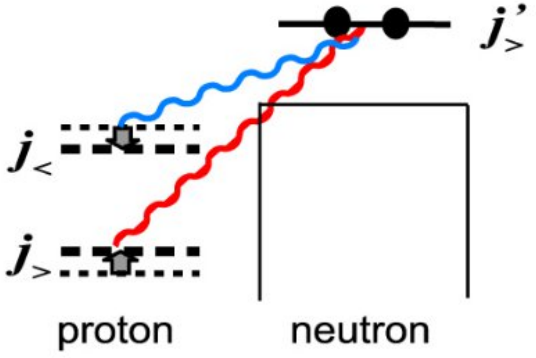
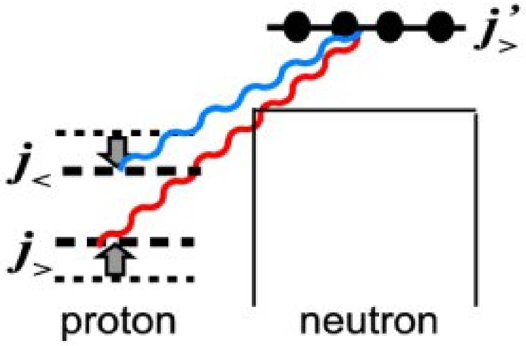
Shell gaps evolve with proton/neutron **occupancies**

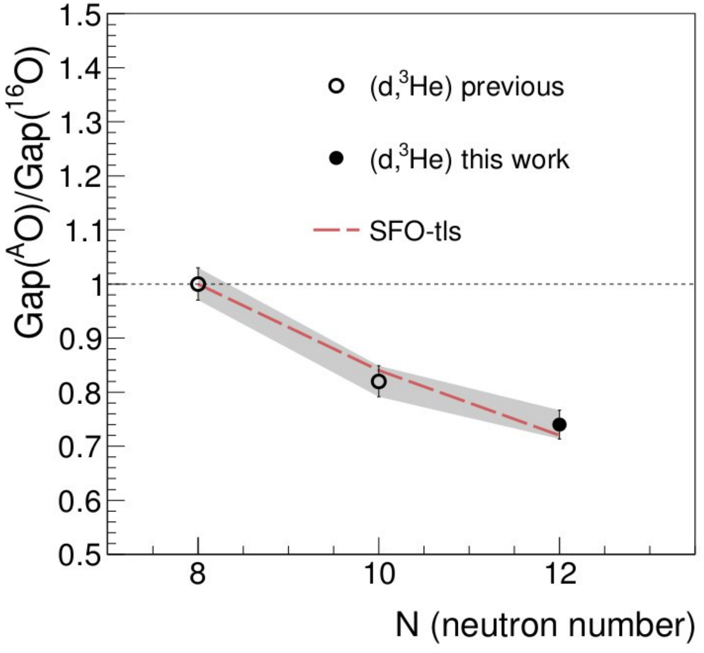




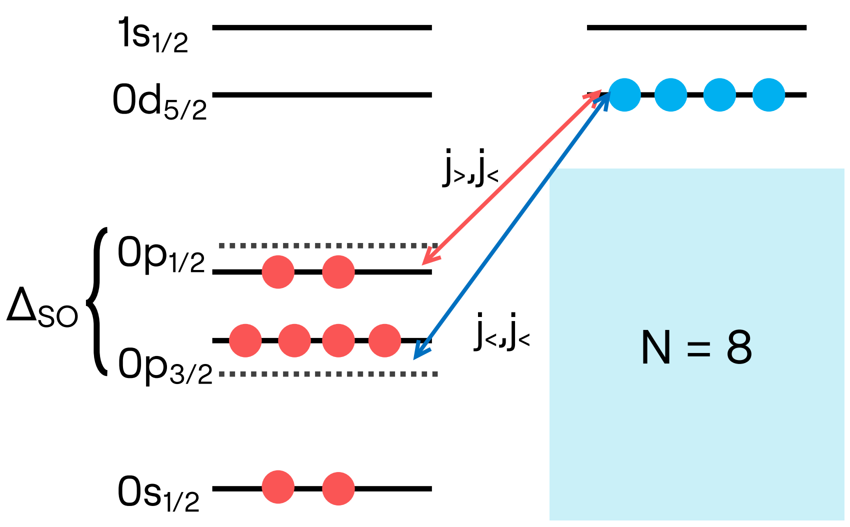
Physics case

E796 to measure **transfer** reactions probing single-particle occupancies in ^{20}O.

1. Proton removal $^{20}O(d,^{3}He)^{19}N$ to investigate persistence of **Z = 6**



J. Lois-Fuentes, PhD thesis (2023)



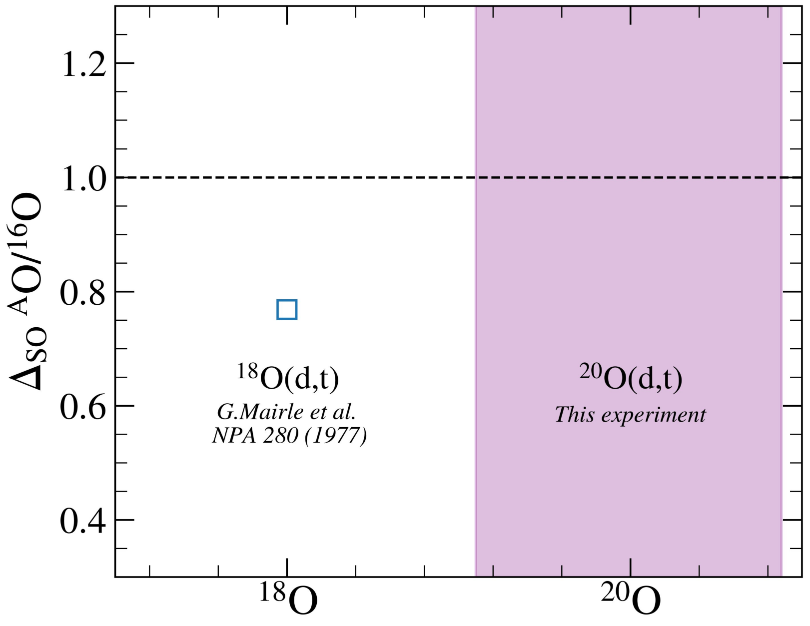
Schematic view of tensor interaction in ^{20}O

Tensor V_{pn} reduces Z = 6 gap as neutrons are added to $\nu 0d_{5/2}$

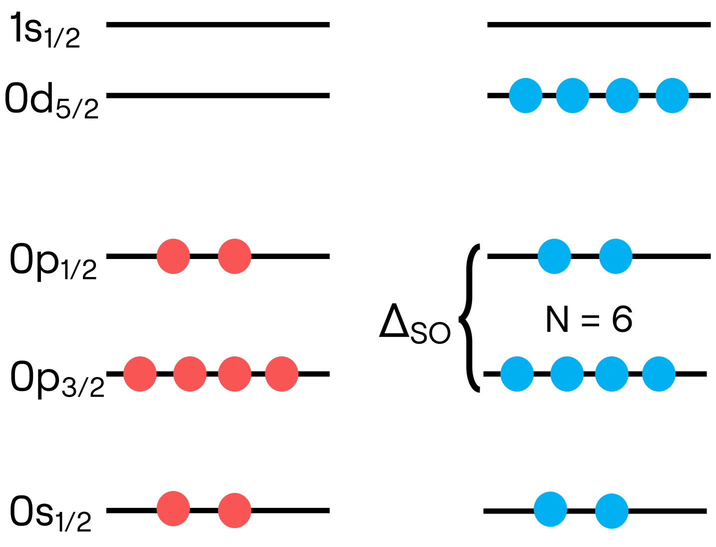
Physics case

E796 to measure **transfer** reactions probing single-particle occupancies in ^{20}O.

2. Neutron removal ^{20}O(d,t)^{19}O to extract **N = 6 SO gap**



Reanalyis of previous data



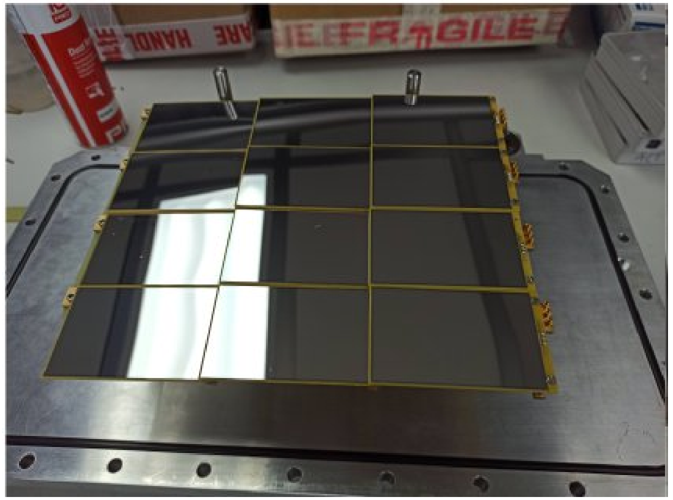
IPSM of ***^{20}O***

Would the gap decrease in ^{20}O?

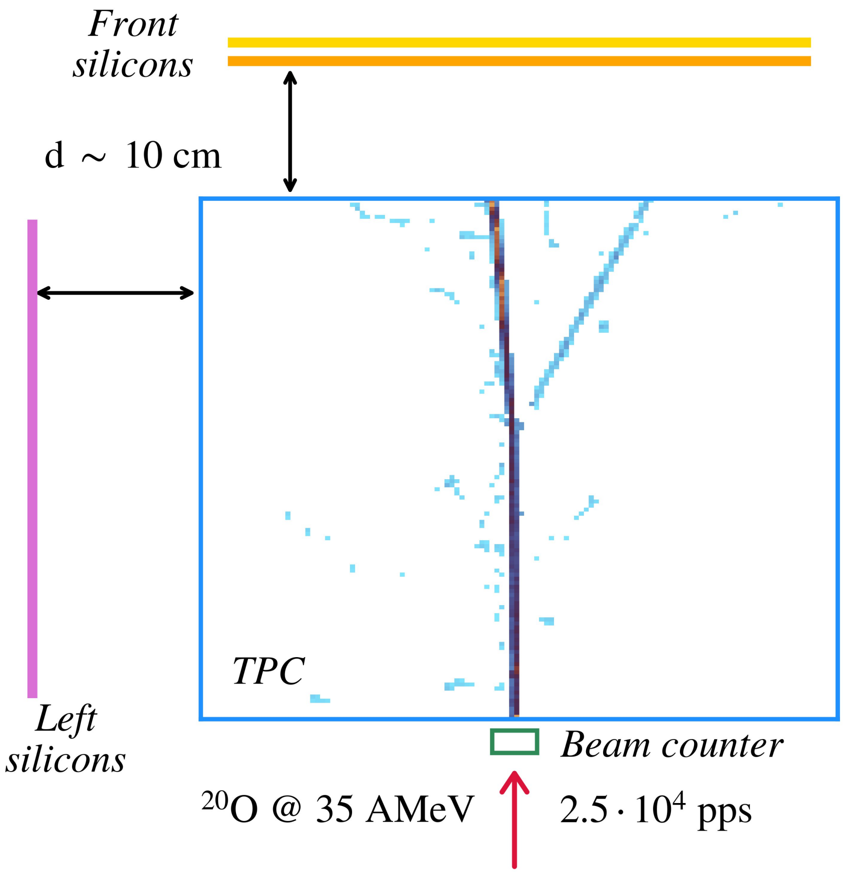
Can we constrain the tensor force?

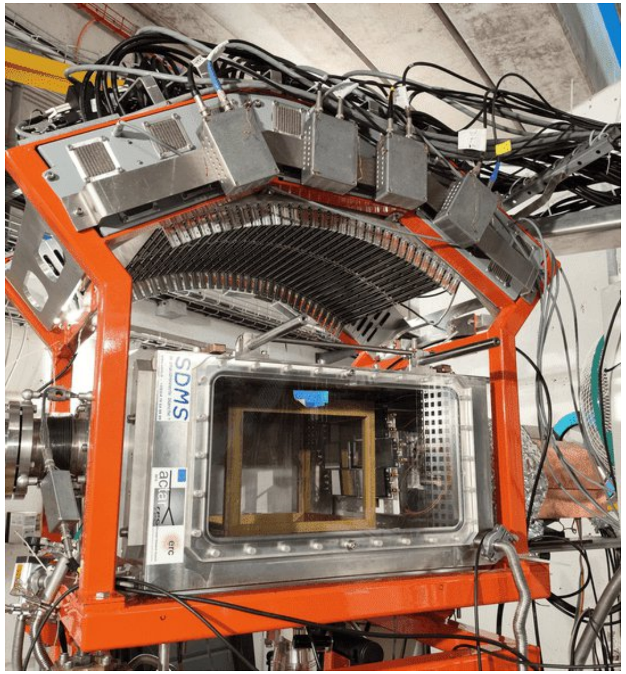
Experimental setup

E796 @ LISE in 2022. First transfer experiment with ACTAR TPC!



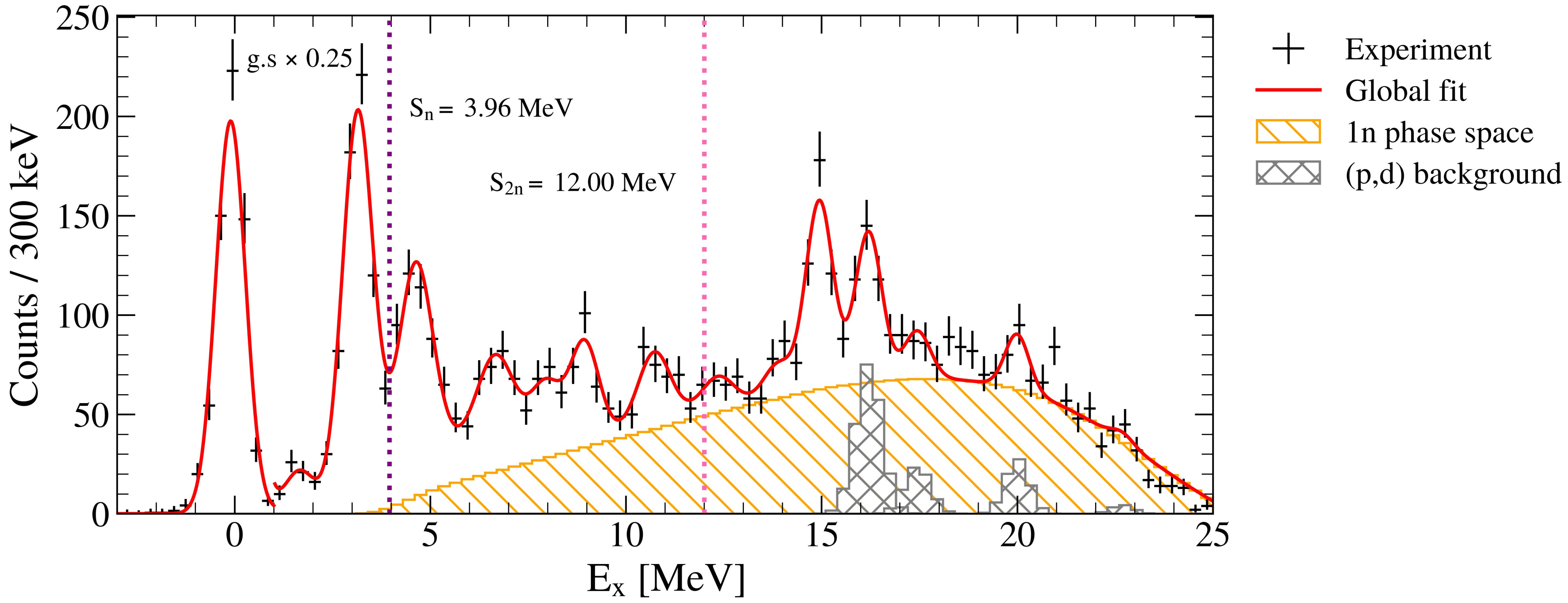
Silicon sizes:
80 x 50 x 0.5 mm^3





Gas mixture:
90% D_2 + 10 % iC_4H_{10}
at 952 mbar

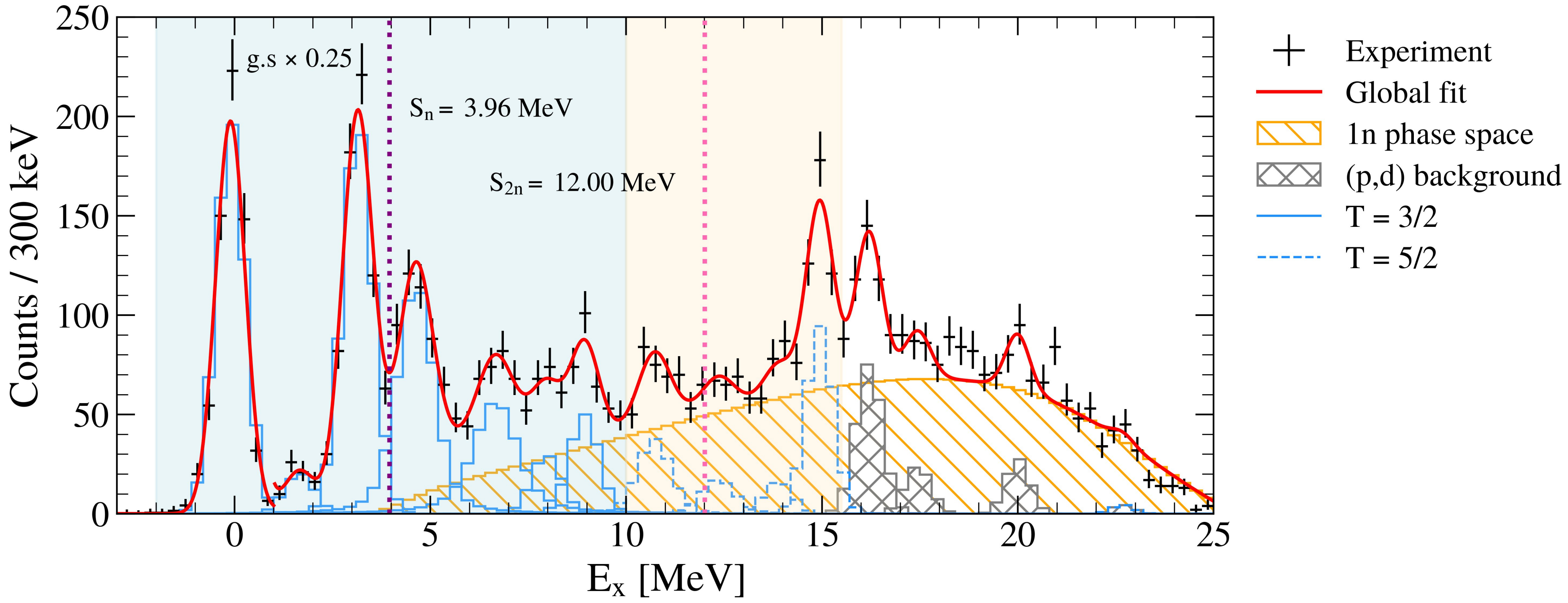
Results: E_x spectrum



- 11 observed states
- At E_x > 15 MeV **(p,d) contamination** appears

- 1n phase space considered: $^{19}O \Rightarrow {}^{18}O + n$
- 2n phase space is negligible

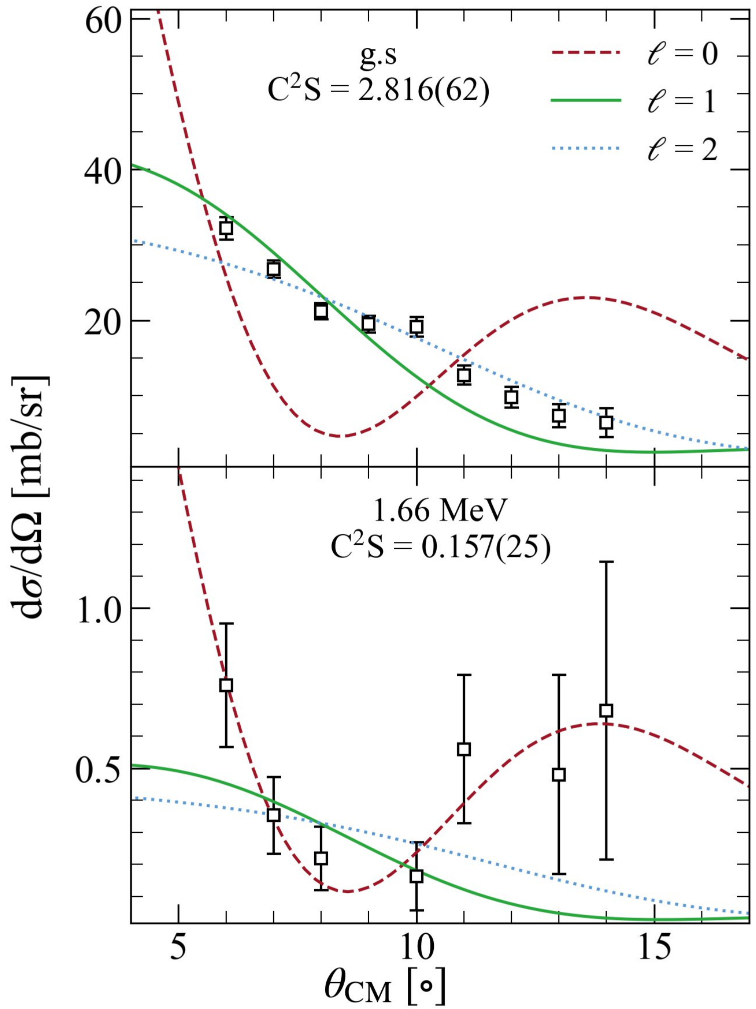
Results: E_x spectrum

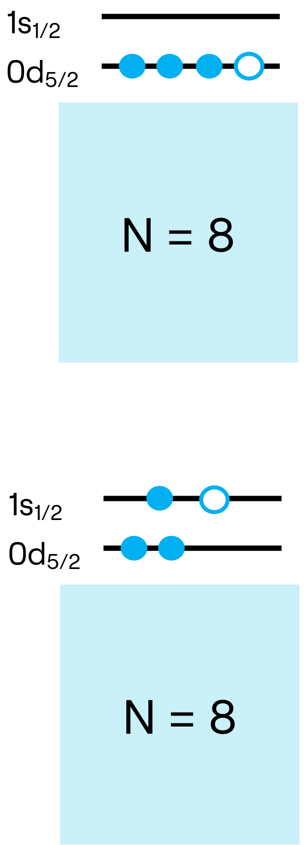


T = 3/2 states @ E_x < 10 MeV

T = 5/2 at E_x > 10 MeV, based on comparison with **$^{20}O(d,^{3}He)^{19}N$**

Results: *sd* cross-sections



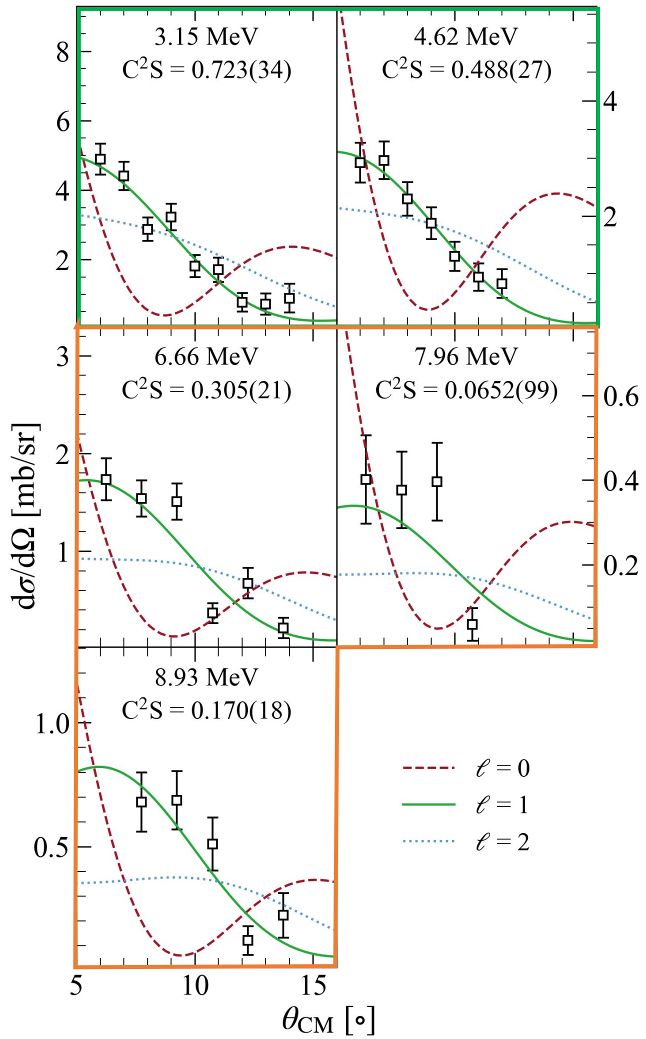


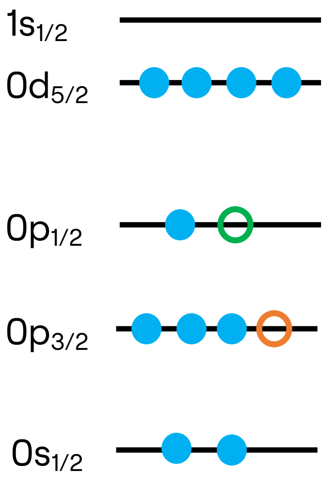
DWBA with Fresco

- OMP:
  - ^{20}O + d: Daehnick
    W. W. Daehnick et al. PRC 21 (1980)
  - ^{19}O + t: Pang
    D.Y. Pang et al. PRC 79 (2009)
- ⟨ d | t ⟩ from ab-initio GFMC
  I. Brida et al., PRC 84 (2011)
- ⟨ ^{20}O | ^{19}O ⟩ from standard WS

- g.s: $5/2^+$, taking up 71% of the occupation
- 1st: $1/2^+$, with 8% of $1s_{1/2}$ occupancy

Results: *p* cross-sections





Based on shell-model calculations (see next slide):

- E_x = 3.1 and 4.6 MeV ⇒ $0p_{1/2}$
- E_x = 6.7, ..., 8.9 MeV ⇒ $0p_{3/2}$

T = 3/2 states:

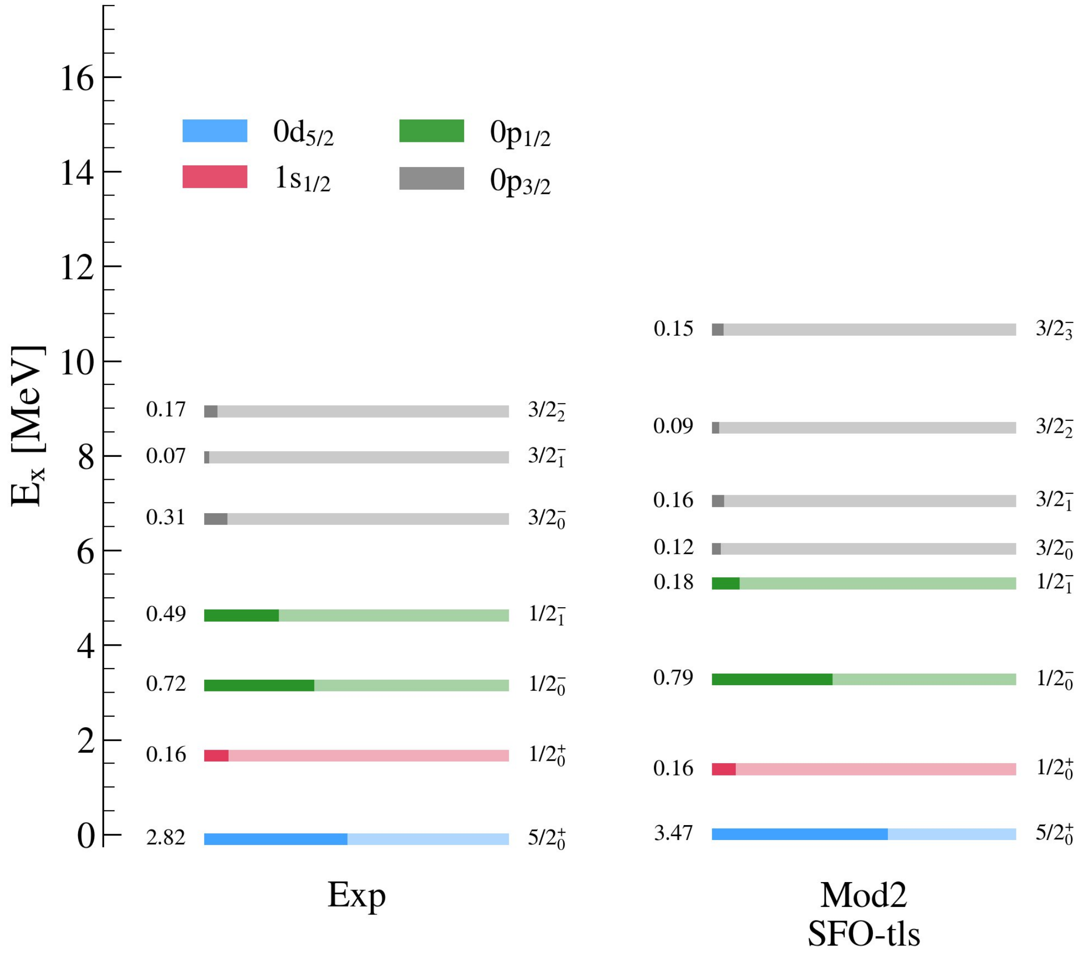
- $0p_{1/2}$: 61 % of strength
- $0p_{3/2}$: just 14 % of occupancy!

Results: comparison with models

SFO-tls interaction

T. Suzuki, T. Otsuka PRC 78 (2008)

- For *p-sd* neutron-rich nuclei
- ***Modified***: reduced *sd-sd* and *p-sd* monopole matrix el.



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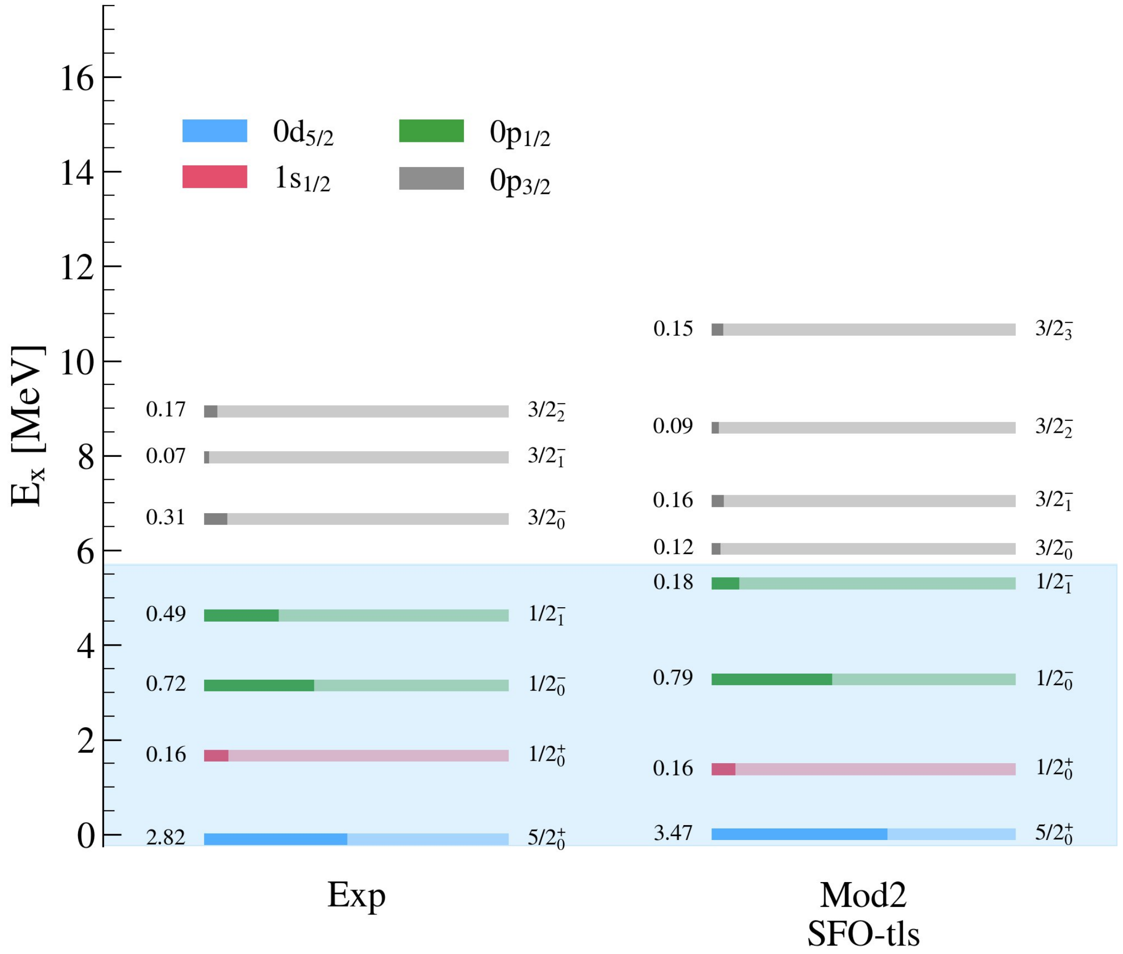
- C^2S reduced wrt SFO-tls



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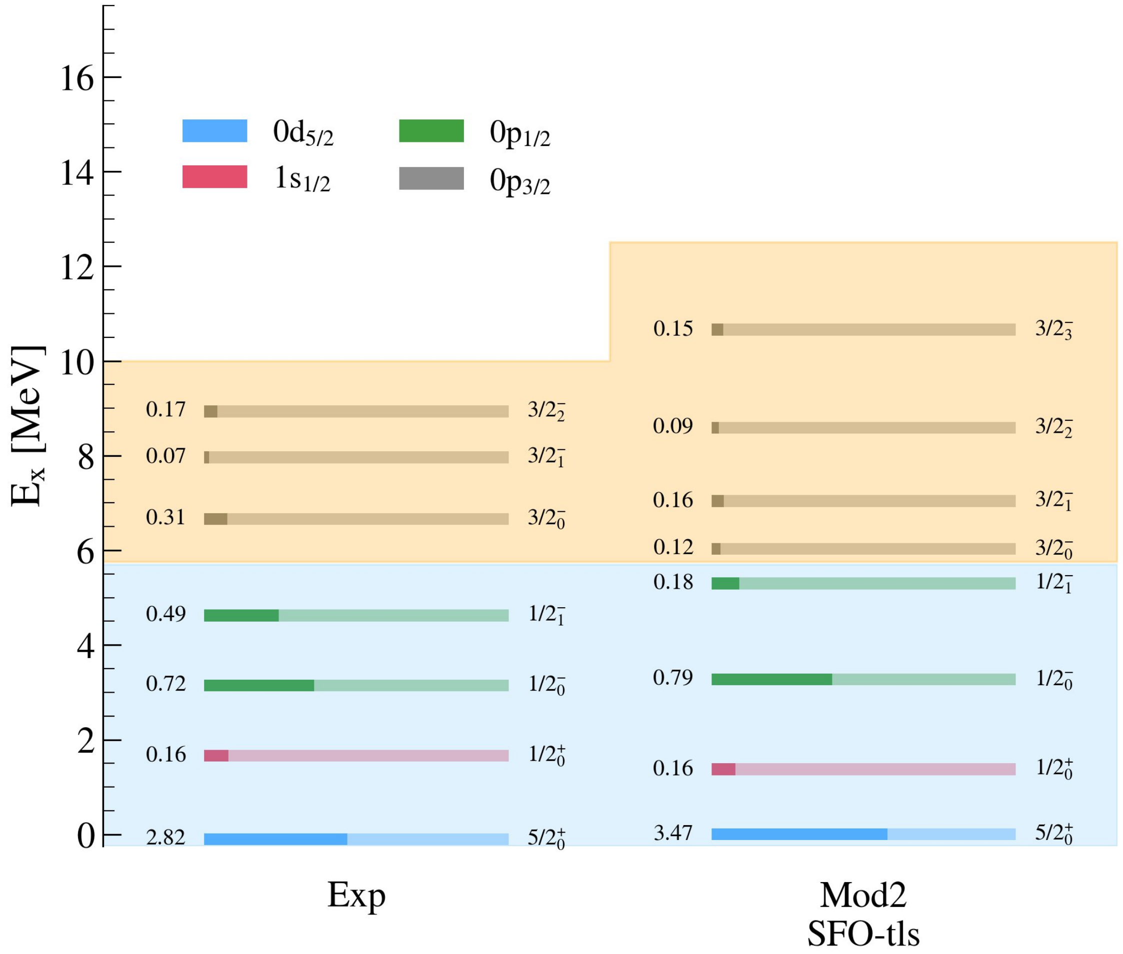
- $0p_{3/2}$ less fragmented than predicted
- Last $0p_{3/2}$ predicted at much higher E_x



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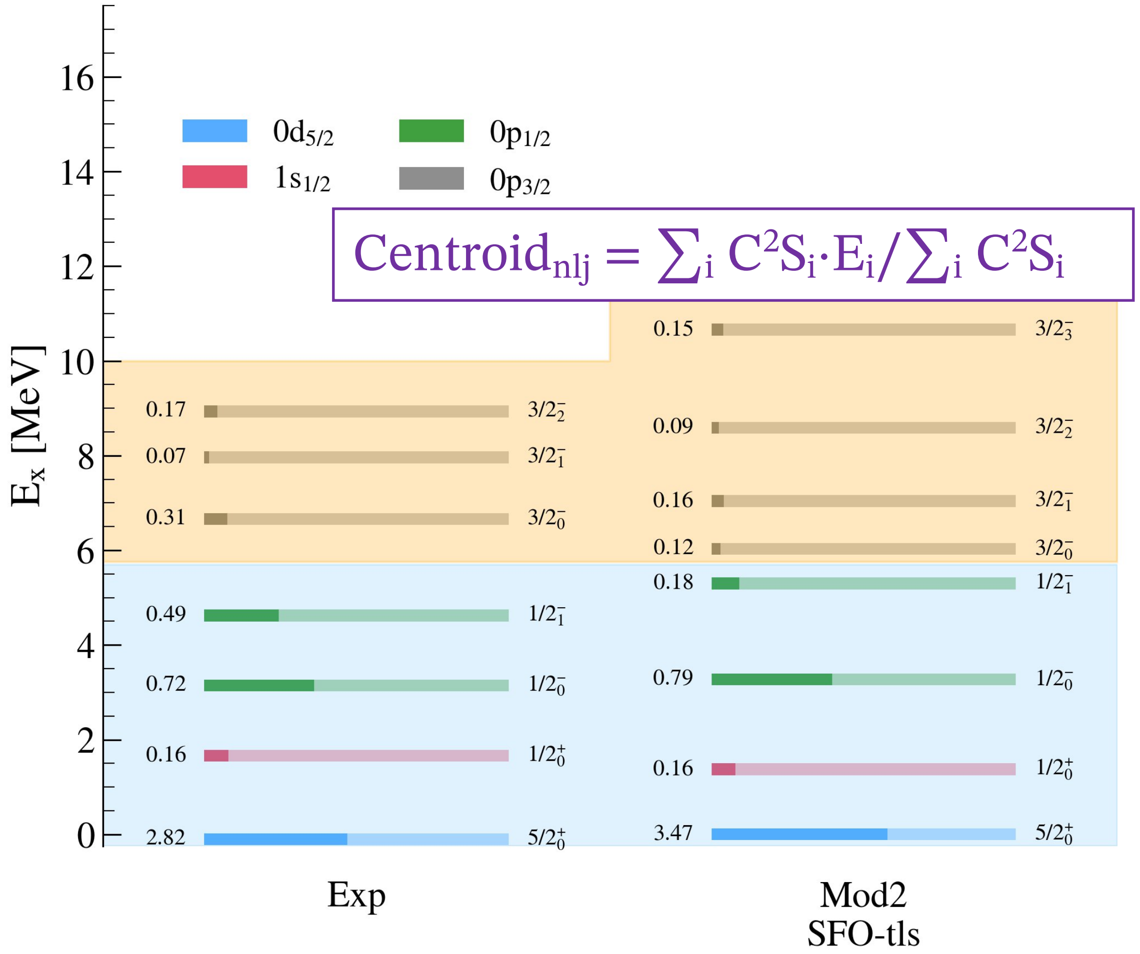

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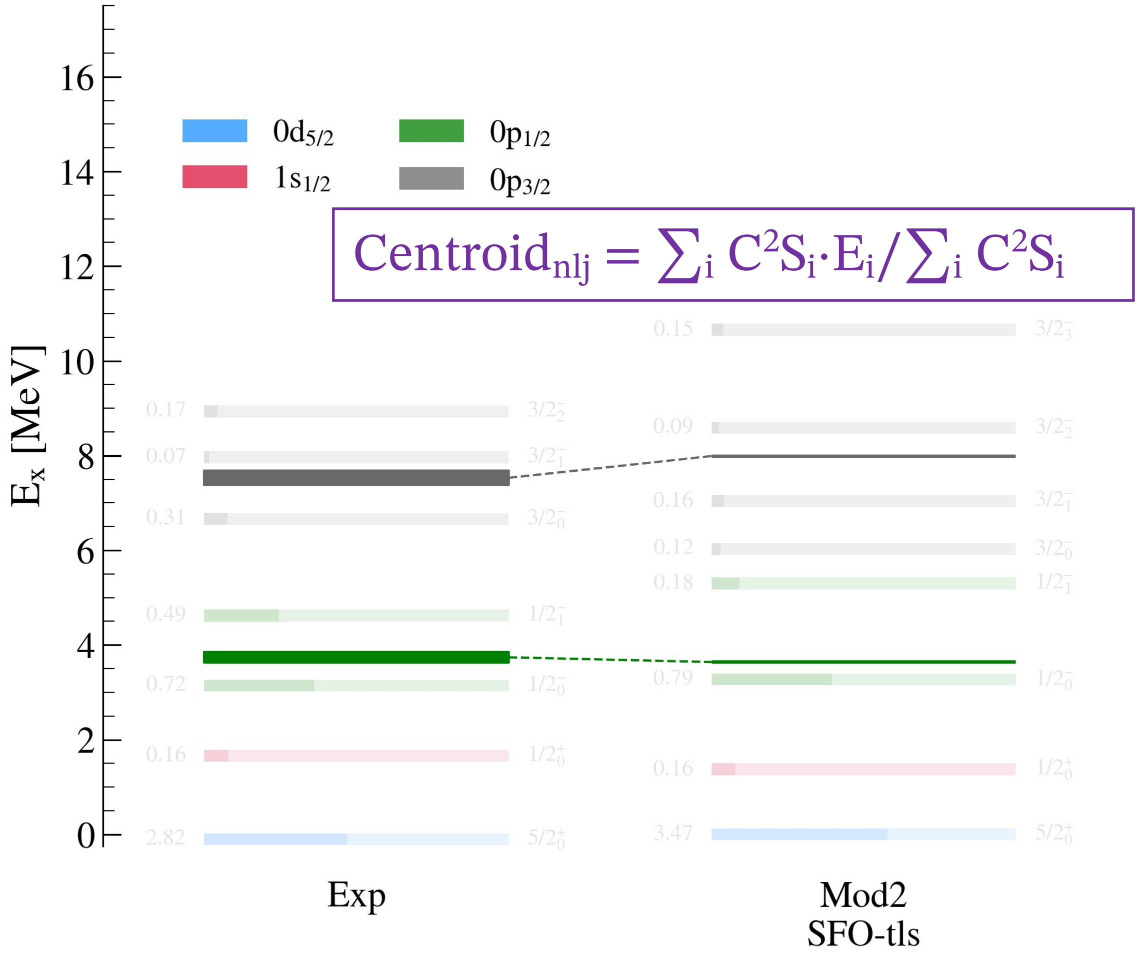


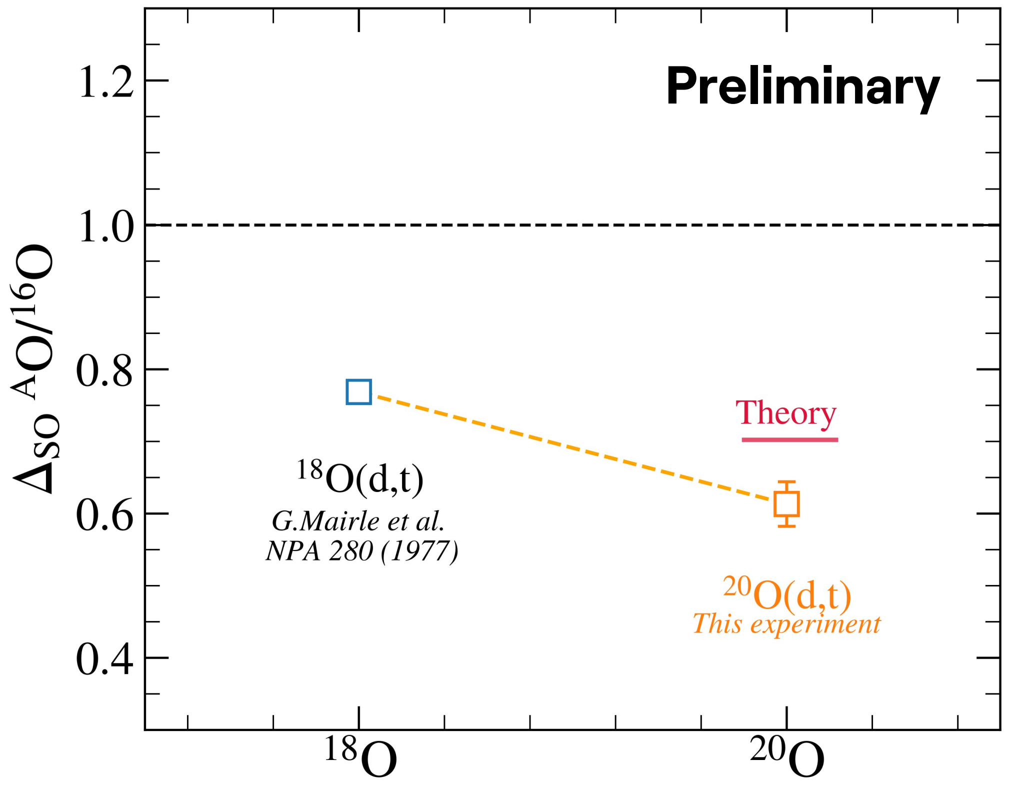
Results: SO gap

Gap = $\mathrm{Cent}_{0p1/2}$ - $\mathrm{Cent}_{0p3/2}$

- **Exp**: 40 % reduction wrt ^{16}O
- **Theo**: ~ 30% quenching

Tensor also plays a major role in N=6 SO evolution!

Theoretical predictions needed for ^{18}O before drawing any final conclusions



Conclusions

$^{20}O(d,t)^{19}O$ reaction as a way to measure SO gap in exotic O isotopes

DWBA analysis to extract spectroscopic factors and E_x centroids for T=3/2 states

Comparison with SFO-tls reproduces measured centroids

40% exp. reduction of N = 6 SO gap ^{20}O / ^{16}O

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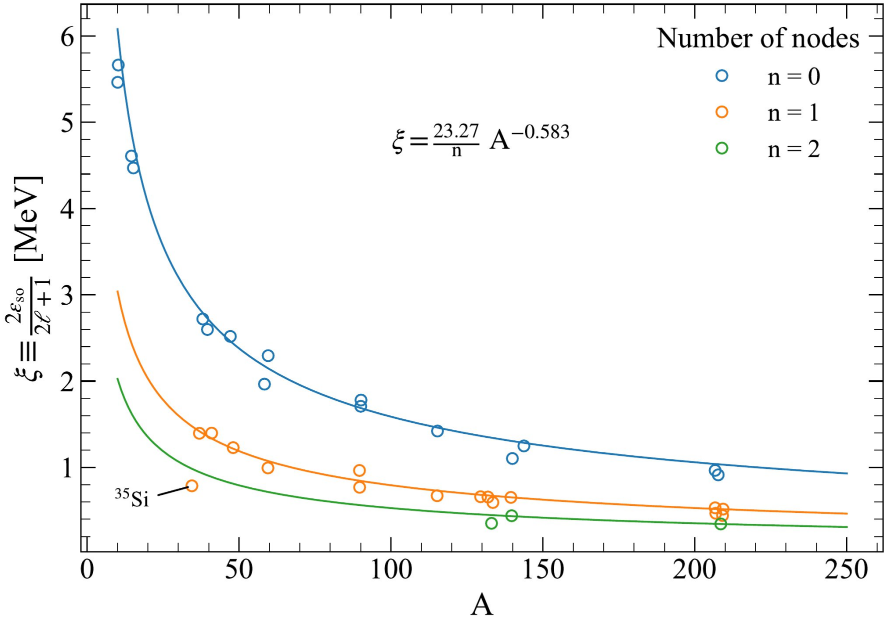
Extra slides

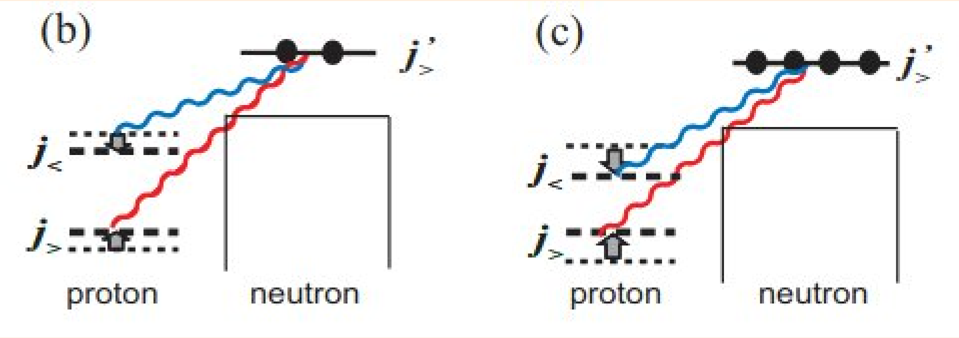
A recap on the SO splitting

G .Mairle *et al.* (PLB 304 (1993)) found systematic trends easily parametrizable.



Deviations from the trend are found due to:

- Loosely bound orbitals
- Nuclear matter depletion (^{35}Si)
- Role of tensor force

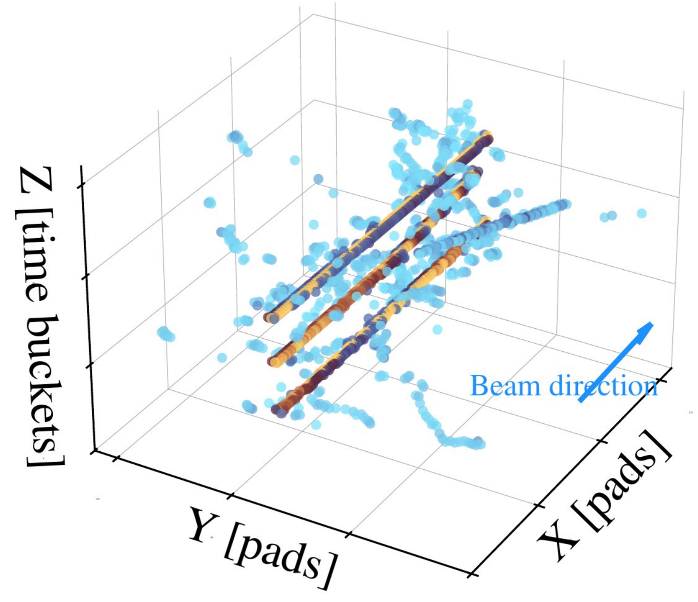


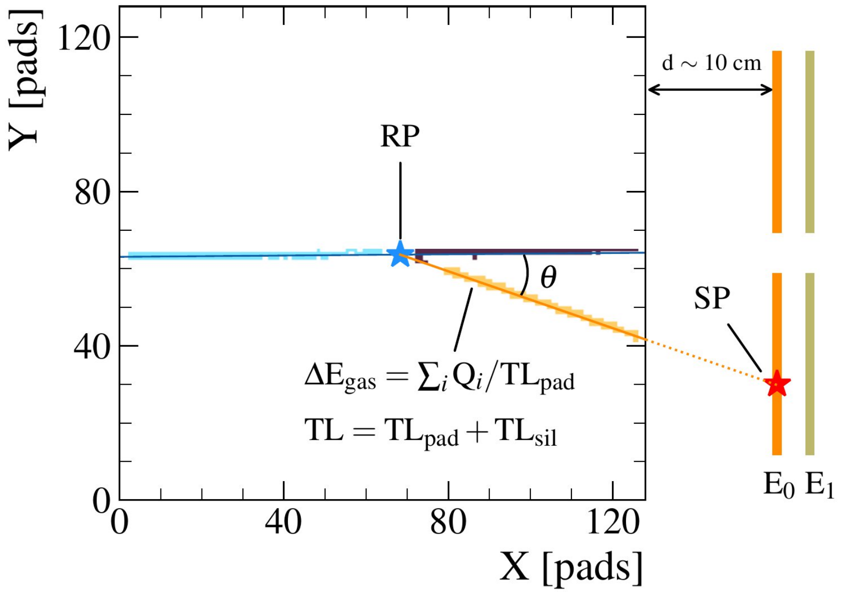
T.Otsuka and Y. Tsunoda, JPG 43 (2016)

Shell gaps evolve with proton/neutron **occupancies**

A window to the analysis

Intricate analysis to extract reactions of interest out of noisy data.





Unique advantages from the TPC:

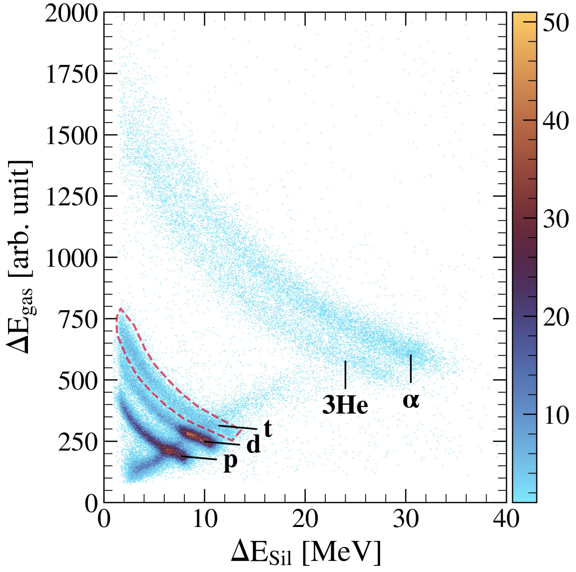
- Precise **vertex** determination
- Improved ΔE corrections

- Factor 10 in target number
- Implicit PID with ΔE_{gas}

A window to the analysis

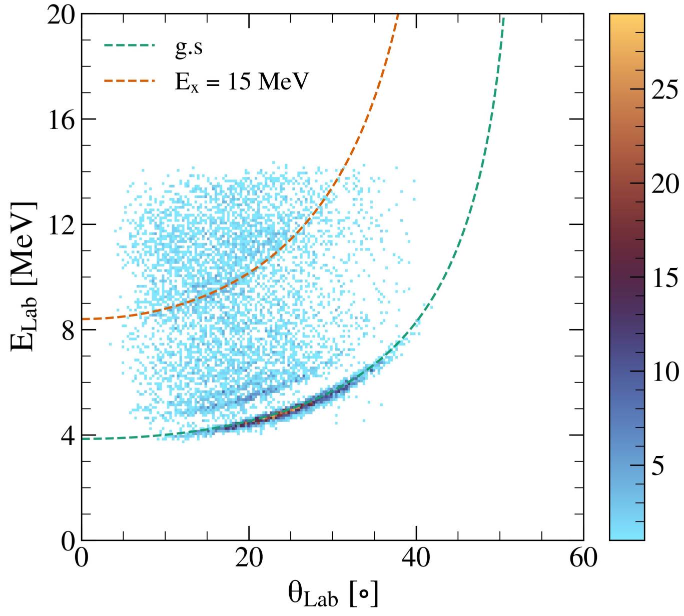
Intricate algorithms to identify binary reactions. Then standard procedures apply:

1. PID of tritons by plotting ΔE_{gas} vs ΔE_{Sil}

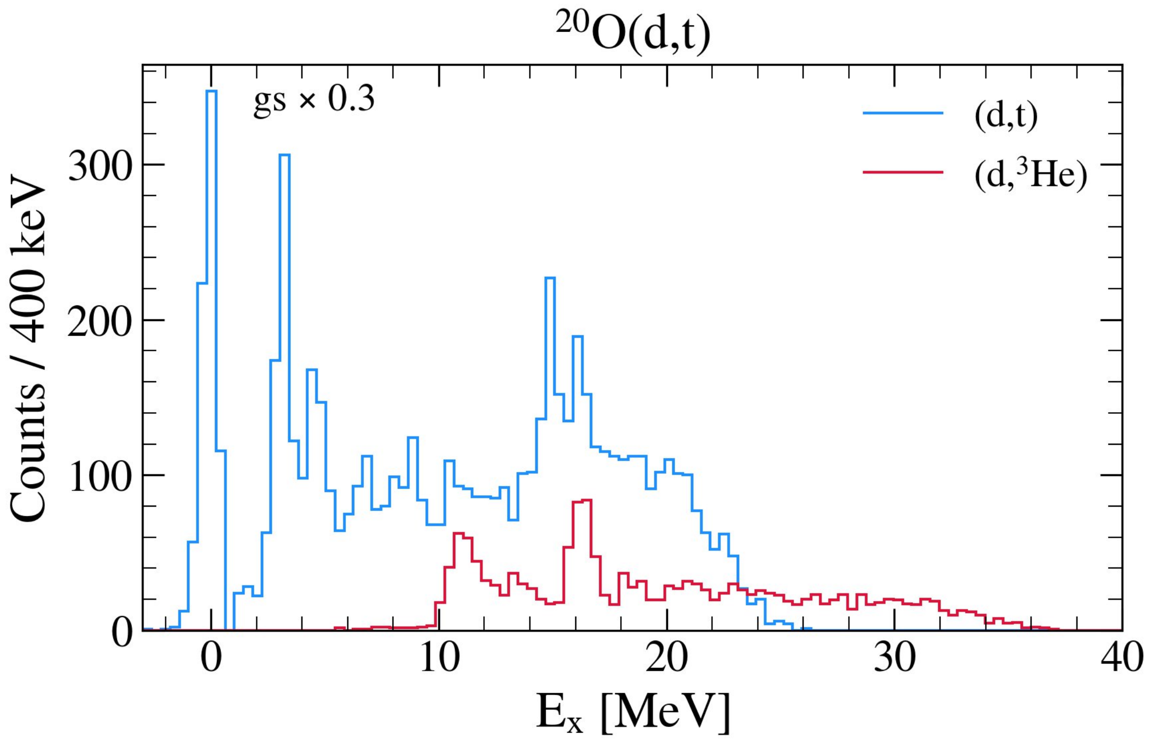


Masked punch-through to 2nd front layer

2. E_x reconstructed by the **missing-mass** technique



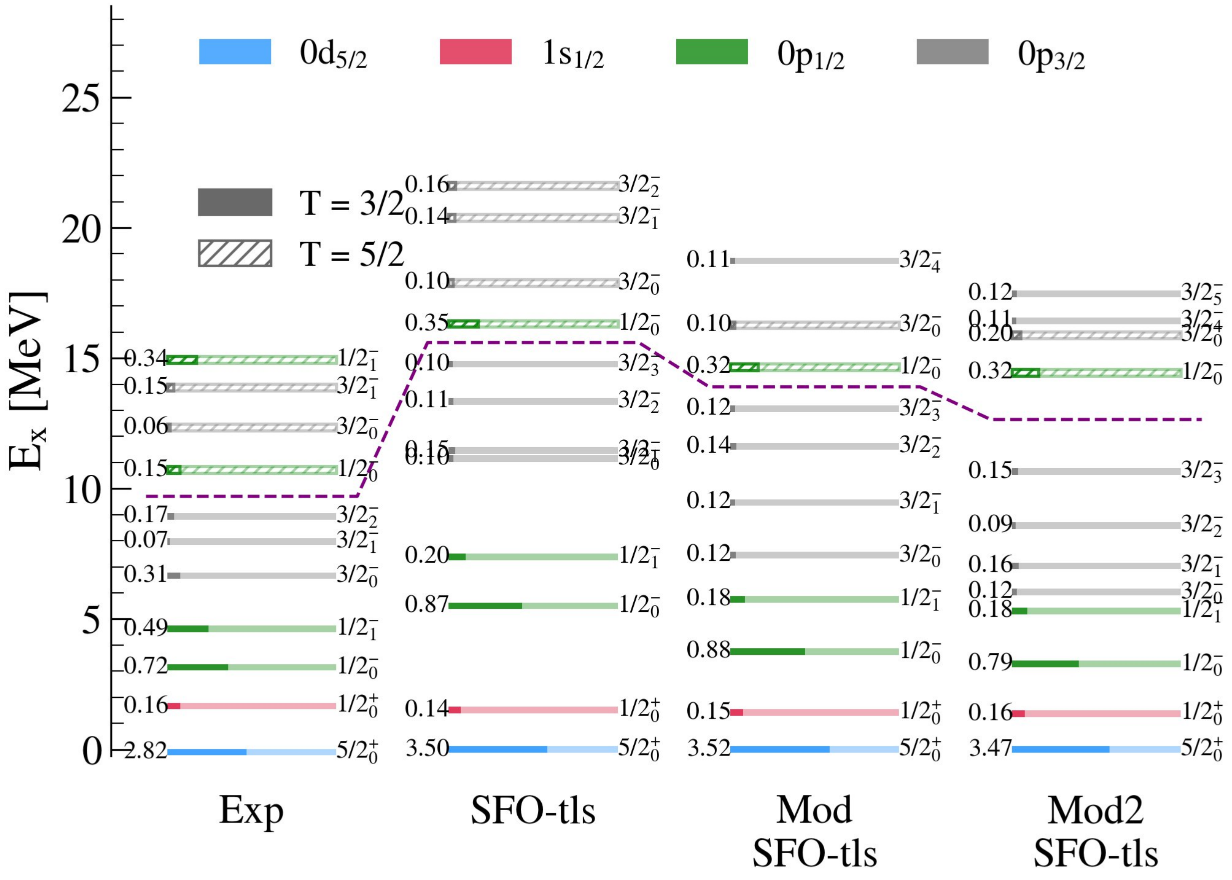
(d,^{3}He) comparison



Binding energy difference of ~ 11 MeV considered.

SFO-tls modifications

- **SFO-tls**: Original interaction *PRC 78 (2008).* Reproduces ^{17}C reduced B(M1, $1/2^+ \rightarrow 3/2_{gs}^+$) strength and Z = 6 gap in C chain.
- **Mod SFO-tls**: Monopole p-sd and sd-sd matrix el. were lowered by -0.375 MeV in T=0 channel and -0.125 MeV in T=1.
- **Mod2 SFO-tls**: Same but reducing the N=6 gap by 1.5 MeV



Results: centroids

Modified **SFO-tls**:

- Excellent agreement for $0d_{5/2}$, $1s_{1/2}$ and $0p_{1/2}$
- $0p_{3/2}$ shifted towards high E_x

$0p_{1/2}$ – $0p_{3/2}$ SO gap:

- Exp: 3.79(19) MeV
- Theo: 4.34 MeV

⇒ 0.5 MeV difference