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

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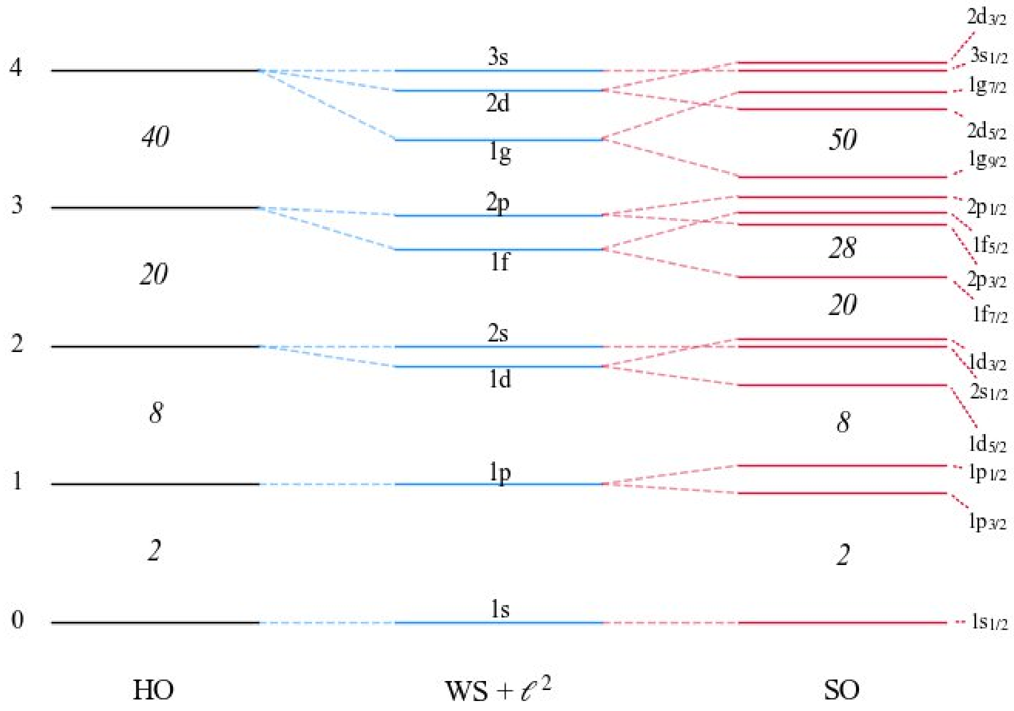
IGFAE-USC, GANIL and LPC-Caen

EuNPC 2025 - Caen

A recap on the SO splitting

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



SO splitting is mainly a surface effect:

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

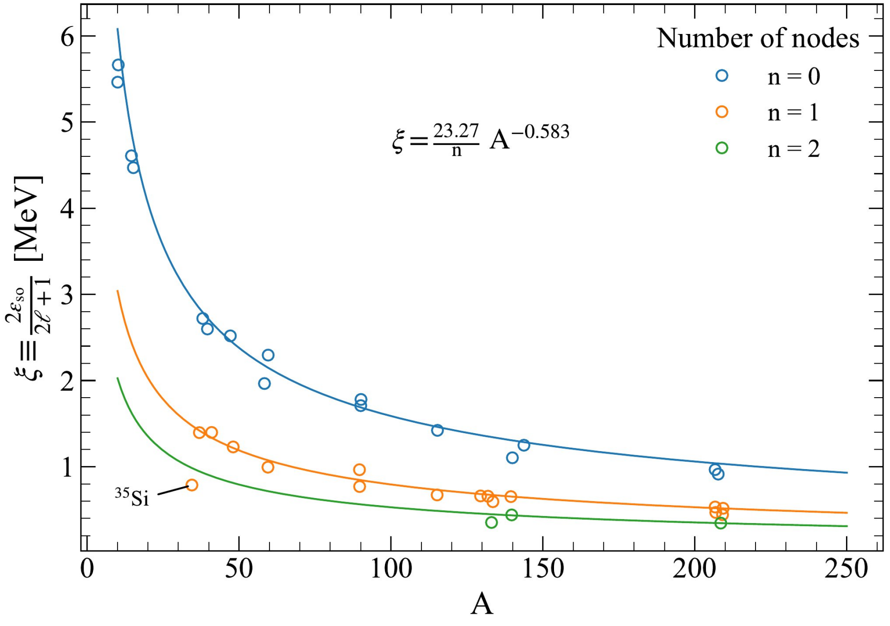
which yields a l-depending gap:

$$\Delta_{so} = \frac{\hbar^2}{2} (2\ell + 1) \xi$$

⇒ Expected to evolve towards more exotic nuclei, where surface blurs

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

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

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

$\Rightarrow$ Mainly driven by $\pi\nu$ interactions

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

A recap on the SO splitting

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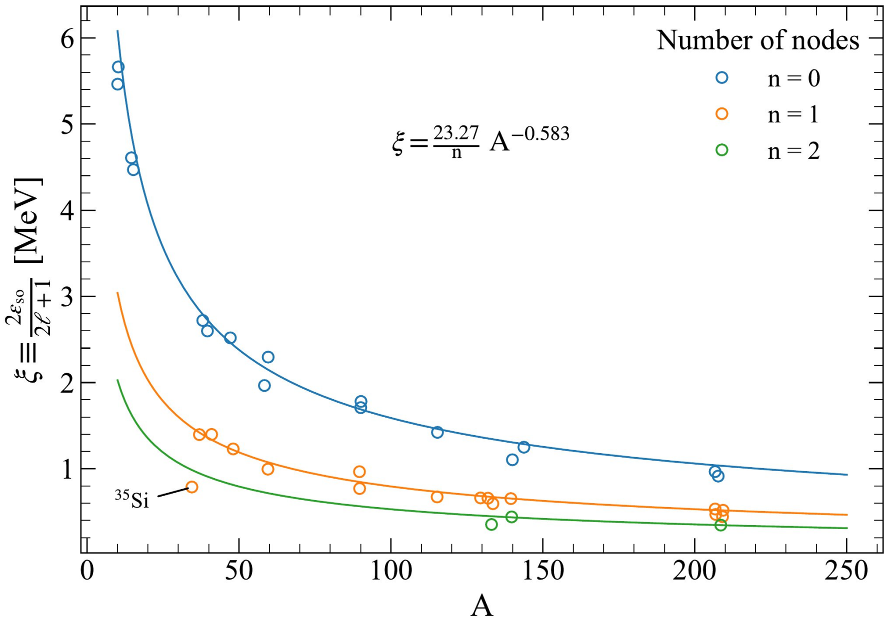
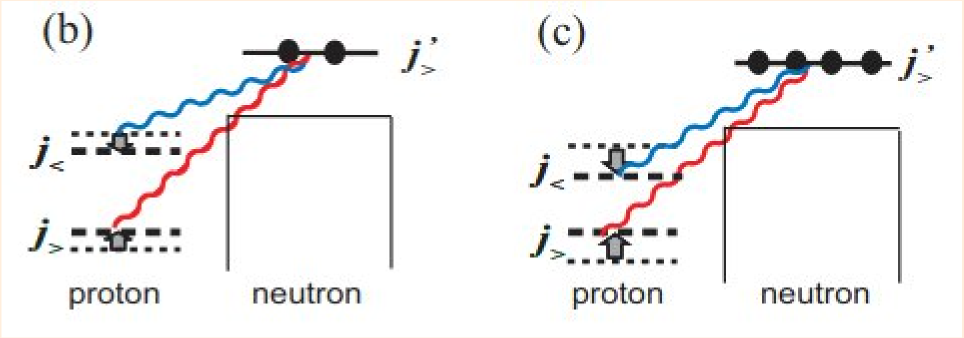


Shell gaps evolve with proton/neutron **occupancies**

Deviations from the trend are found due to:

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

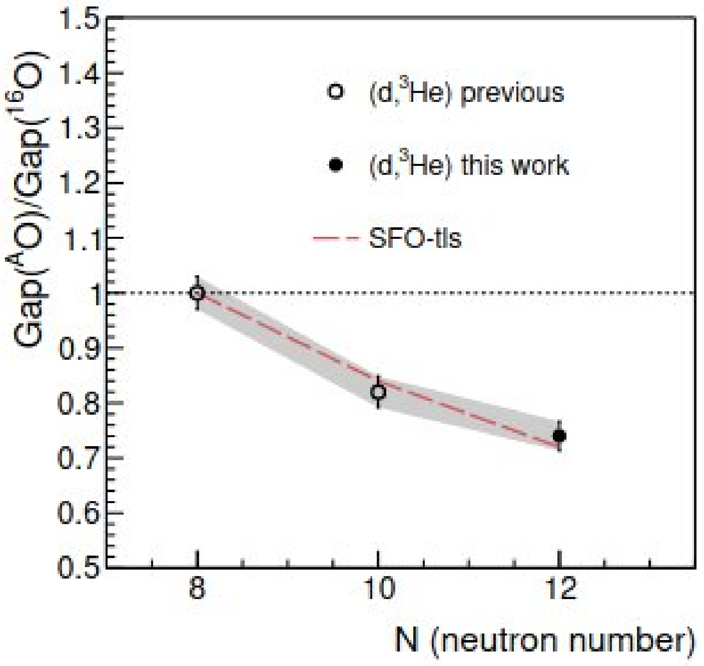


T.Otsuka and Y. Tsunoda, JPG 43 (2016)

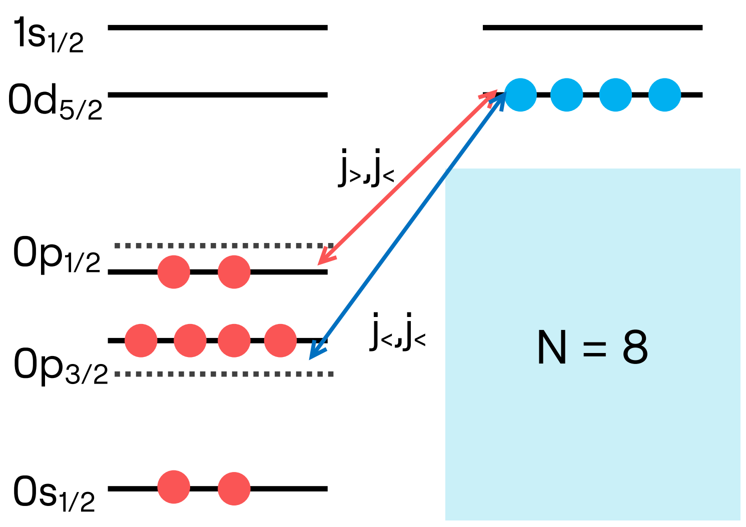
Physics case

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)



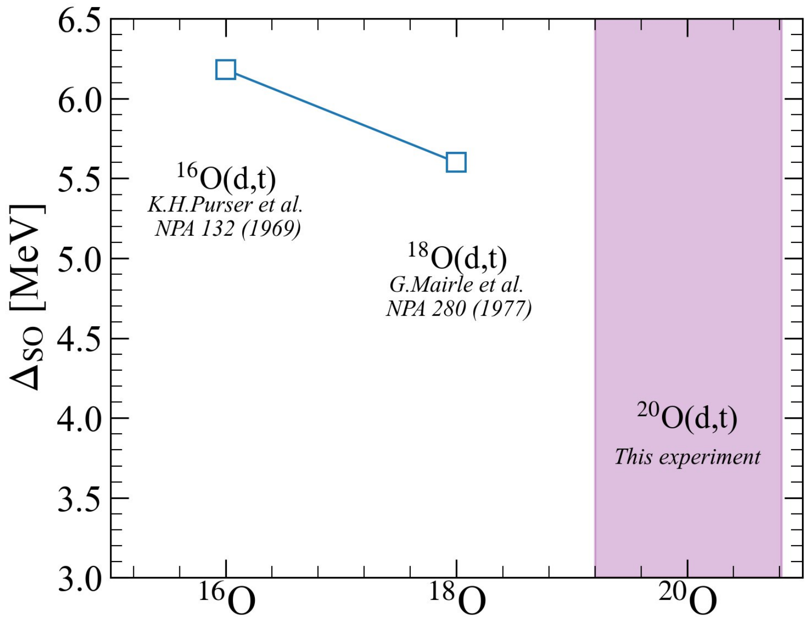
Schematic view of tensor interaction in ^{20}O

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

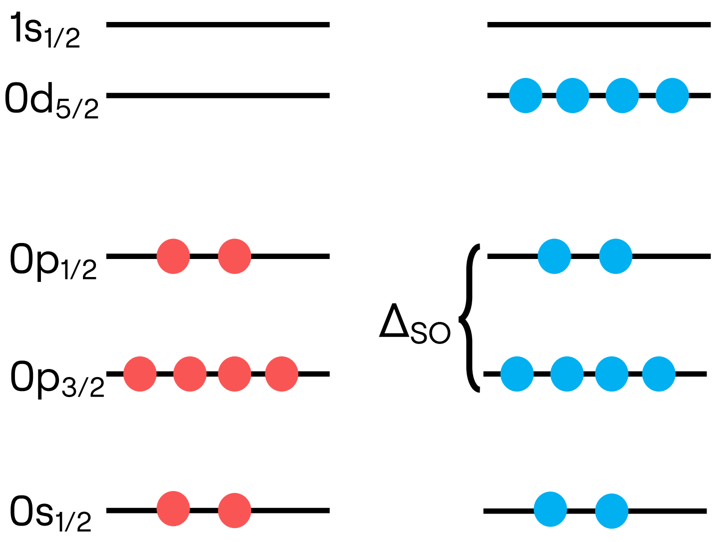
Physics case

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



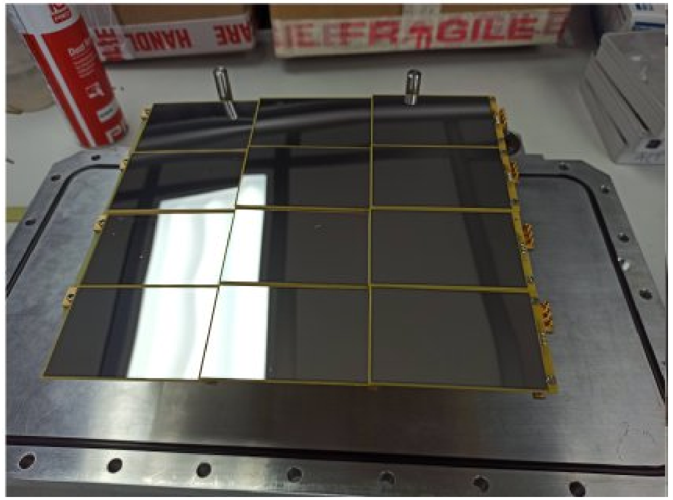
IPSM of $\boldsymbol{^{20}O}$

Would the gap decrease in ^{20}O?

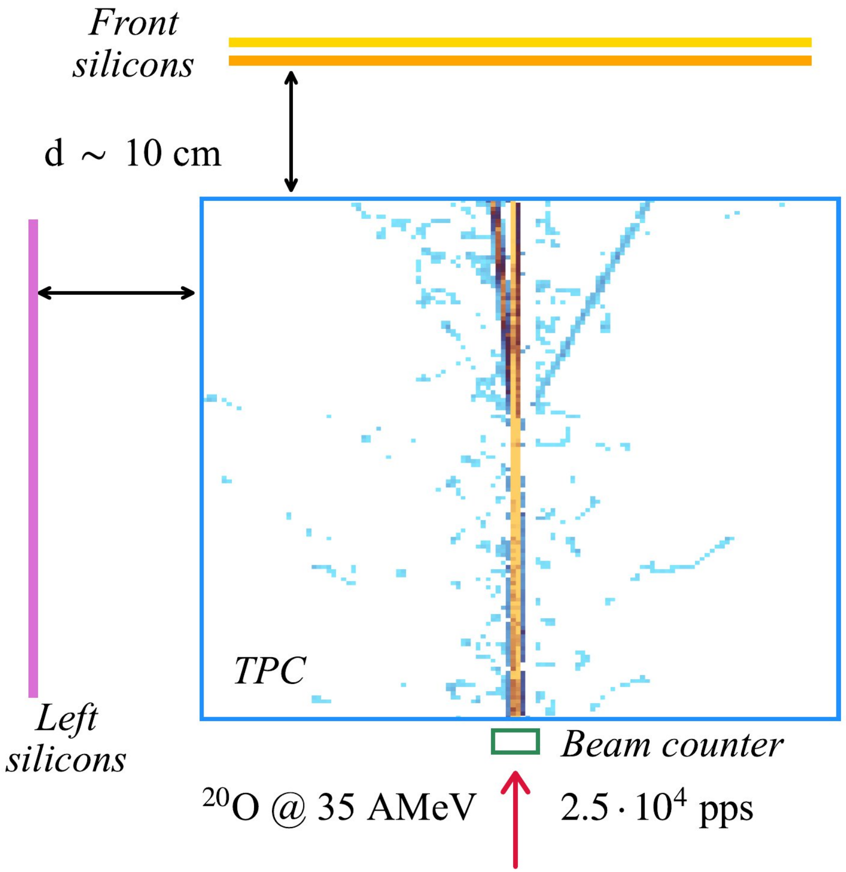
Can we extract magnitude of tensor force?

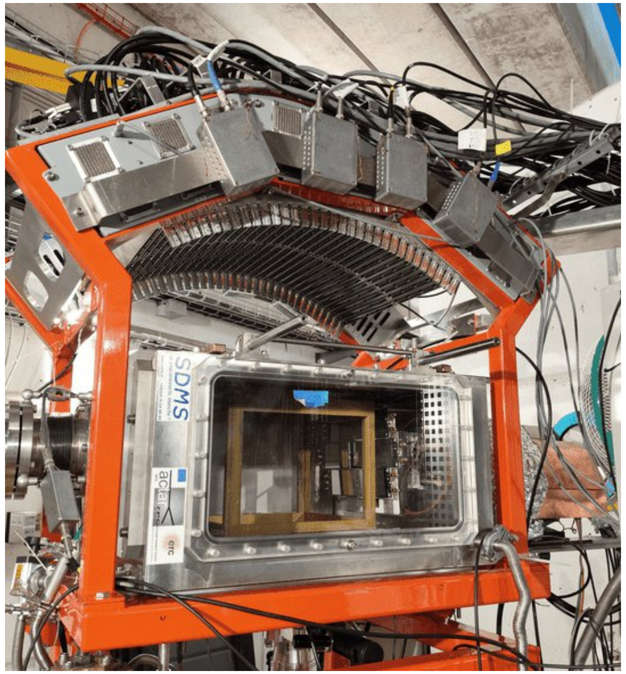
Experimental setup

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



Silicon sizes:
80 x 50 x 0.5 mm^3

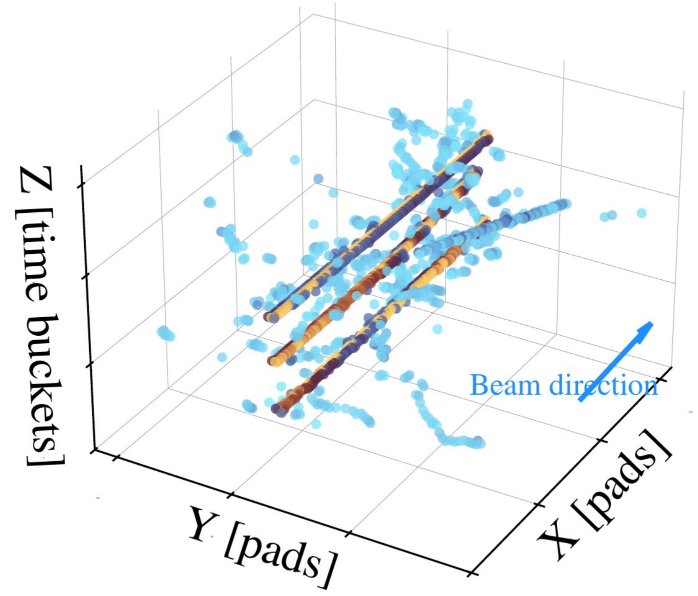


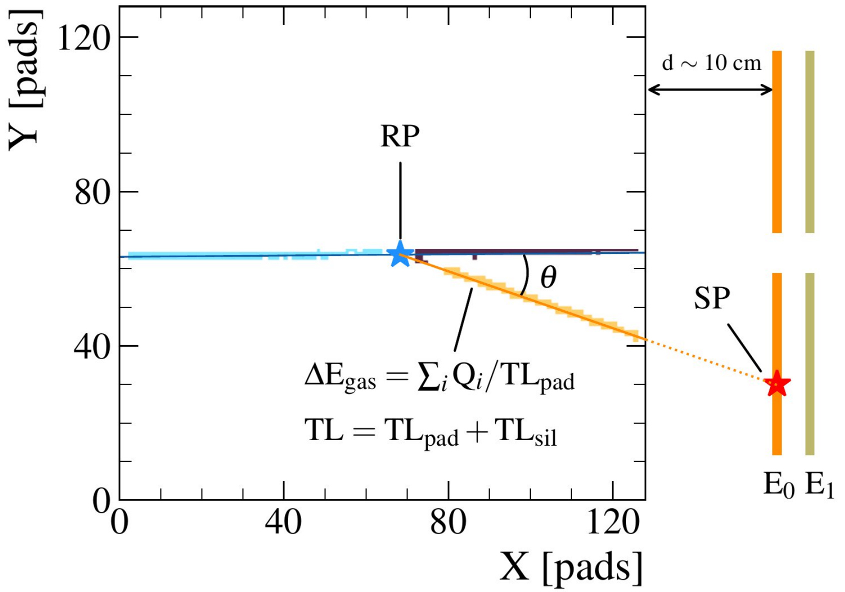


Gas mixture:
90% D_2 + 10 % iC_4H_{10}
at 952 mbar

A window to the analysis

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





Unique advantages from the TPC:

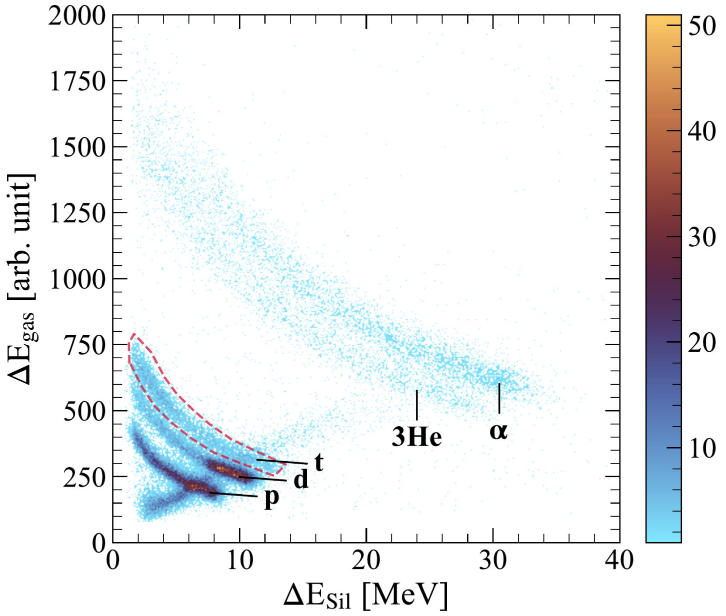
- Precise **vertex** determination
- Improved ΔE corrections

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

A window to the analysis

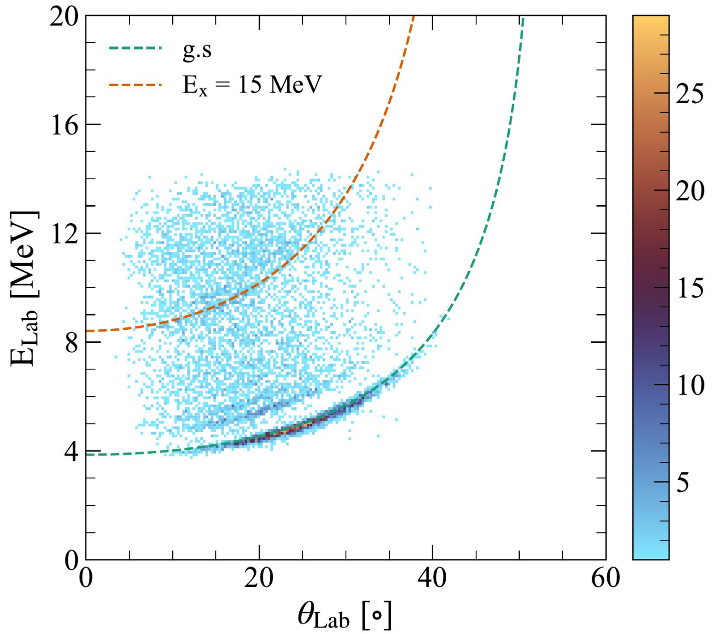
Two steps are needed after a binary reaction has been identified.

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

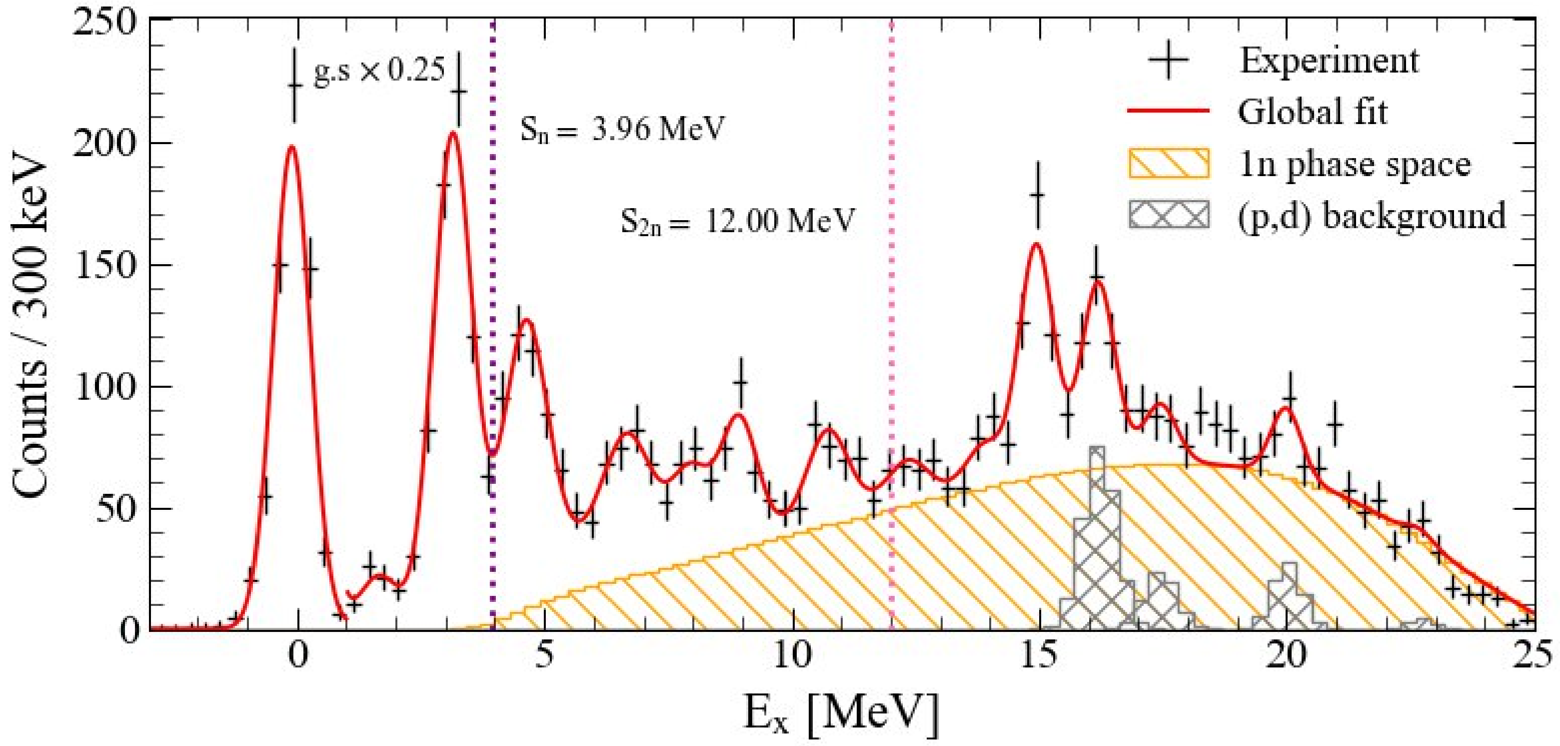


Masked punch-through to 2nd front layer

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



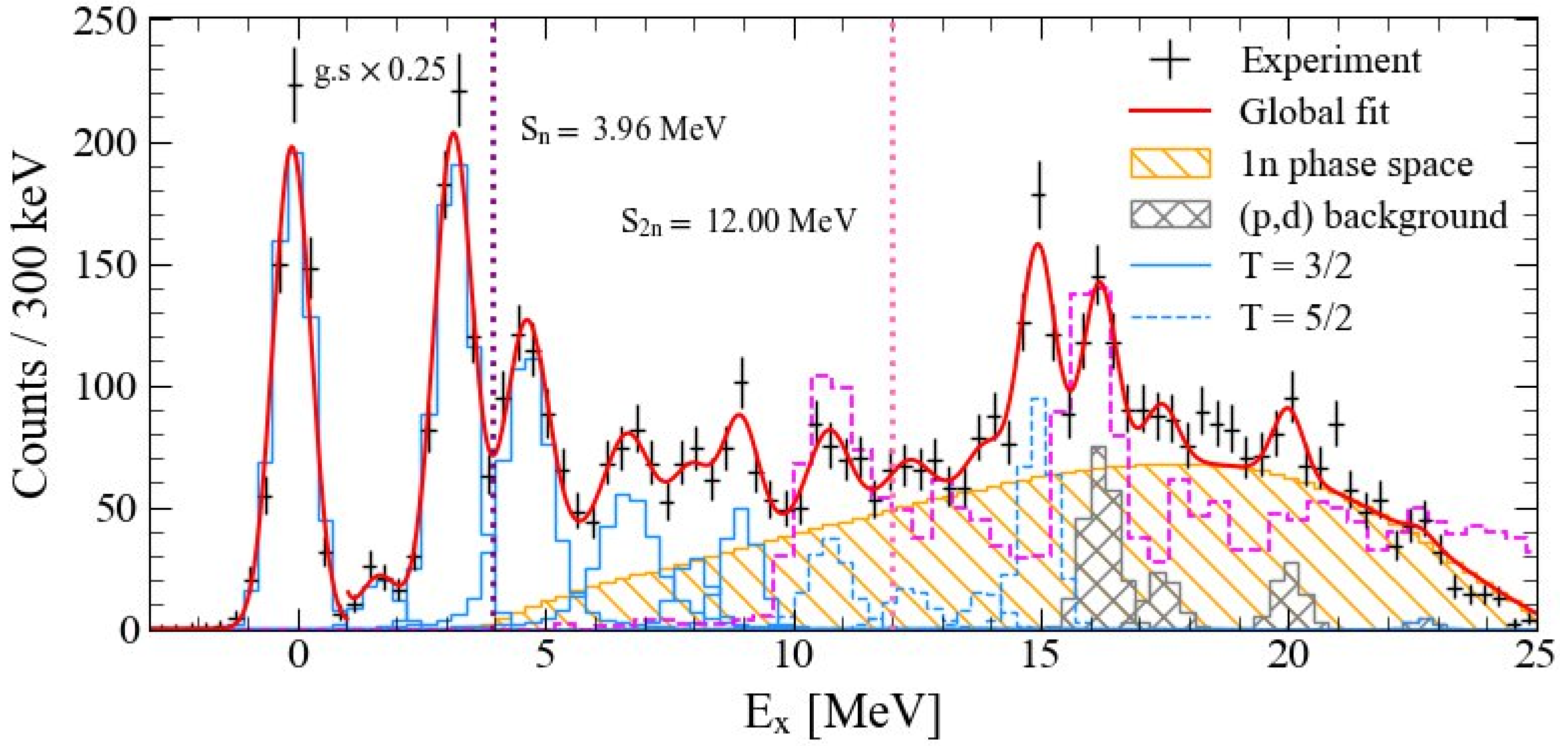
Results: E_x spectrum



- 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

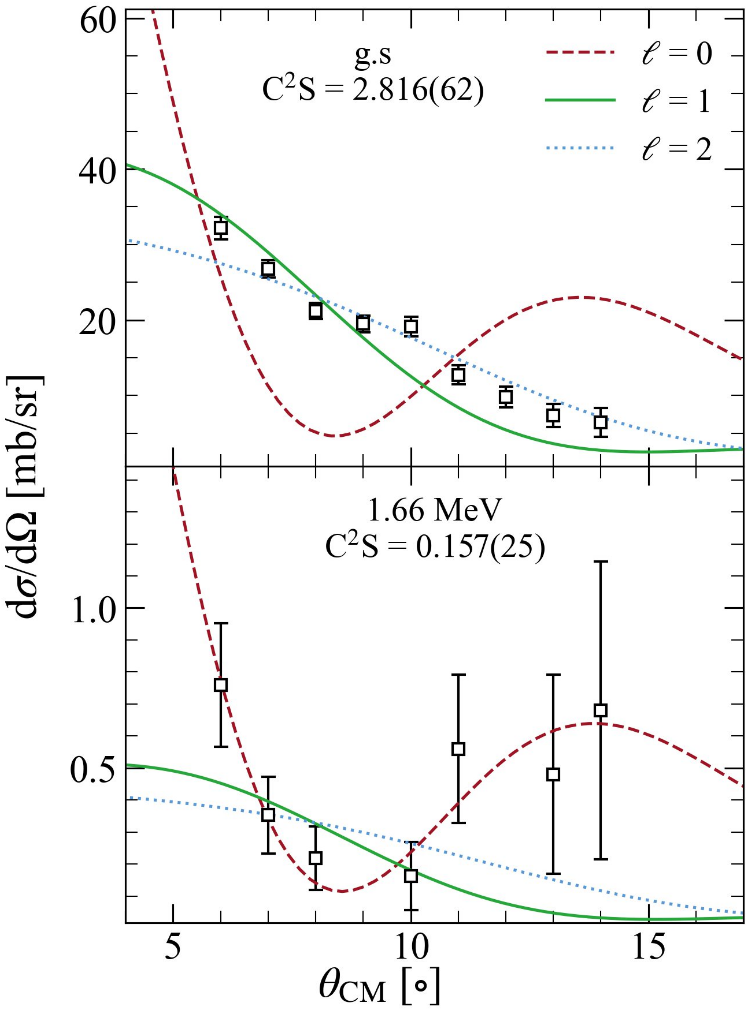
Results: E_x spectrum

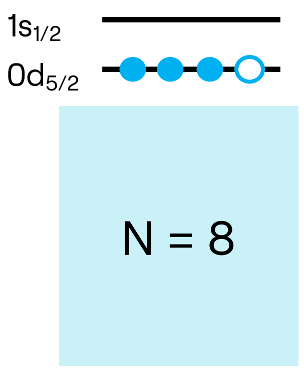


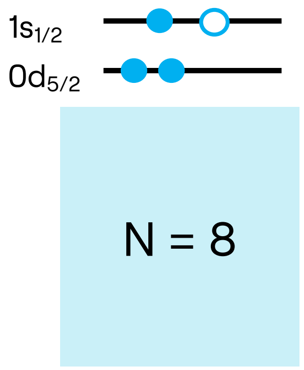
T = 3/2 states @ $E_x < 10$ MeV

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

Results: cross-sections





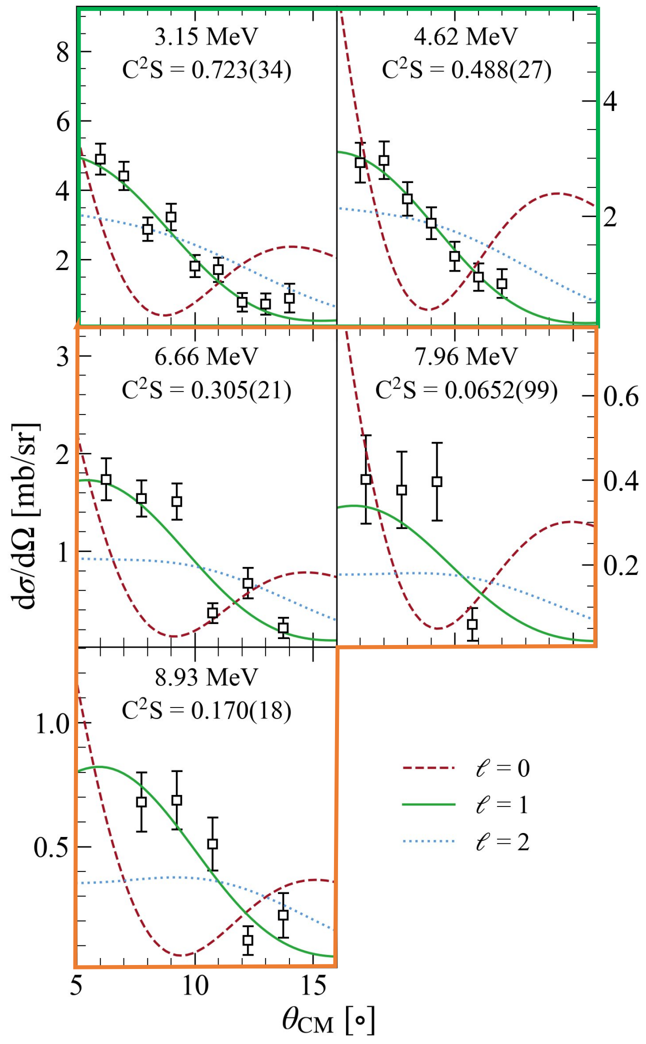


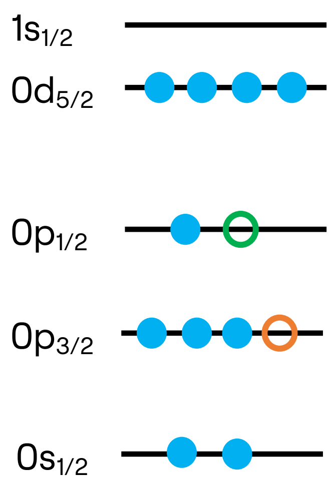
DBWA with Fresco

- 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: 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

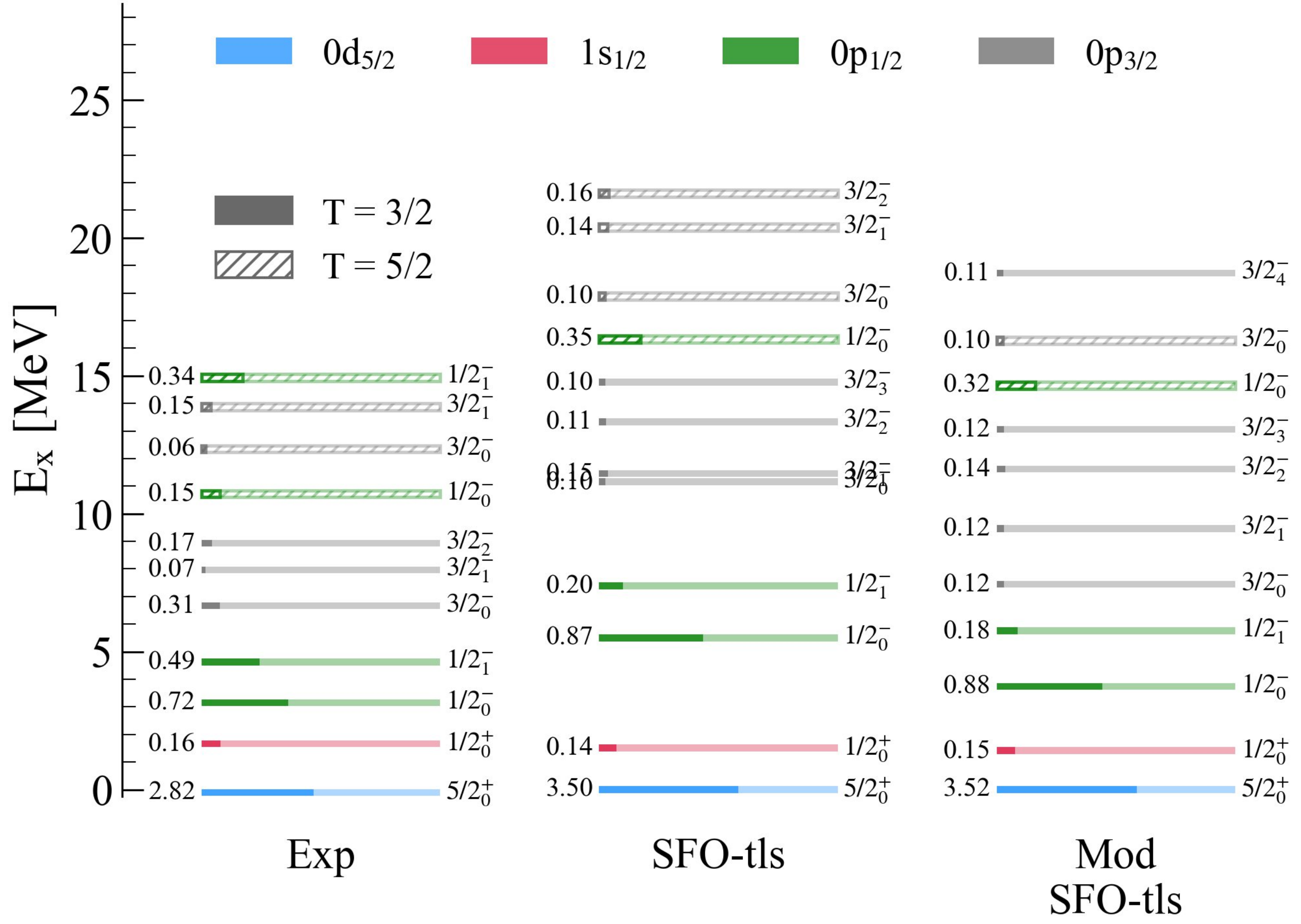
SFO-tls interaction

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

- For *p-sd* neutron-rich nuclei
- ***Modified***: reduced tensor $\nu\nu$ and $\nu\pi$ monopole matrix el.

- C^2S reduced wrt SFO-tls
- Great reproduction of low-lying states

- $0p_{3/2}$ less fragmented than predicted



Results: comparison with models

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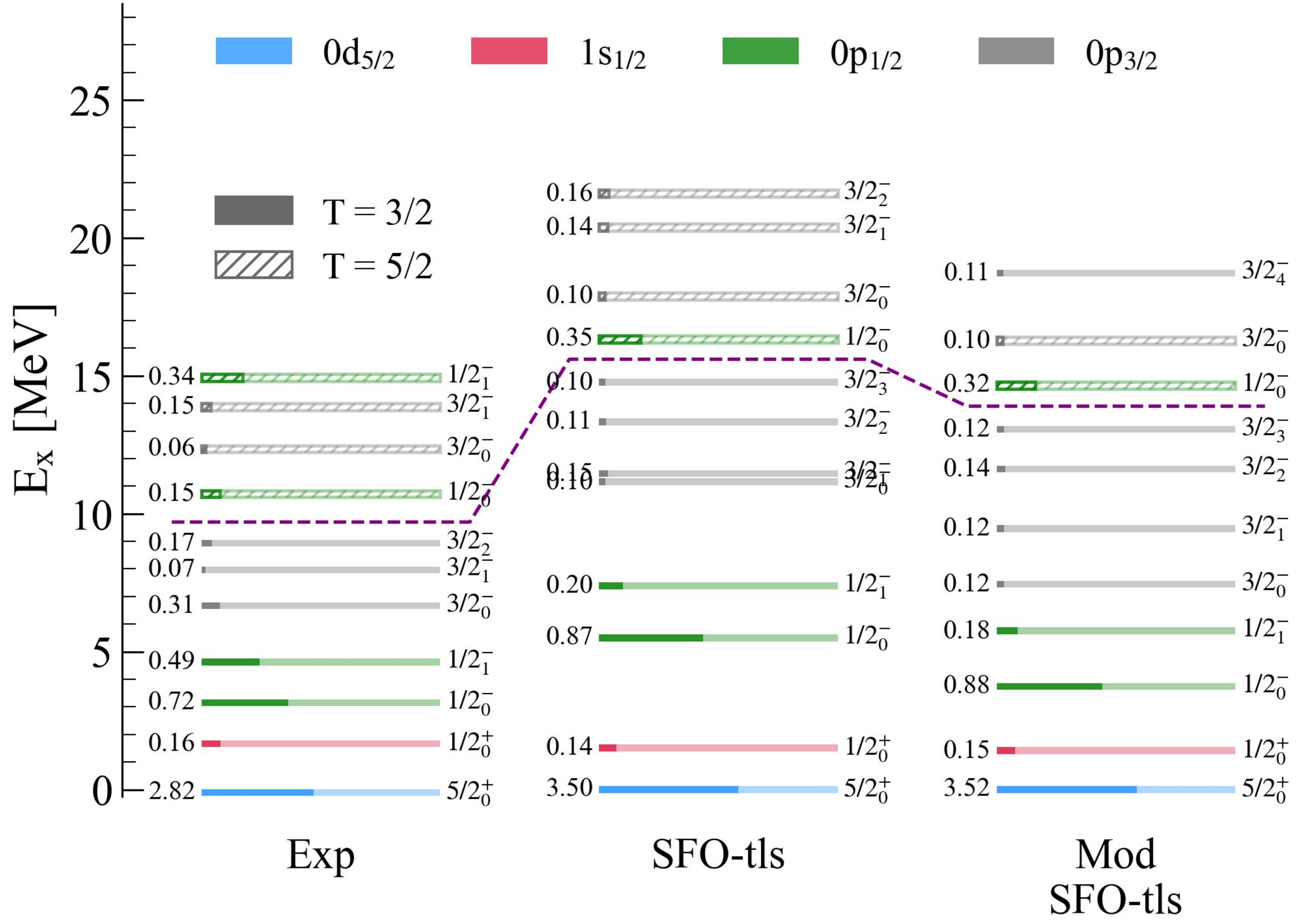
- C^2S reduced wrt SFO-tls
- Great reproduction of low-lying states

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



Results: centroids

***Modified* SFO-tls**:

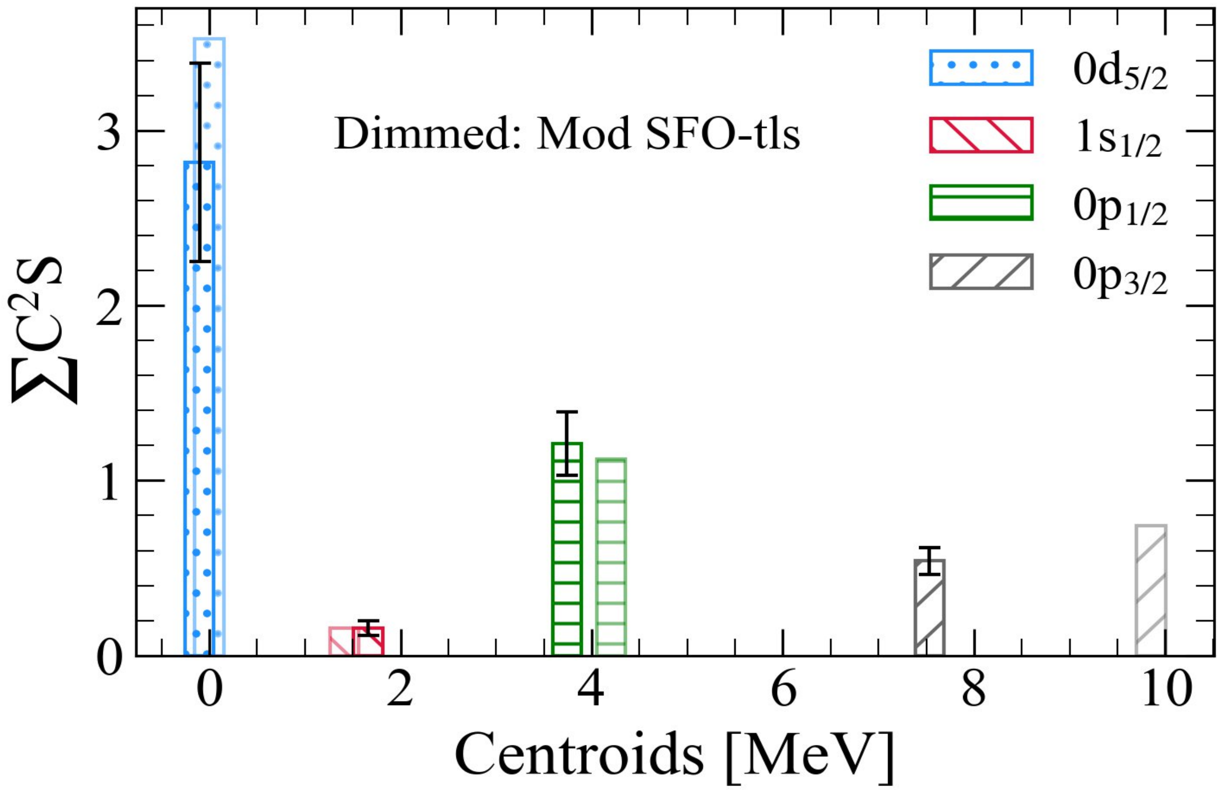
- Excellent agreement for $0d_{5/2}$, $1s_{1/2}$ and $0p_{1/2}$
- $0p_{3/2}$ shifted towards high E_x

$0p_{1/2}$ – $0p_{3/2}$ SO gap:

- Exp: 3.79(9) MeV
- Theo: 5.64 MeV

⇒ Gap is reduced by ~ 1.8 MeV!

Systematic error of 20% from OMPs variety has been included in error bars



No 0p vacancies were observed through $^{20}O(d,p)^{21}O$

B. Fernández-Domínguez et al. PRC 84 (2011)

Conclusions

$^{20}O(d,t)^{19}O$ reaction as a means 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 interaction overestimates SO gap due to $0p_{3/2}$ states

Theoretical efforts needed to reconcile those states with experimental data!

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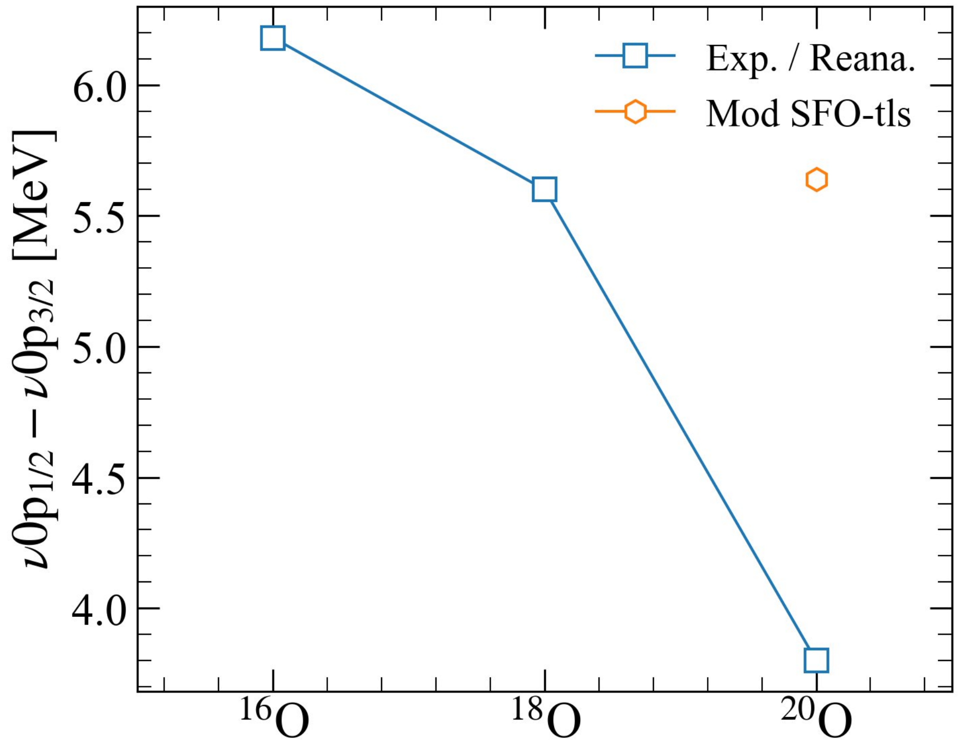
Extra slides

Results: gap evolution

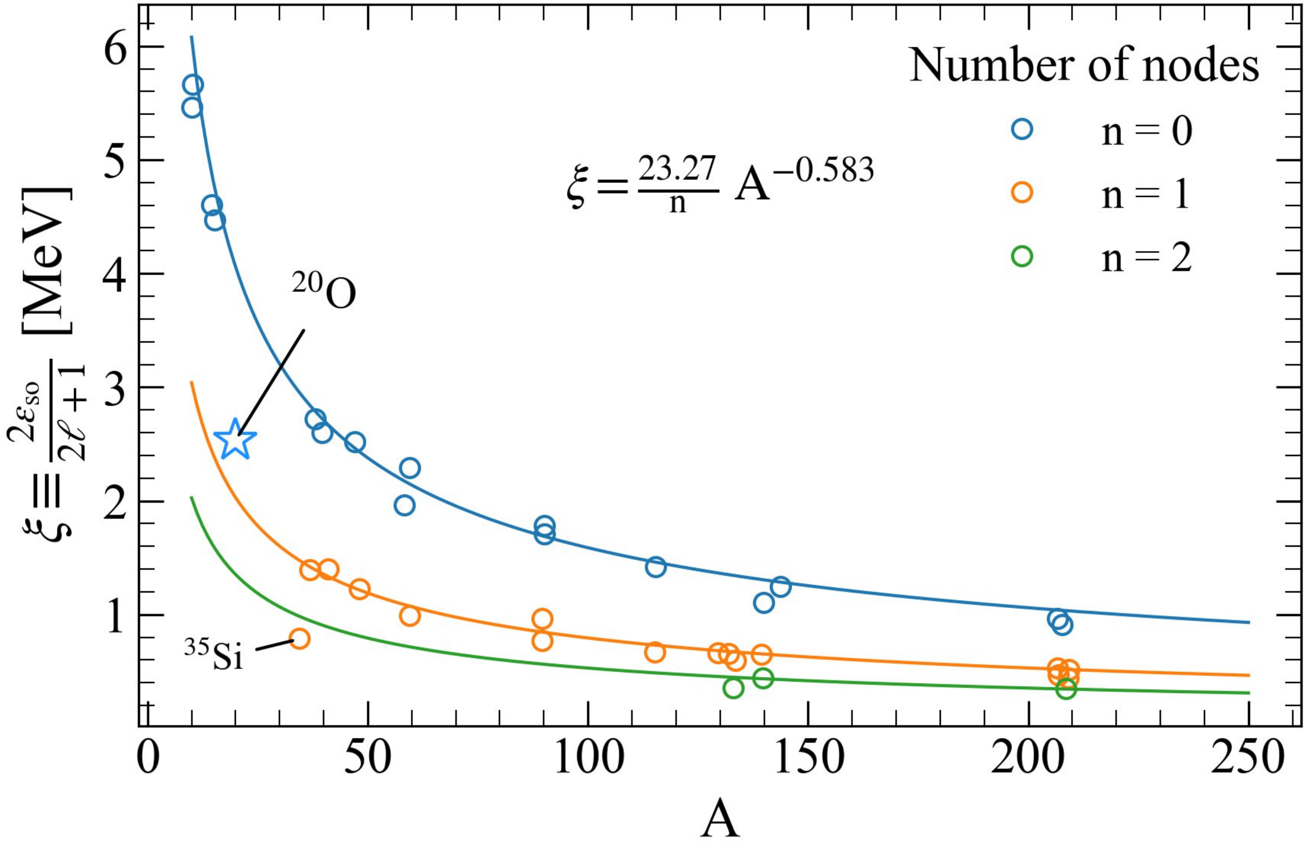
- $^{16}O(d,t)$: *K. H. Purser et al. NPA 132 (1969)*. No need to reanalyze xs bc there is only one state per nlj; just take the Ex
- $^{16}O(d,p)$: Alleged state 3/2- is not *single-particle* but j-forbidden stripping. See *K. Hosono JPSP 25 (1968)* Table II. This state is neutron $0d_{5/2}$ + proton $0p_{1/2}^{-1}0d_{5/2}^{1}$ as I understood from it
- $^{18}O(d,t)$: *G. Mairle et al. NPA 280 (1977)*. Reanalysis of xs with our OMPs and Fresco. Major discrepancies with their paper
- $^{20}O(d,t)$: this experiment



We are lacking theo calculations for 16O and 18O

Conclusions

- To be determined



A window to the analysis