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

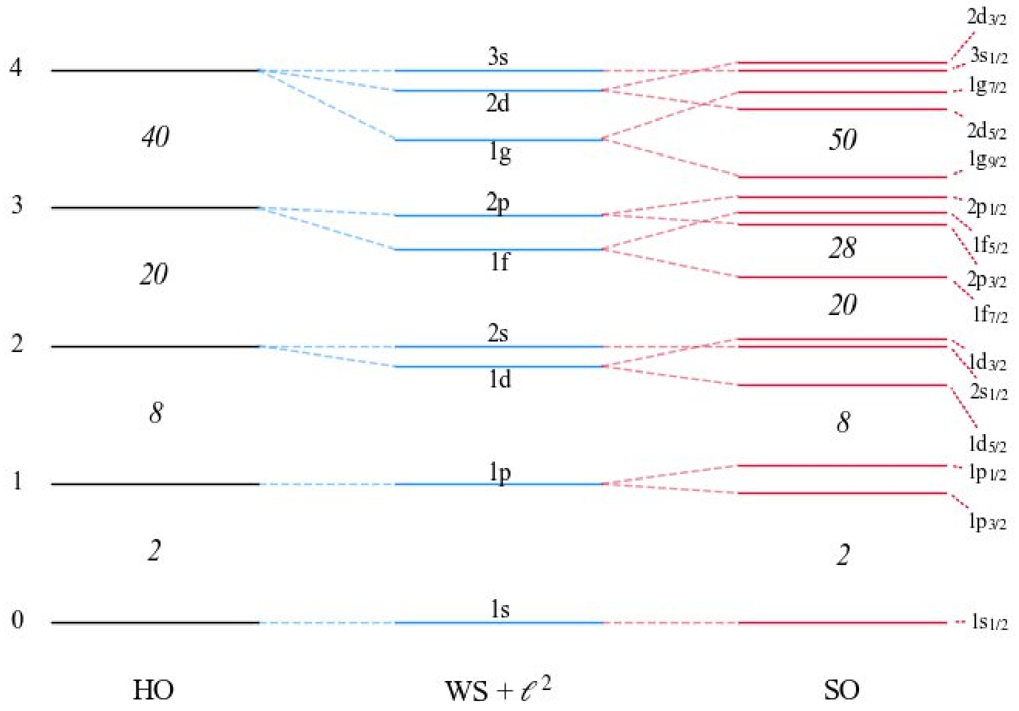
M. Lozano-González, B. Fernández-Domínguez, J. Lois-Fuentes,
T. Roger, F. Delaunay

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:

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

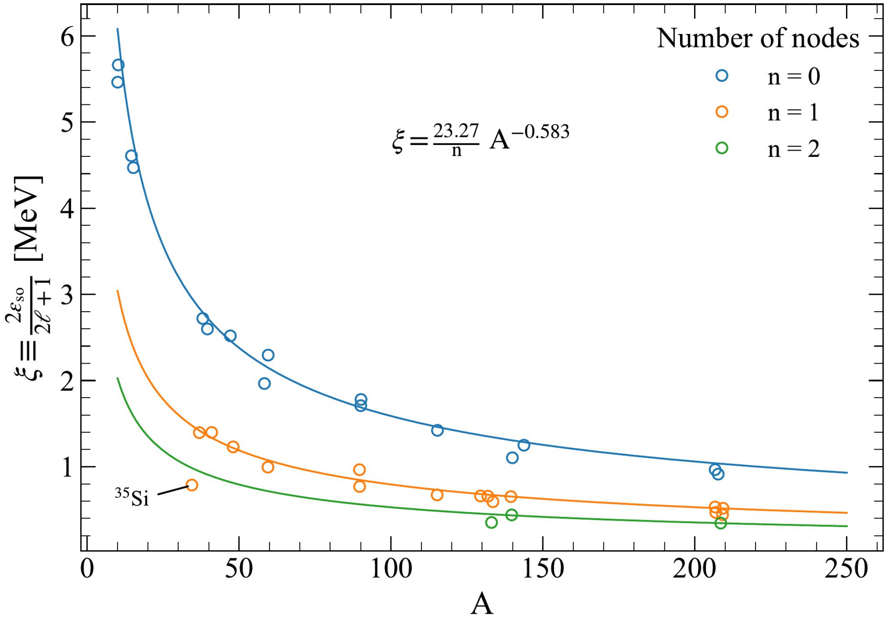
which yields a l-depending gap:

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

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

A recap on the SO splitting

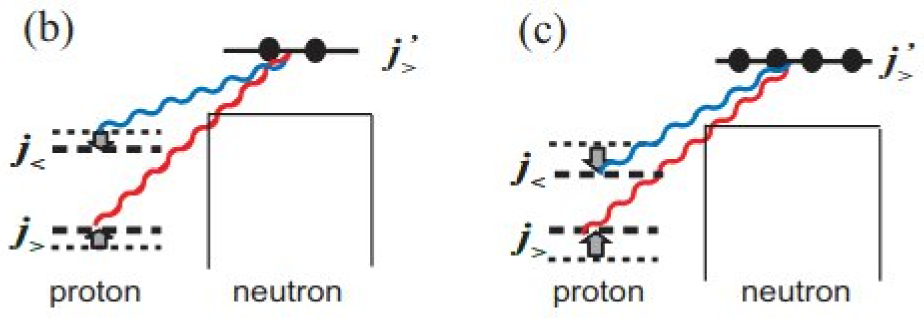
G .Mairle *et al.* (PLB 304 (1993)) found systematic trends easily parametrizable.



Proton-neutron interactions drive **shell evolution**

Deviations from the trend are found due to:

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

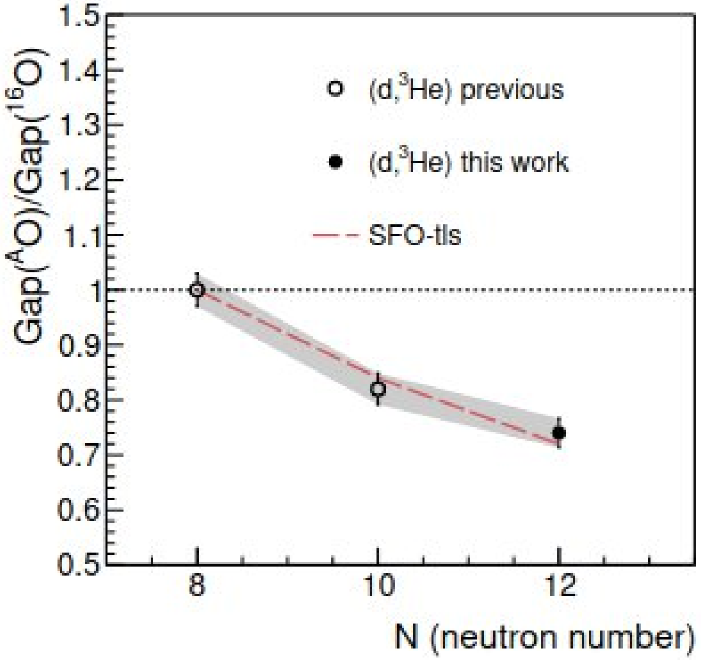


T.Otsuka and Y. Tsunoda, JPG 43 (2016)

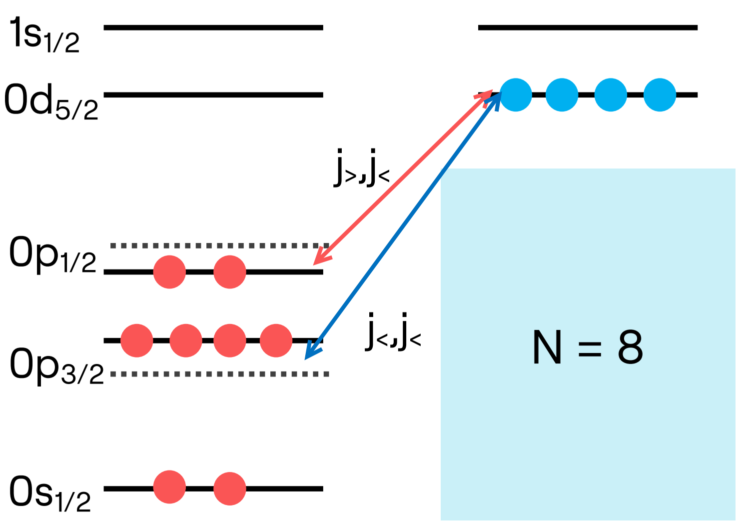
Physics case

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)



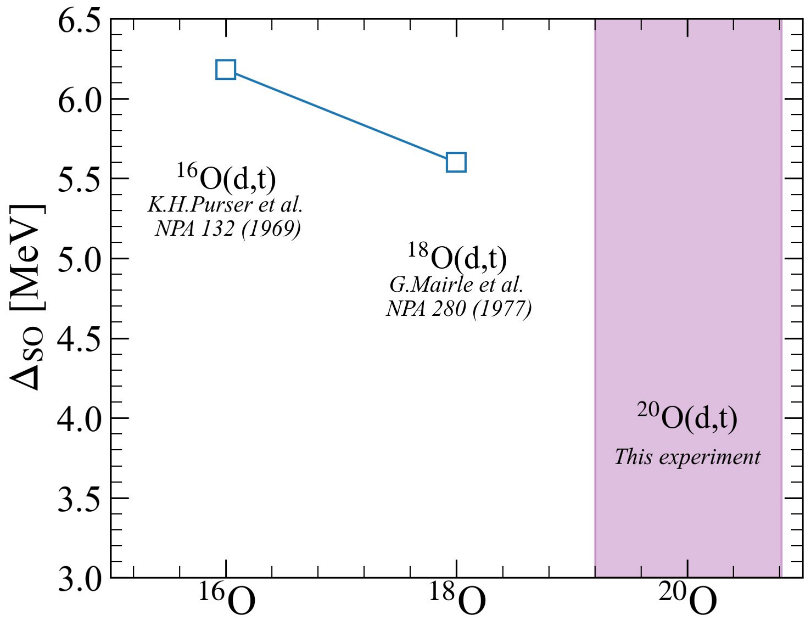
Schematic view of tensor interaction in ^{20}O

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

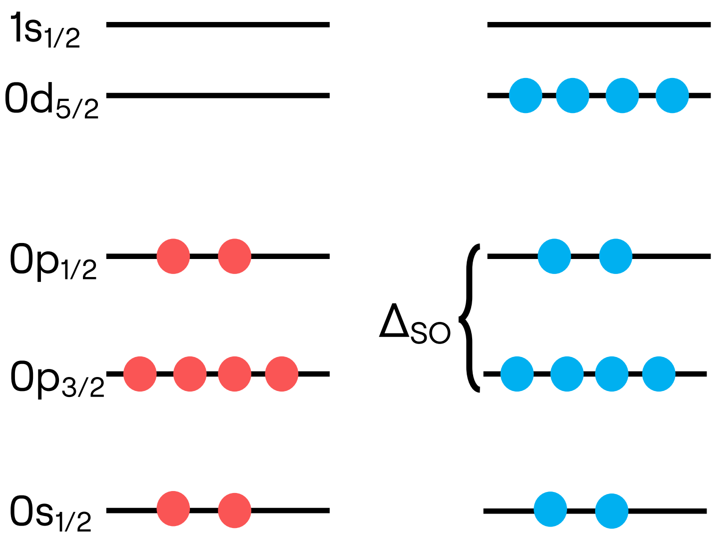
Physics case

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



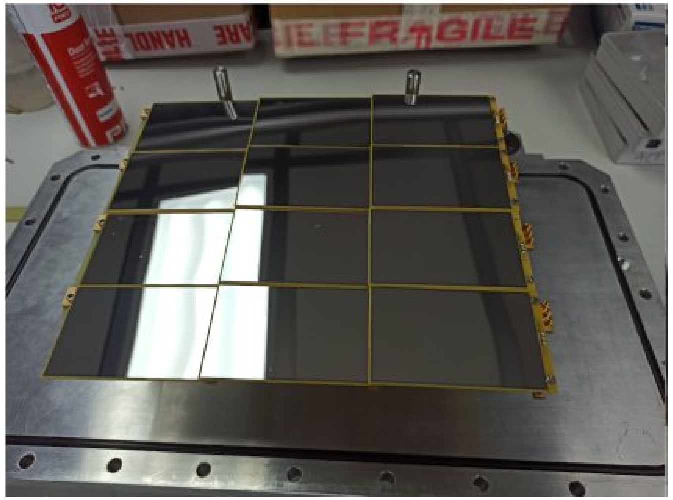
IPSM of ***^{20}O***

Would the gap decrease in ^{20}O?

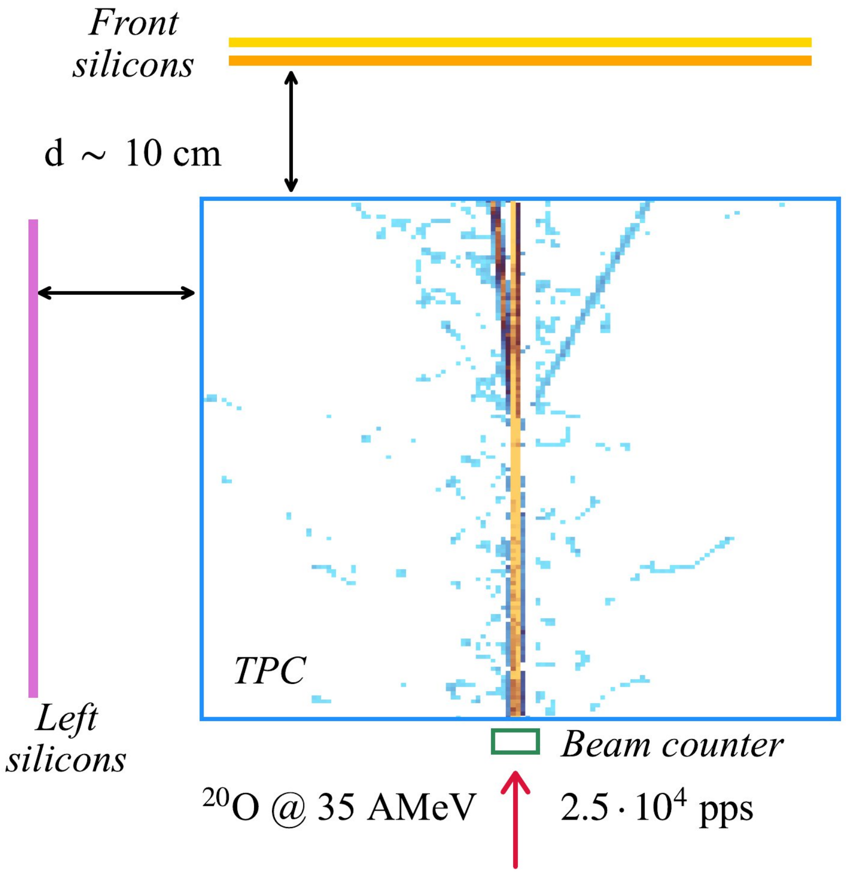
Can we extract magnitude of tensor force?

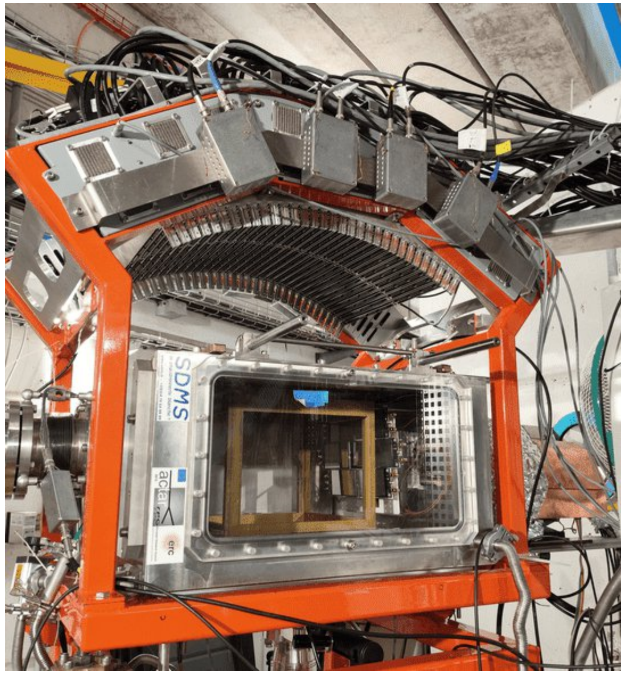
Experimental setup

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



Silicon sizes:
80 x 50 x 0.5 mm^3

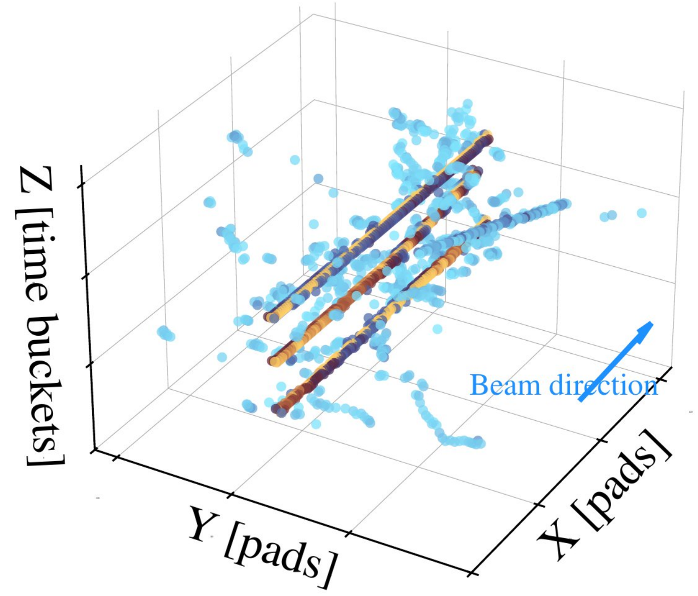


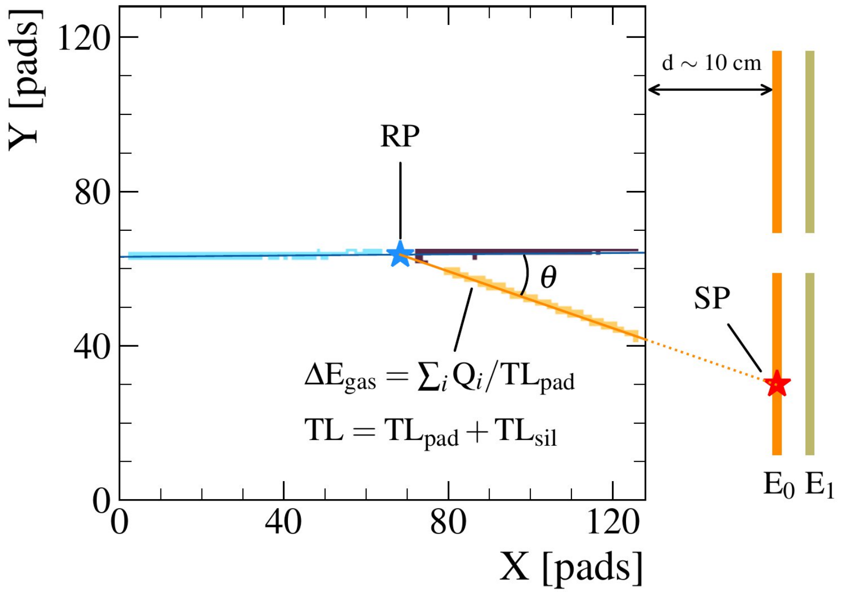


Gas mixture:
90% D_2 + 10 % iC_4H_{10}
at 952 mbar

A window to the analysis

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





Unique advantages from the TPC:

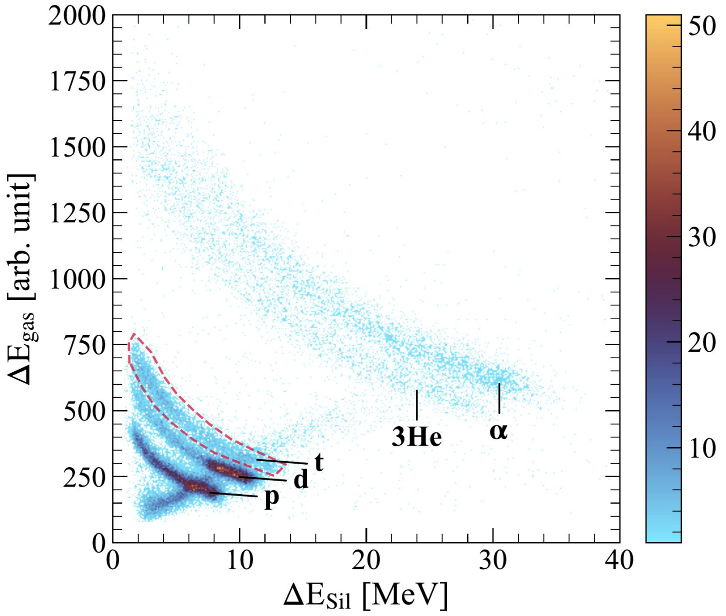
- Precise **vertex** determination
- Improved ΔE corrections

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

A window to the analysis

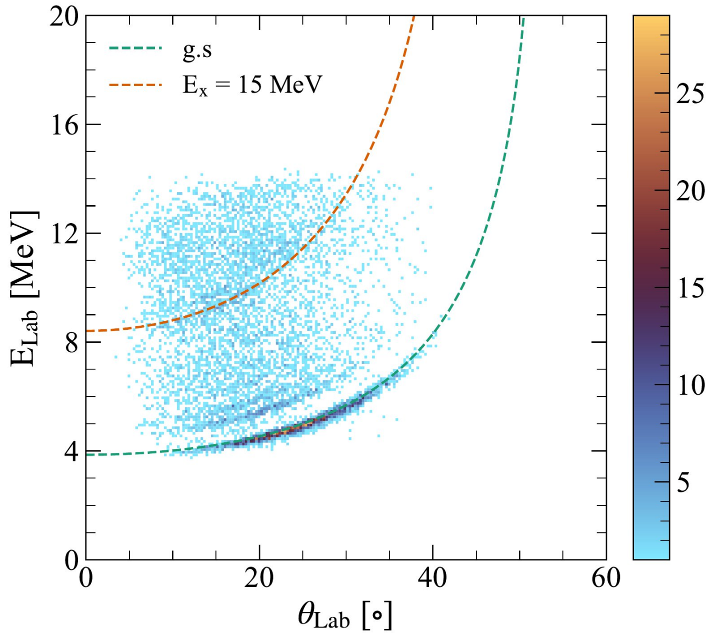
Two steps are needed after a binary reaction has been identified.

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

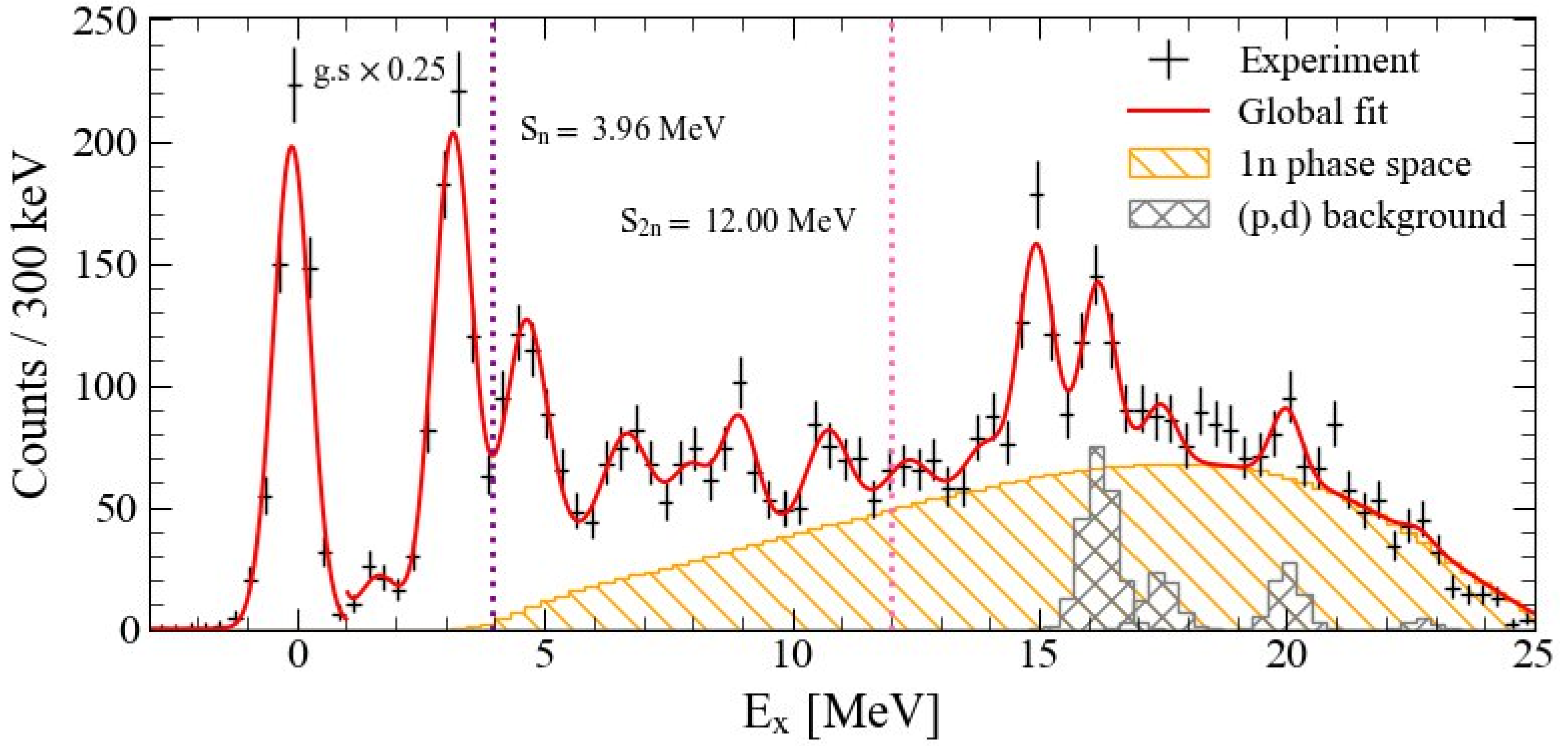


Masked punch-through to 2nd front layer

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



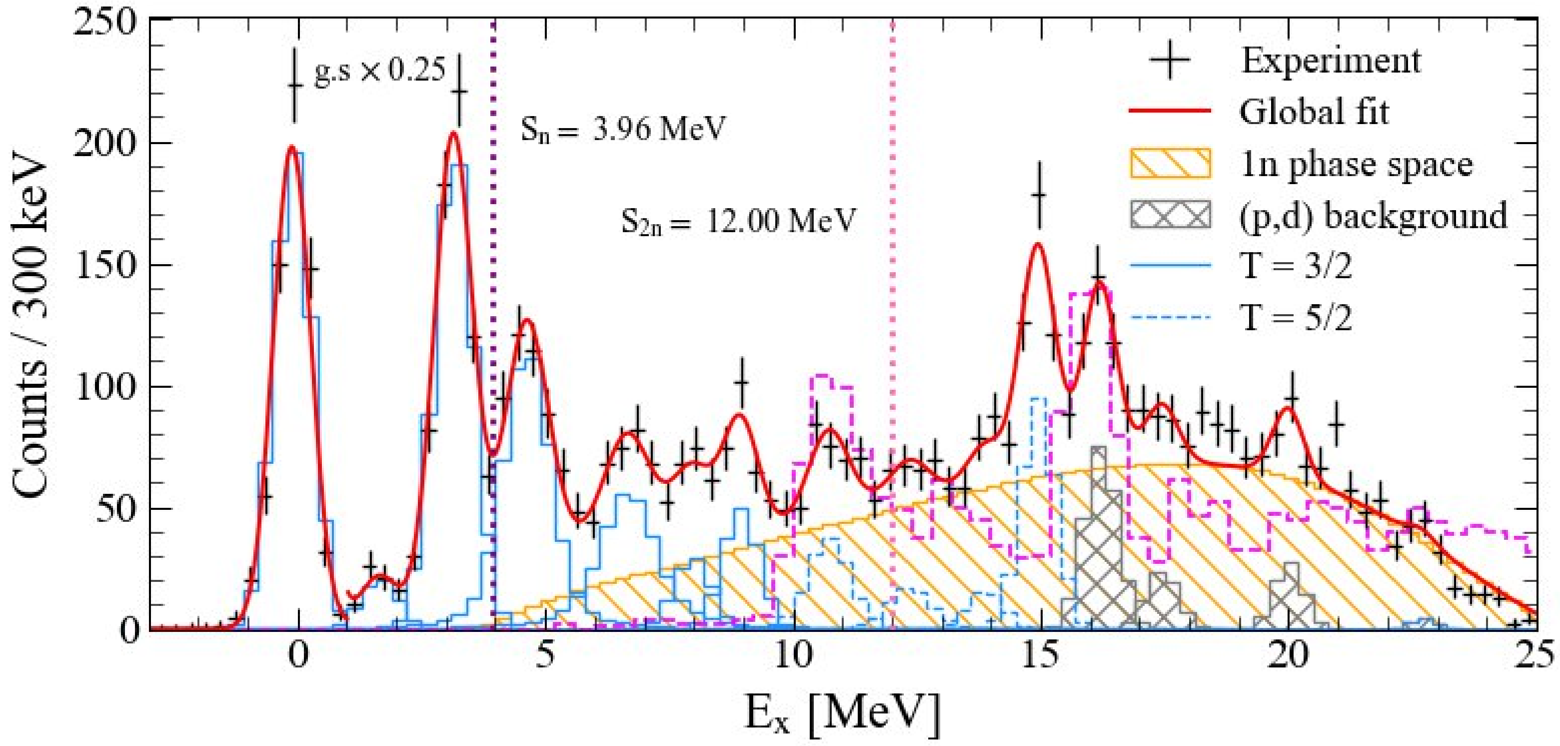
Results: E_x spectrum



- 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

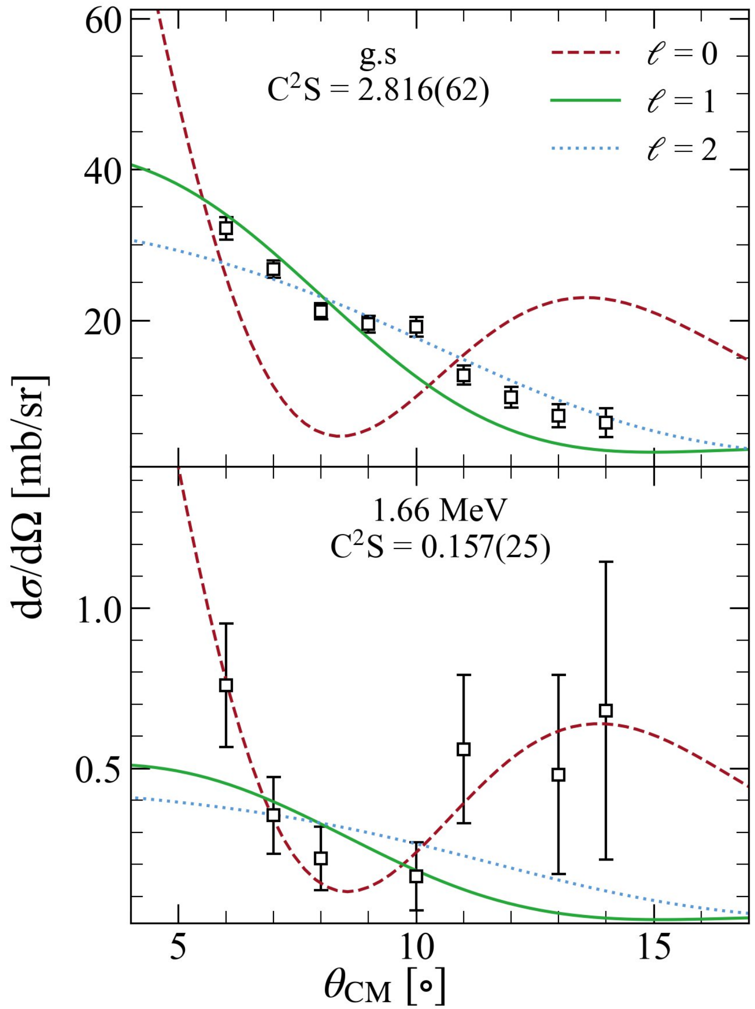
Results: E_x spectrum

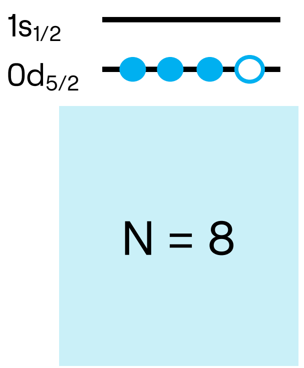


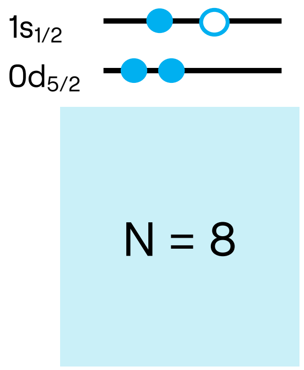
T = 3/2 states @ E_x < 10 MeV

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

Results: cross-sections





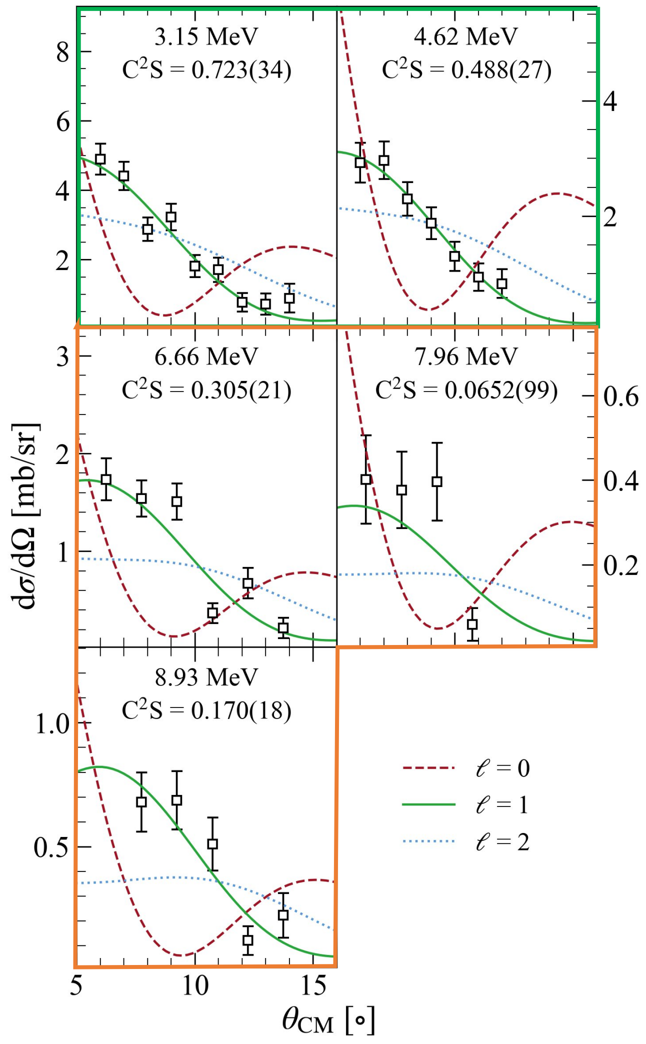


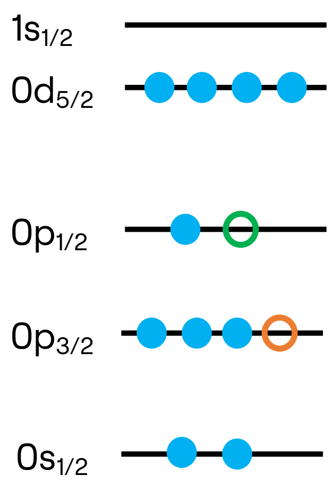
DBWA with **Fresco**

- 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
- 1^{st}: $1/2^+$, 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

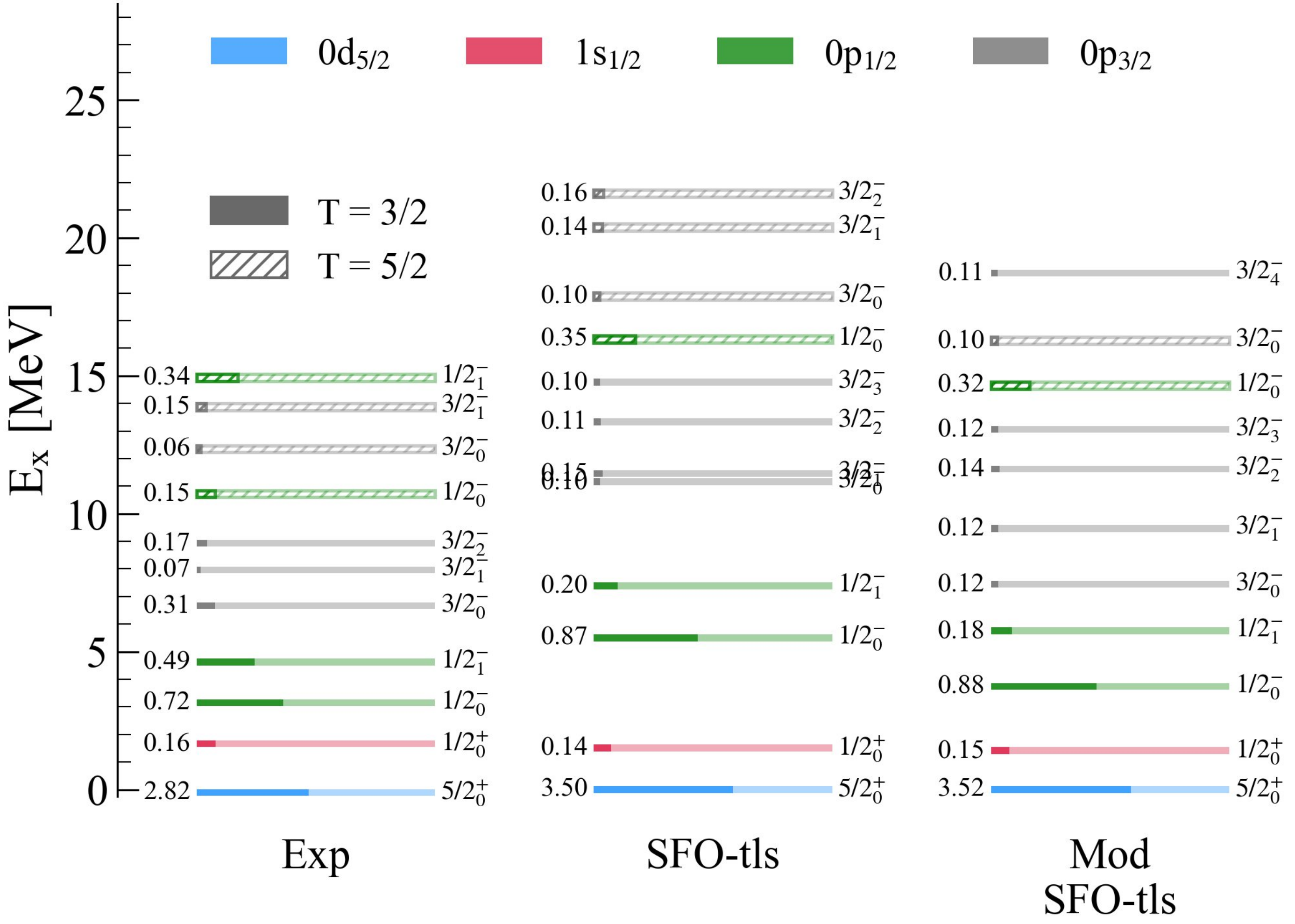
SFO-tls interaction

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

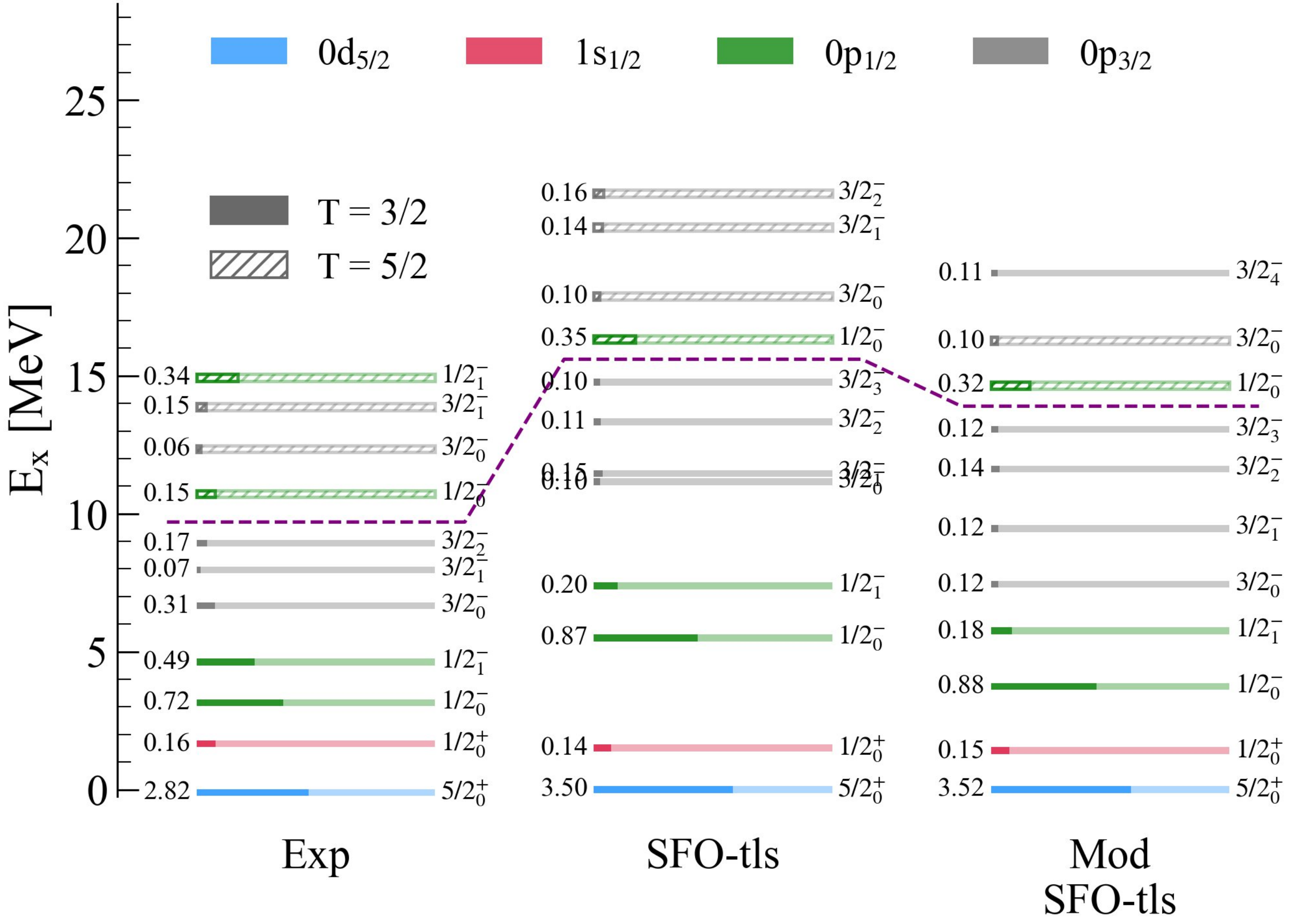
SFO-tls interaction

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



Results: centroids

Modified **SFO-tls**:

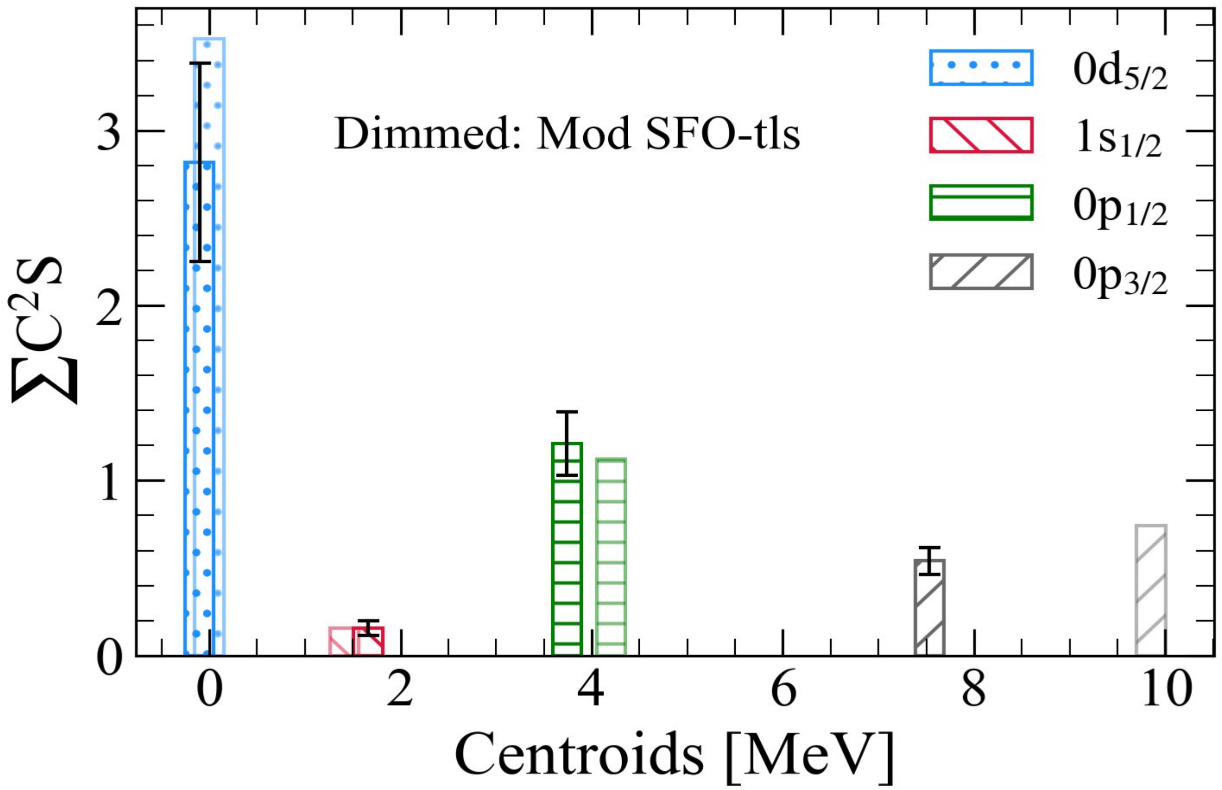
- Excellent agreement for $0d_{5/2}$, $1s_{1/2}$ and $0p_{1/2}$
- $0p_{3/2}$ shifted towards high E_x

$0p_{1/2}$ – $0p_{3/2}$ 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

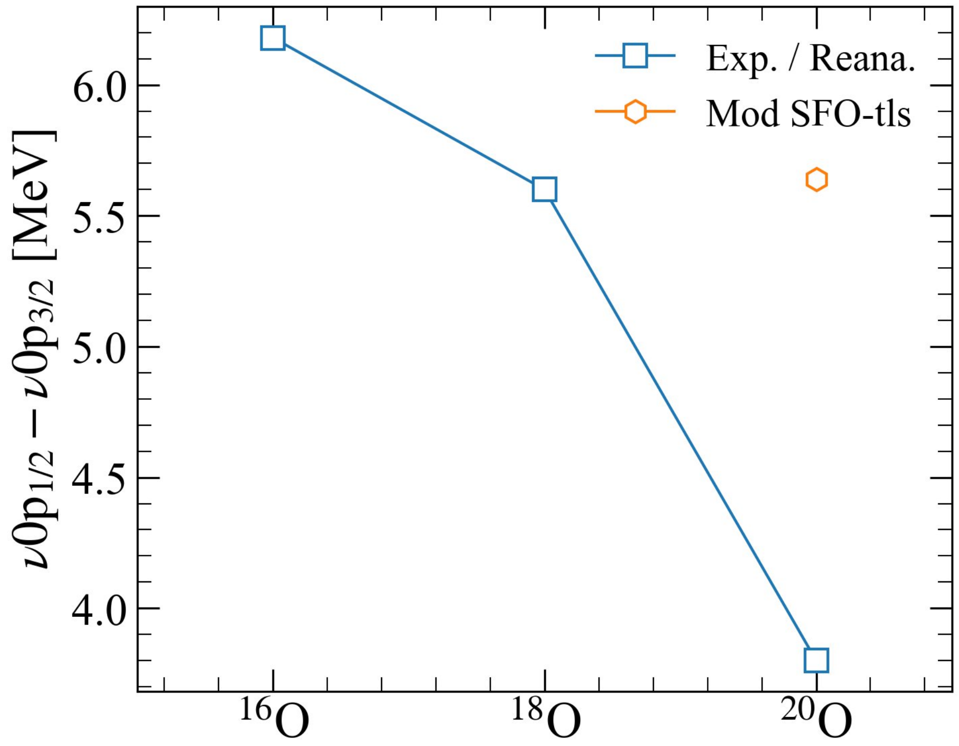
DWBA analysis to extract spectroscopic factors and E_x centroids for T=3/2 states

Comparison with SFO-tls interaction overestimates SO gap due to $0p_{3/2}$ states

Theoretical efforts needed to reconcile those states with experimental data!

Results: gap evolution

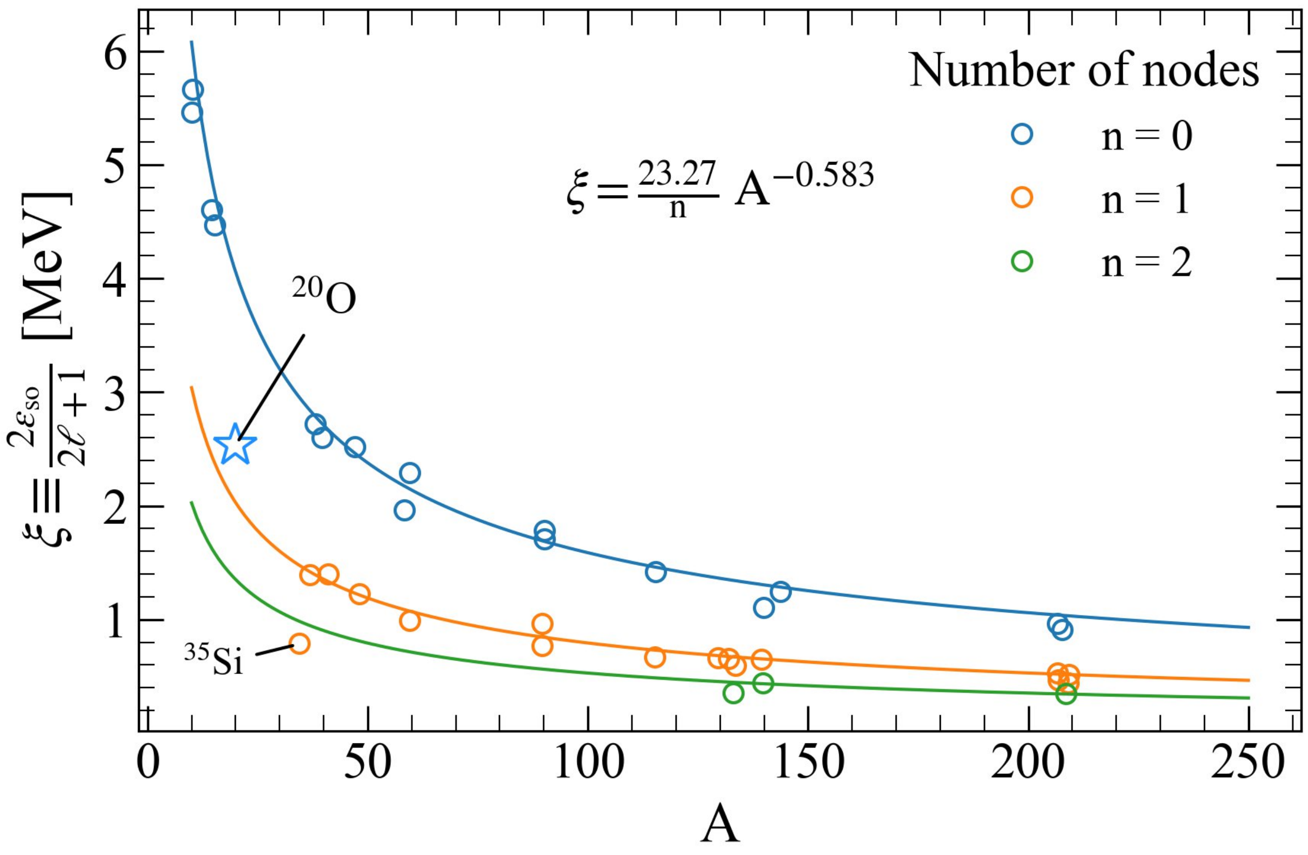
- $^{16}O(d,t)$: *K. H. Purser et al. NPA 132 (1969)*. No need to reanalyze xs bc there is only one state per nlj; just take the Ex
- $^{16}O(d,p)$: Alleged state 3/2- is not *single-particle* but j-forbidden stripping. See *K. Hosono JPSP 25 (1968)* Table II. This state is neutron $0d_{5/2}$ + proton $0p_{1/2}^{-1}0d_{5/2}^{1}$ 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



Acknowledgements

T. Roger
J. Pancin
M. Fisichella
C. Nicole
F. Saillant
G. Wittwer
V. Morel
A. Cassisa
J.C. Thomas
O. Sorlin
L. Cáceres
C. Stodel
F. de Oliveira

J. Lois-Fuentes
B. Fernández-Domínguez
M. Caamaño
D. Fernández
D. Regueira
C. Cabo
H. Álvarez-Pol
Y. Ayyad
G. Mantovani

F. Delaunay
L. Achouri

J. Giovinnazzo
A. Ortega-Moral
S. Grevy
Q. Delignac
T. Kurtikian

R. Raabe
O. Poleschuk
A. Ceuleman
S. Fracassetti
M. Latif

A. M. Martínez
J. Dueñas

D. Suzuki
B. Mauss

M. Pellegretti
T. Marchi

Extra slides

A window to the analysis