



IGFAE

INSTITUTO GALEGO
DE FÍSICA
DE ALTAS ENERXÍAS

25 → 1999
2024

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

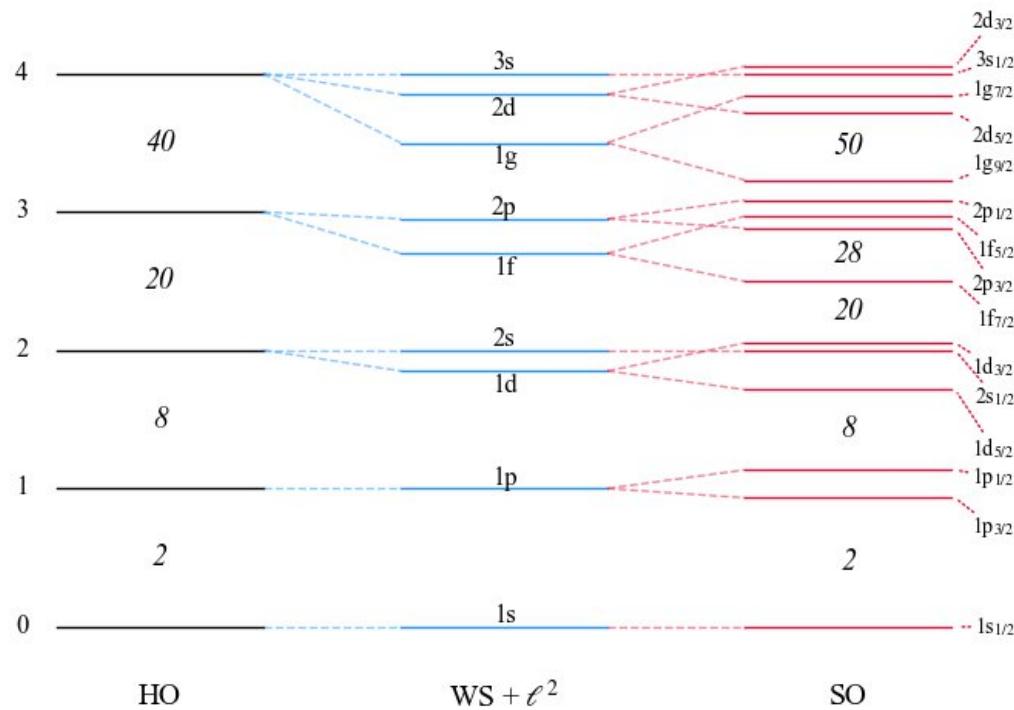
M. Lozano-González, B. Fernández-Domínguez, J. Lois-Fuentes,
T. Roger, F. Delaunay

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:

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

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

A recap on the SO splitting

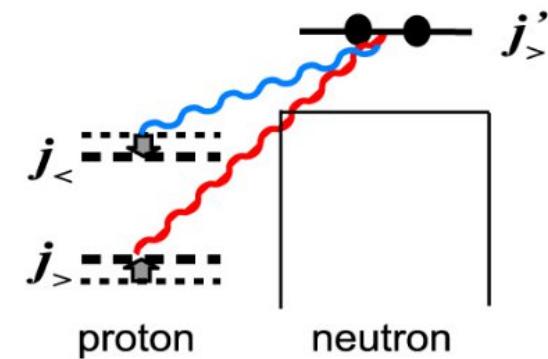
The main cause driving this evolution is the **tensor force**.

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

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

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

⇒ Mainly affected by $\pi\nu$ interactions



A recap on the SO splitting

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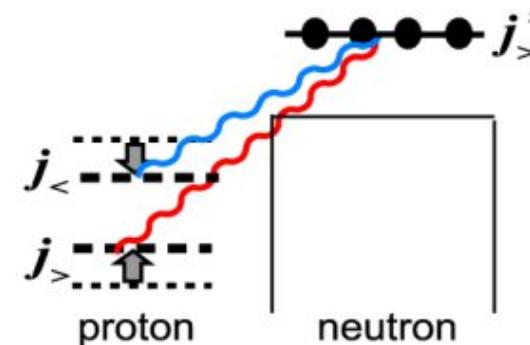
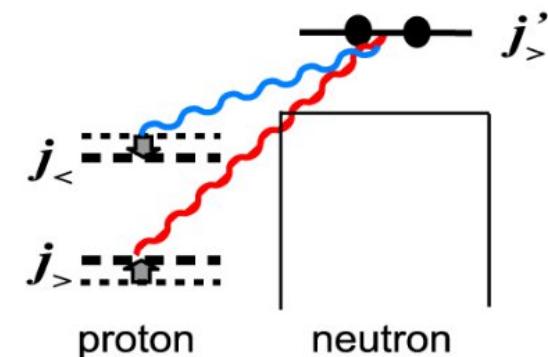
T.Otsuka and Y. Tsunoda, JPG 43 (2016)

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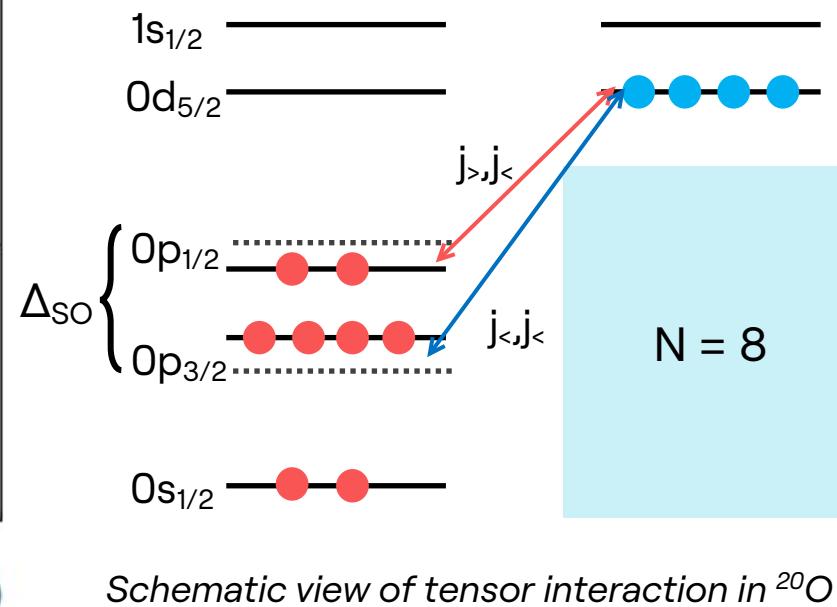
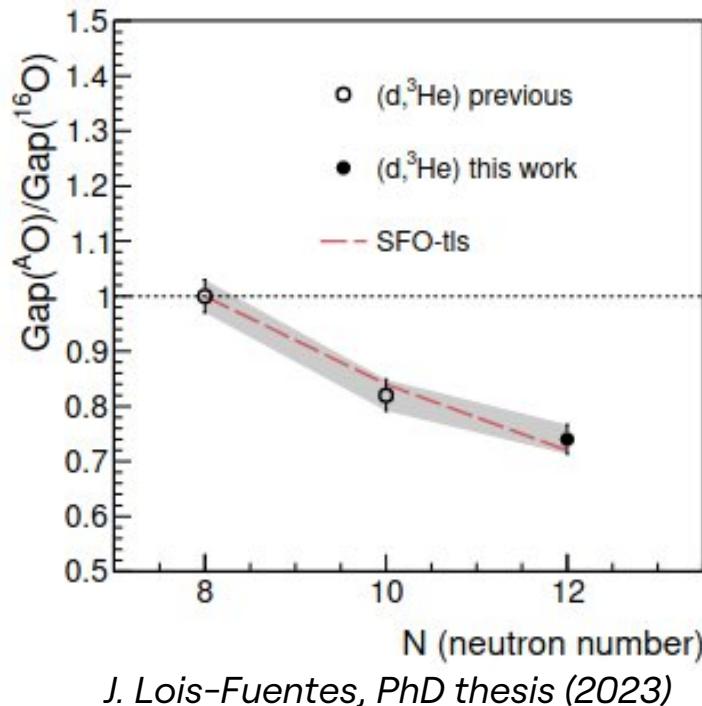
Shell gaps evolve with
proton/neutron
occupancies



Physics case

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

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

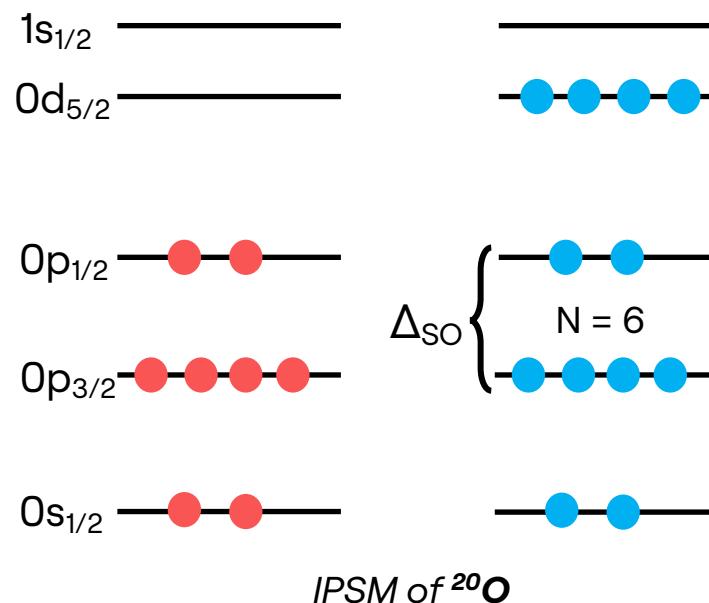
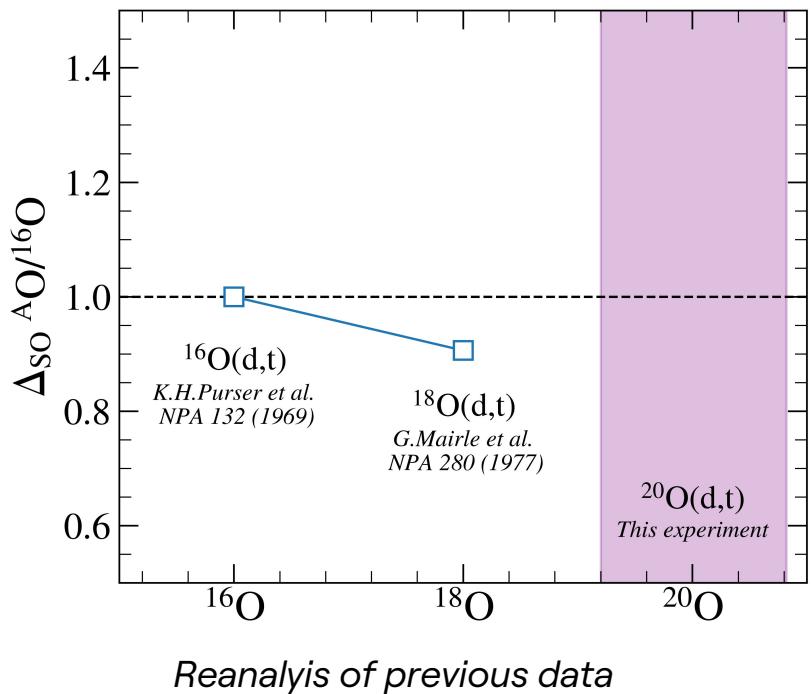


Tensor V_{pn} reduces $Z = 6$ gap as neutrons are added to $v0\text{d}_{5/2}$

Physics case

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

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

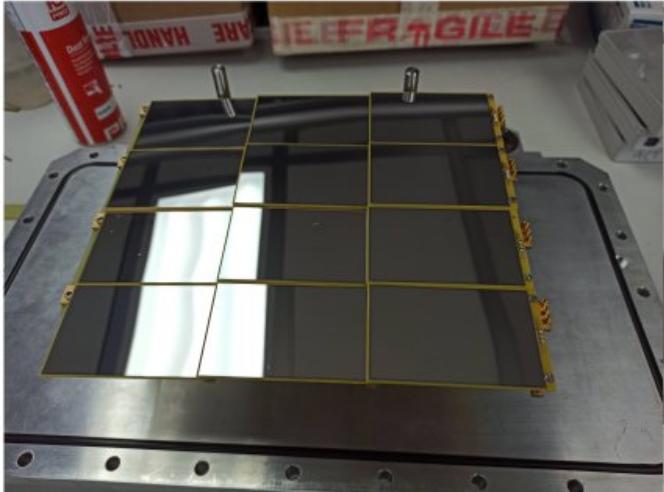


Would the gap decrease in ^{20}O ?

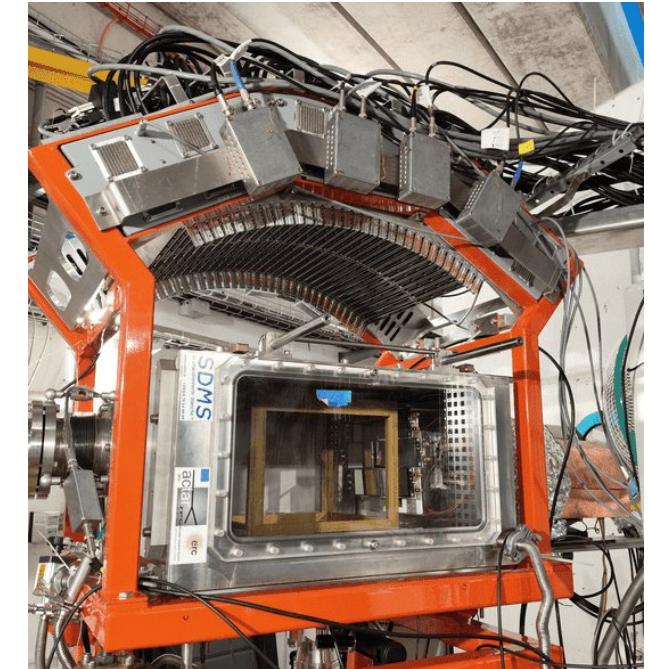
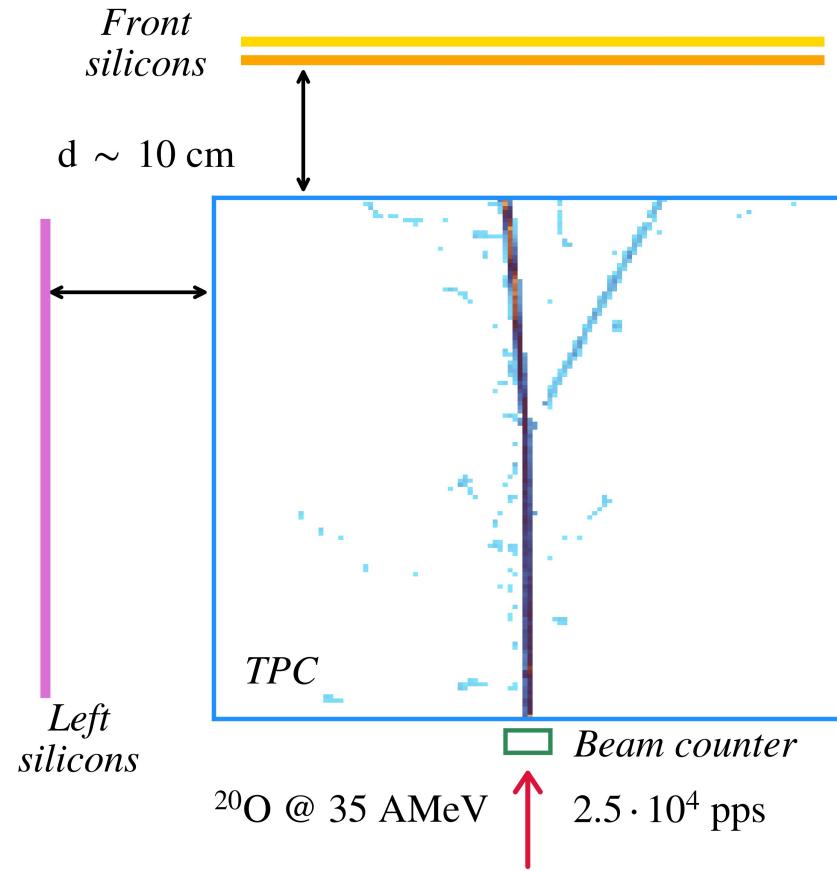
Can we extract magnitude of tensor force?

Experimental setup

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



Silicon sizes:
 $80 \times 50 \times 0.5 \text{ mm}^3$



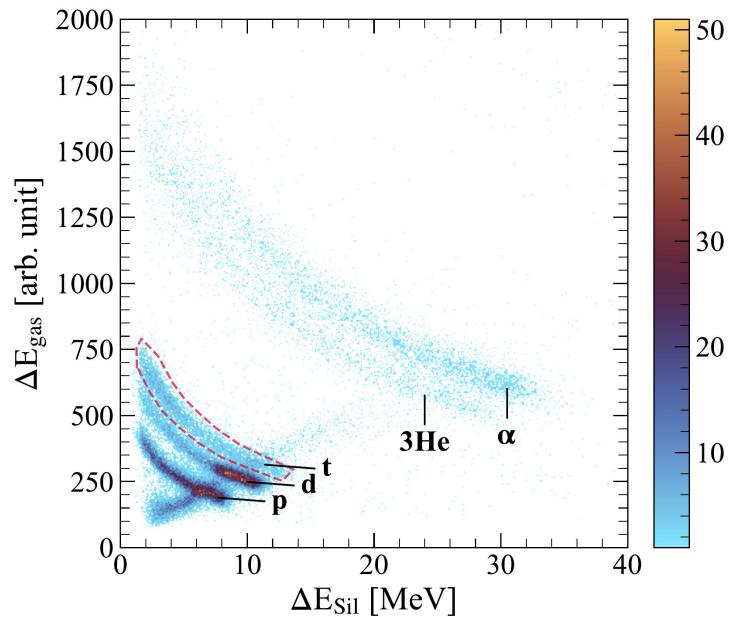
Gas mixture:
 $90\% \text{ D}_2 + 10\% \text{ iC}_4\text{H}_{10}$
at 952 mbar

A window to the analysis

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

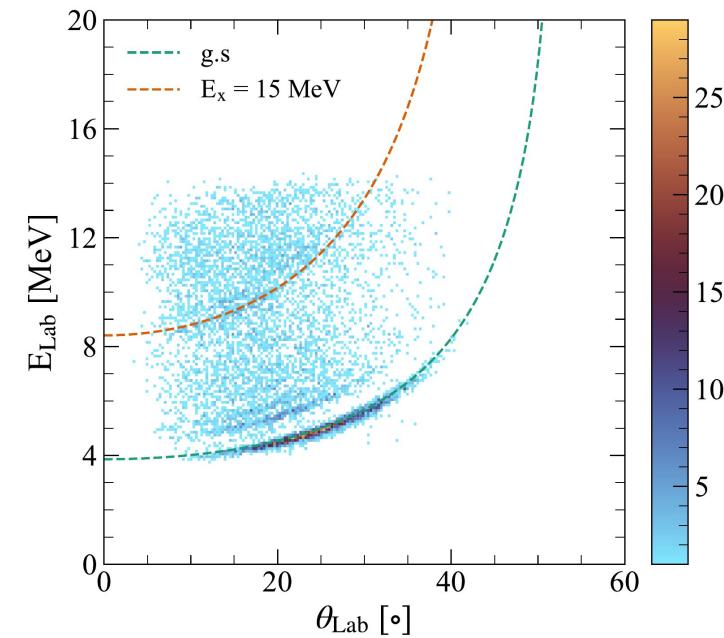
1. PID of tritons by plotting

ΔE_{gas} vs ΔE_{Sil}

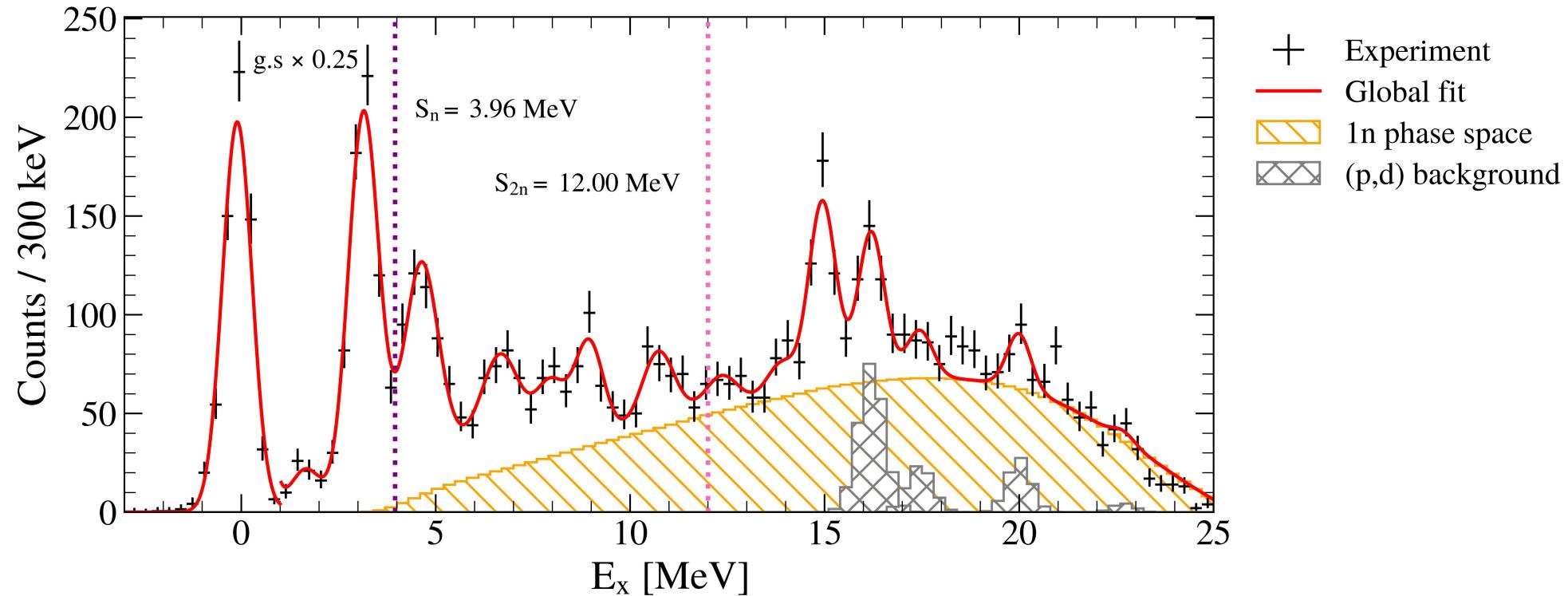


Masked punch-through to 2nd front layer

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



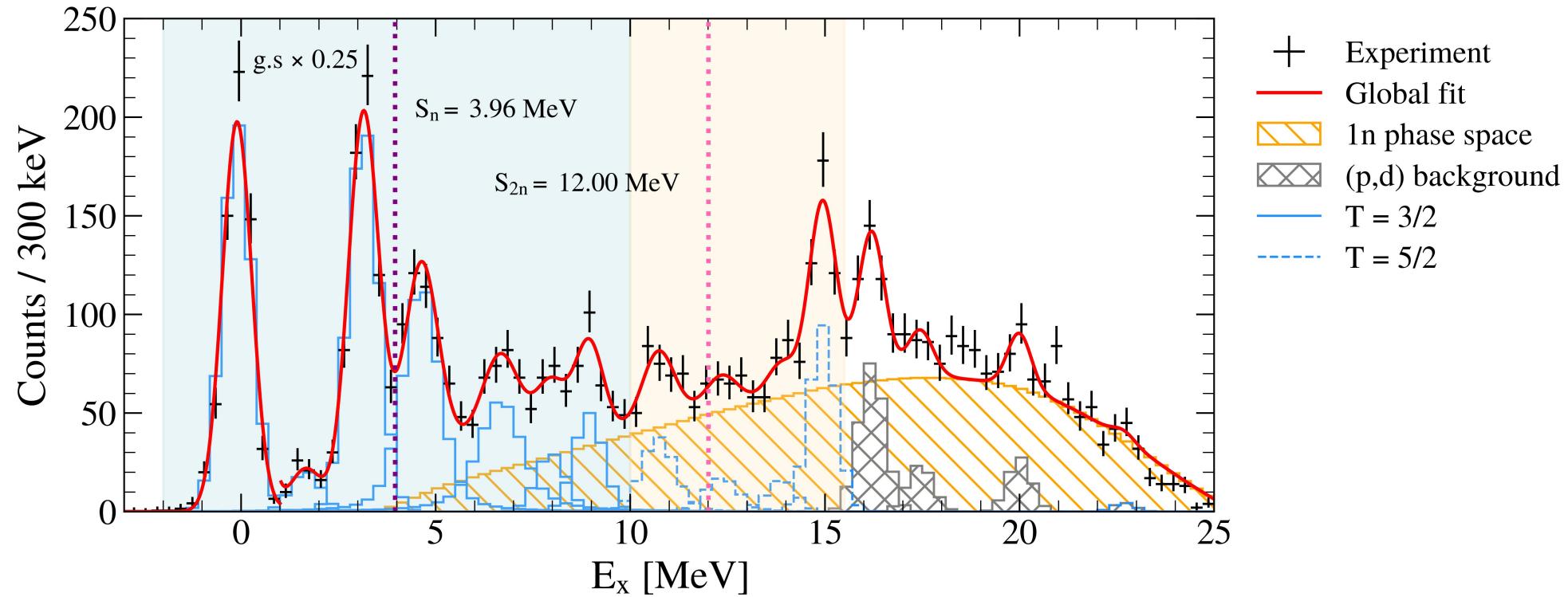
Results: E_x spectrum



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

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

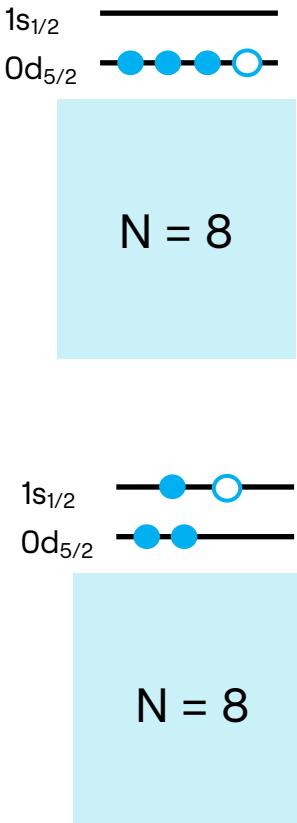
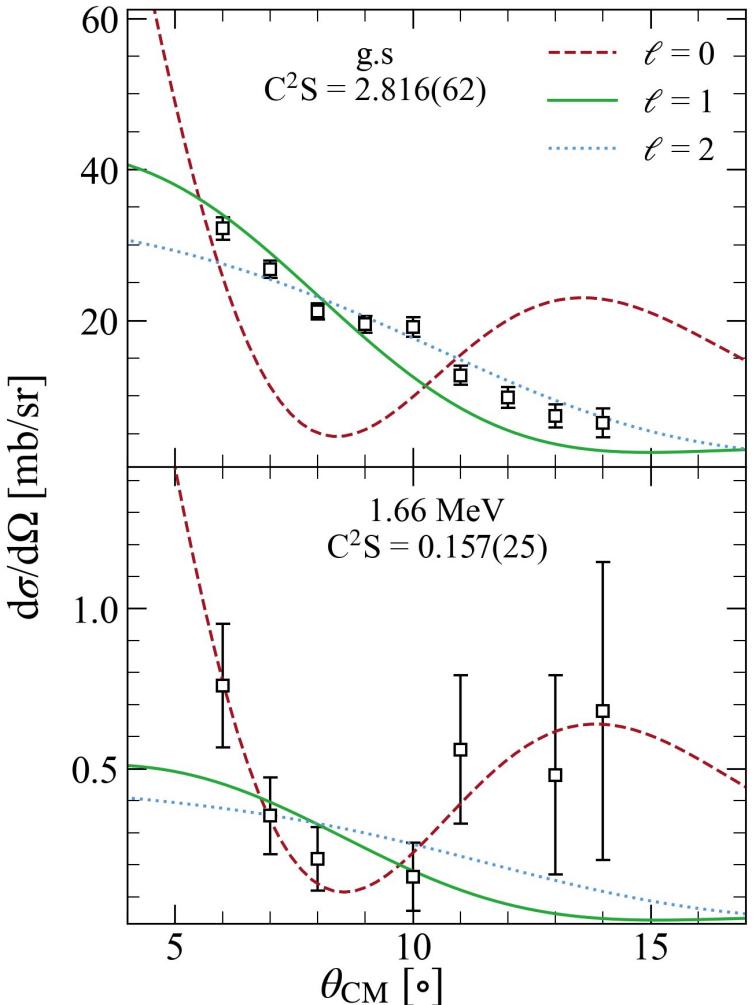
Results: E_x spectrum



T = 3/2 states @ $E_x < 10 \text{ MeV}$

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

Results: cross-sections

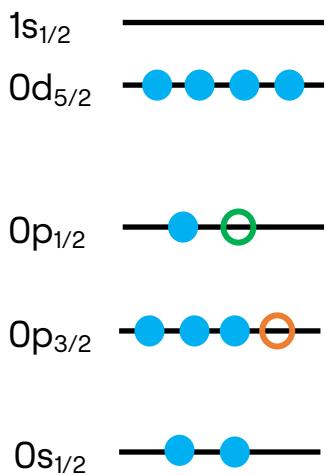
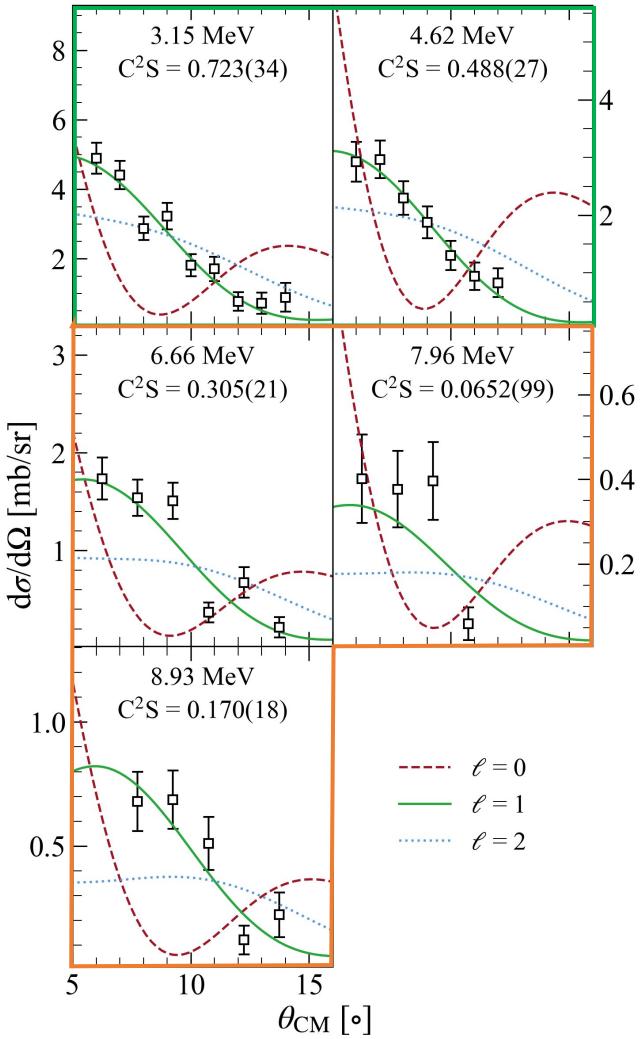


DBWA with Fresco

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

- g.s: $5/2^+$, taking up 71% of the occupancy
- 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 $\Rightarrow 0p_{1/2}$
- $E_x = 6.7, \dots, 8.9$ MeV $\Rightarrow 0p_{3/2}$

T = 3/2 states:

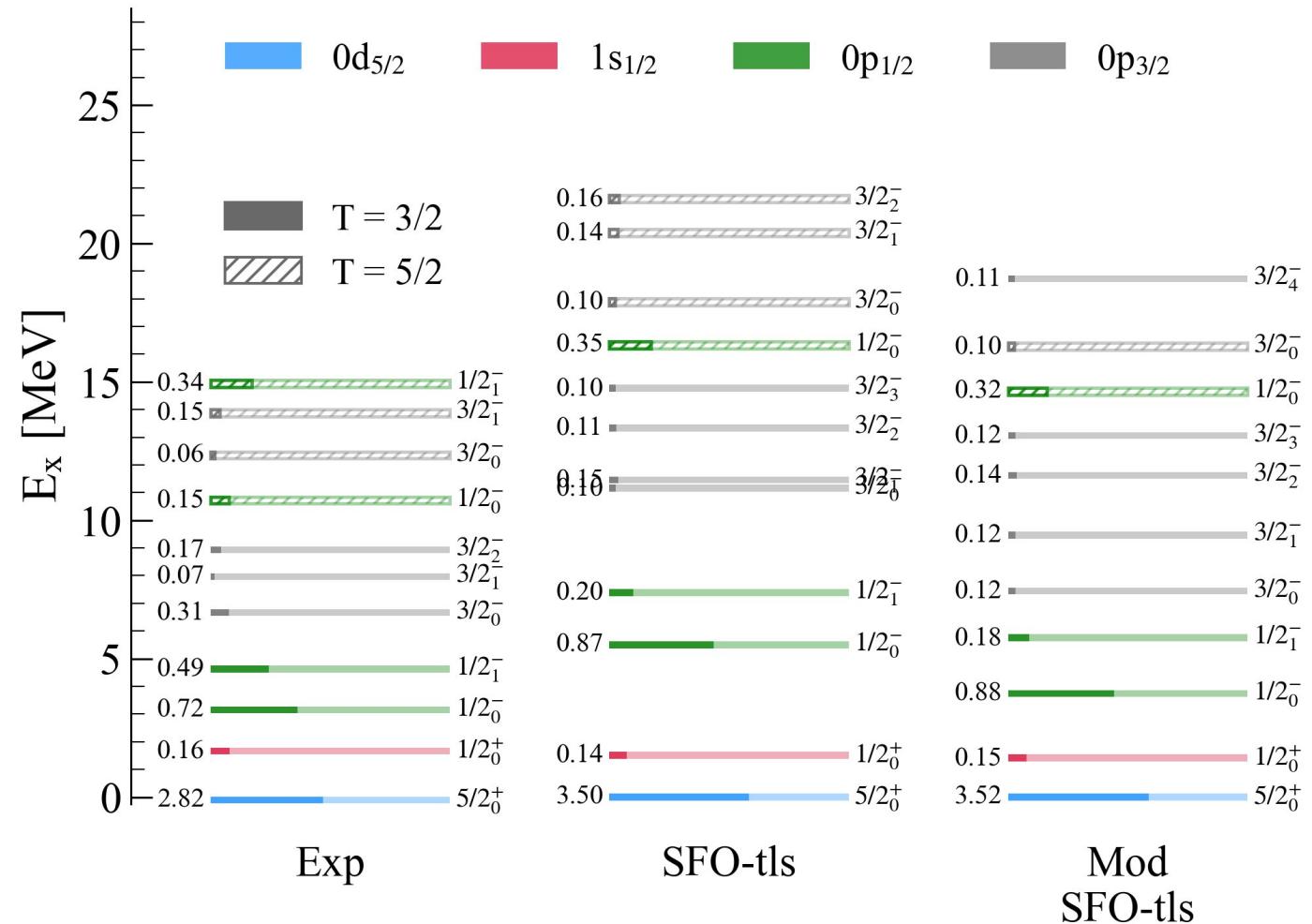
- $0p_{1/2}$: 61 % of strength
- $0p_{3/2}$: just 14 % of occupancy!

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.
- C²S reduced wrt SFO-tls
- Great reproduction of low-lying states
- 0p_{3/2} less fragmented than predicted



Results: comparison with models

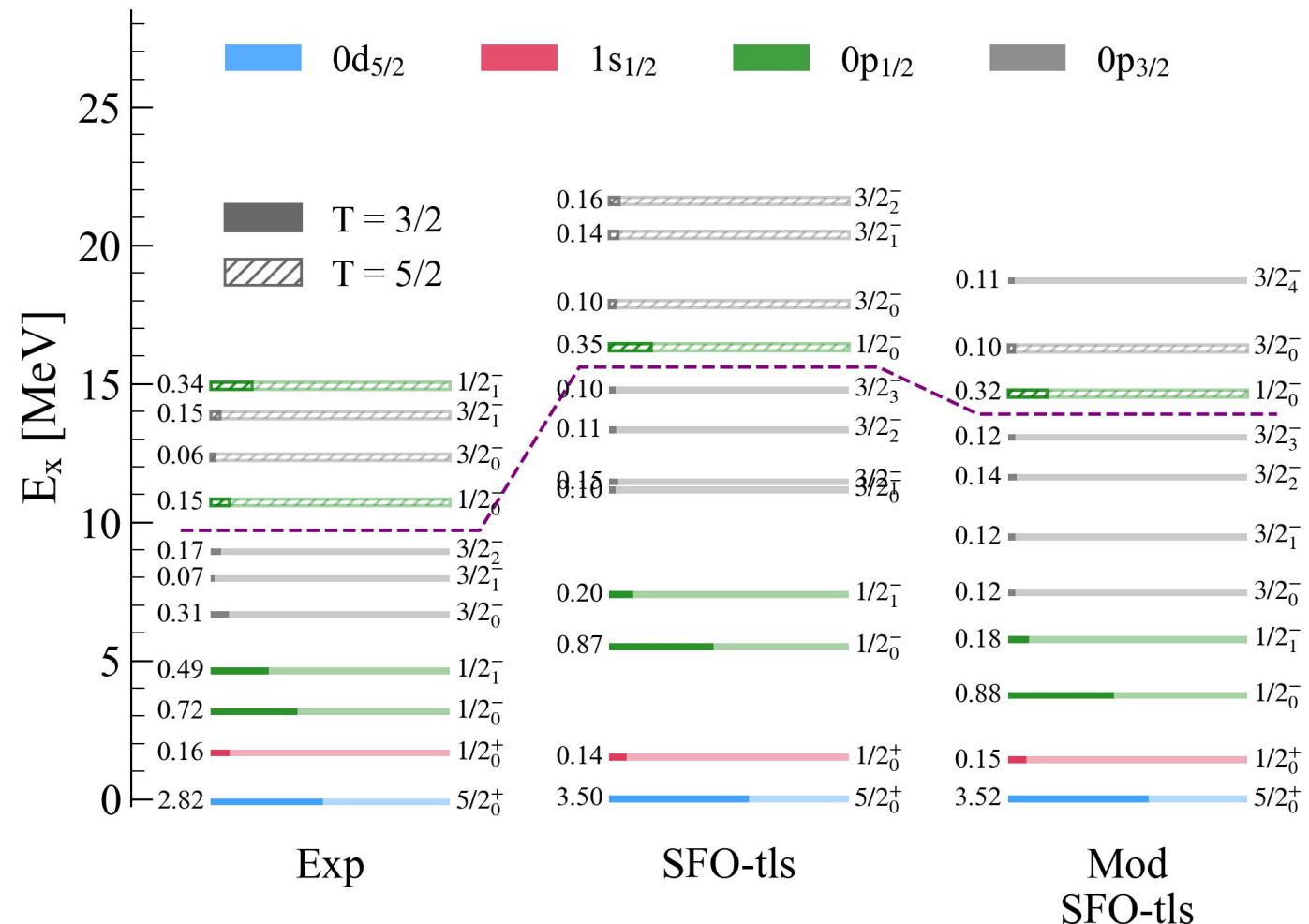
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- 0p_{3/2} less fragmented than predicted
- T = 3/2 0p_{3/2} predicted at much higher E_x



Results: centroids

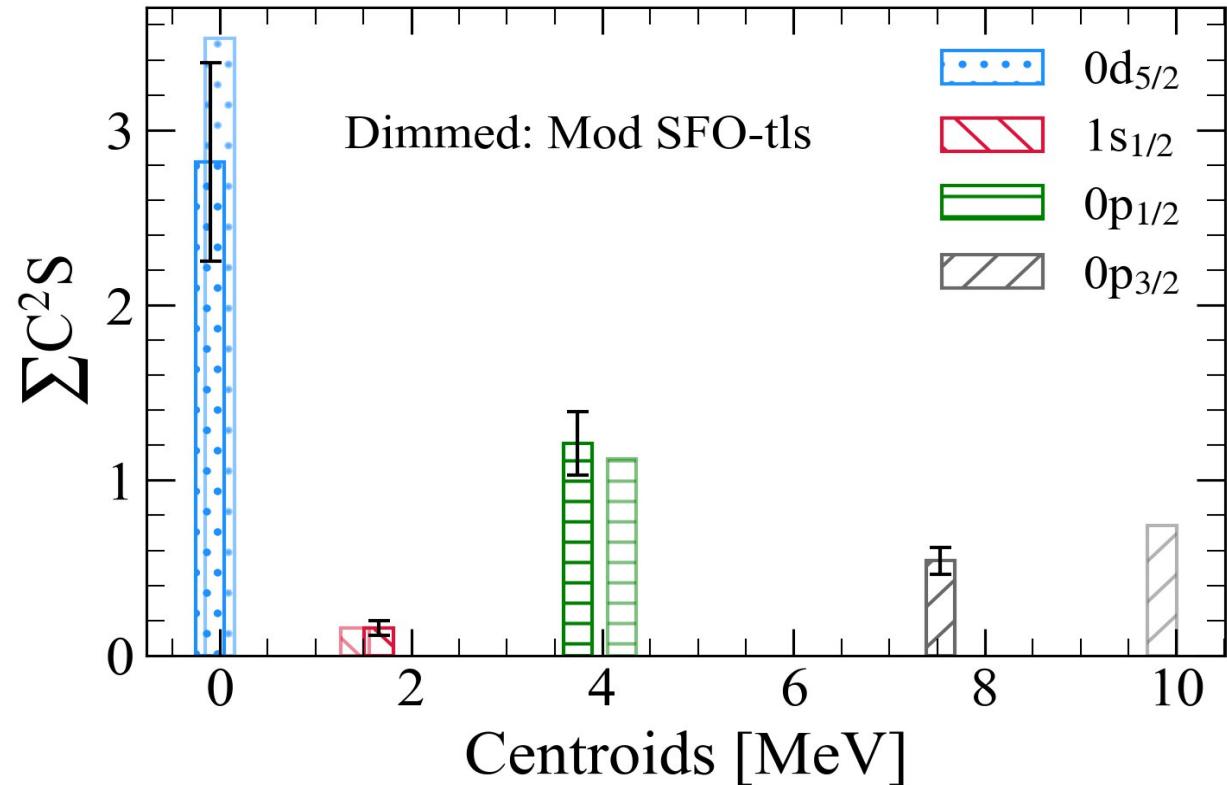
Modified SFO-tls:

- 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 $^{20}\text{O}(\text{d},\text{p})^{21}\text{O}$
B. Fernández-Domínguez et al. PRC 84 (2011)

Conclusions

$^{20}\text{O}(\text{d},\text{t})^{19}\text{O}$ 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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J. Dueñas



D. Suzuki
B. Mauss



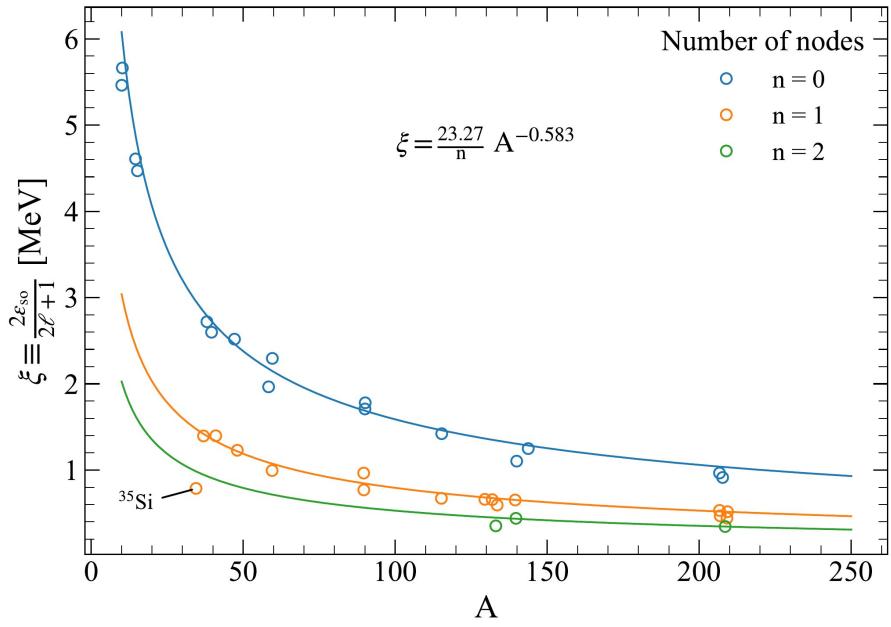
Istituto Nazionale di Fisica Nucleare

M. Pellegretti
T. Marchi

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

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

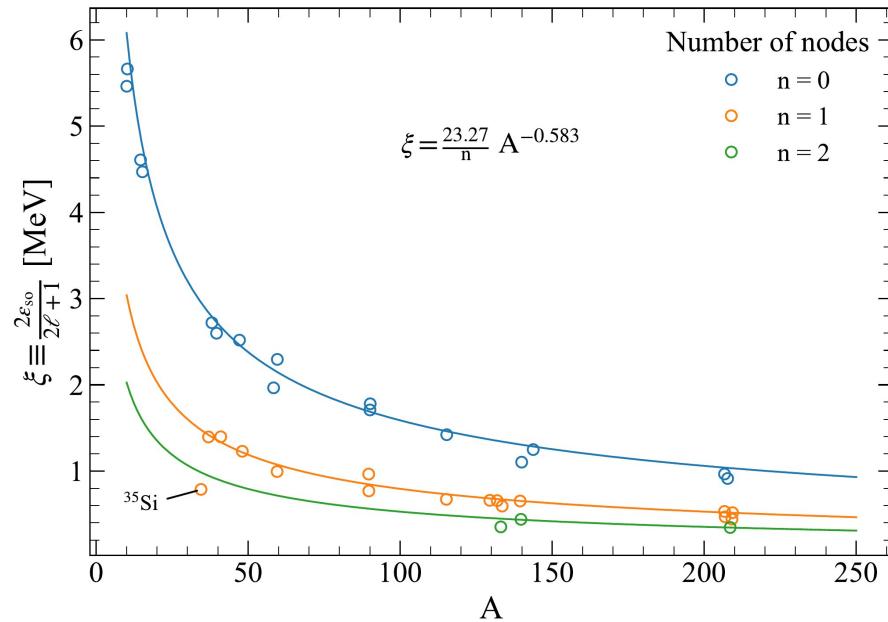
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T.Otsuka and Y. Tsunoda, JPG 43 (2016)

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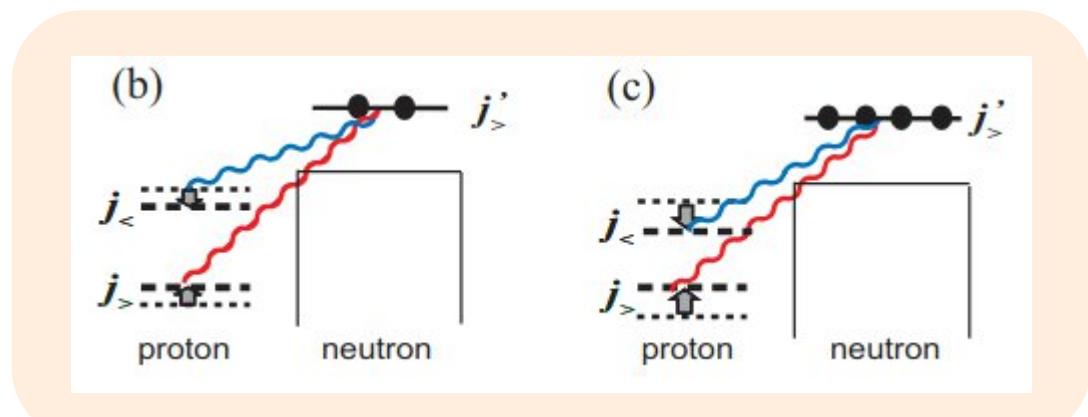
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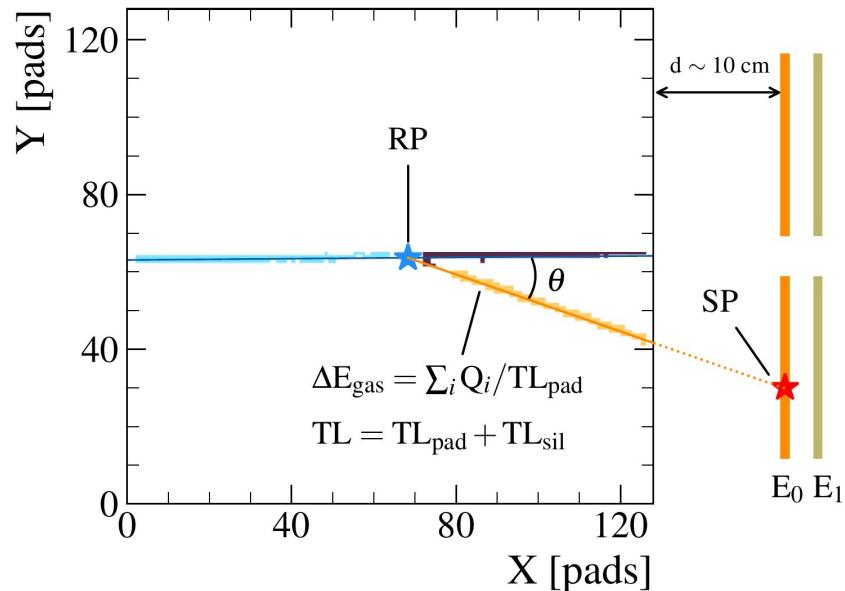
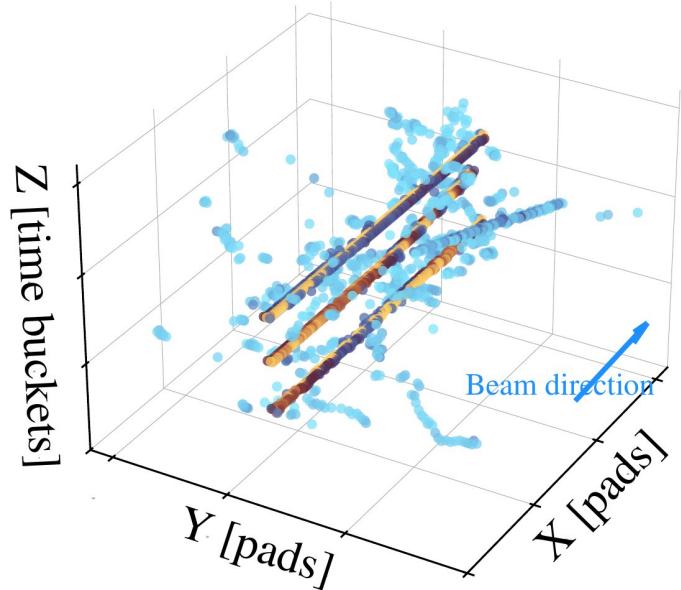
- Loosely bound orbitals
- Nuclear matter depletion (³⁵Si)
- Role of tensor force



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

A window to the analysis

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



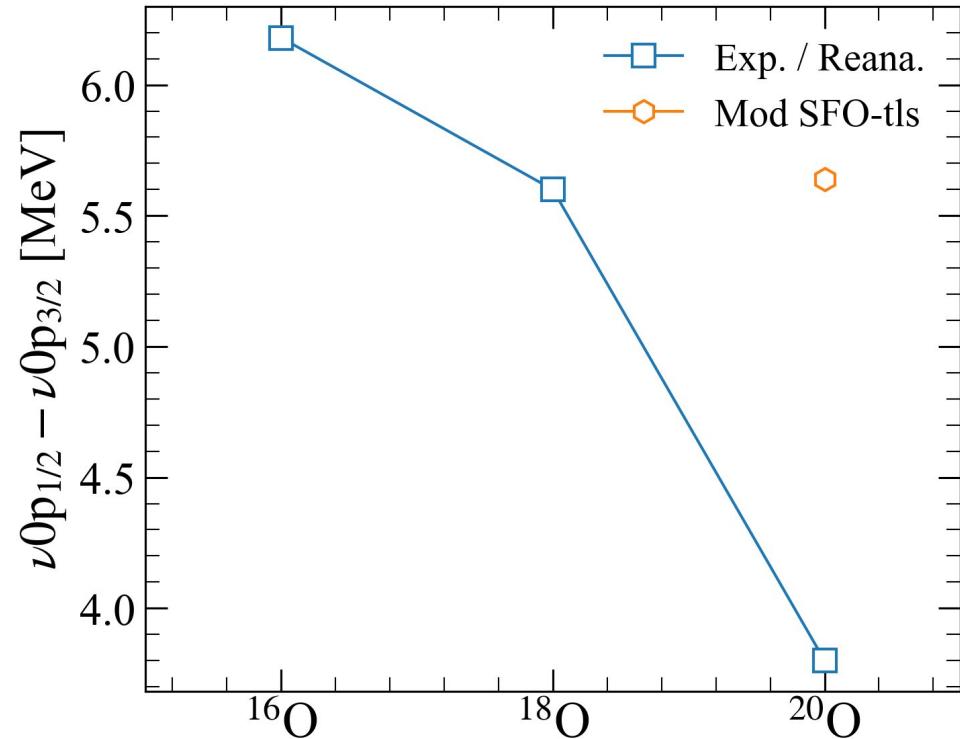
Unique advantages from the TPC:

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

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

Results: gap evolution

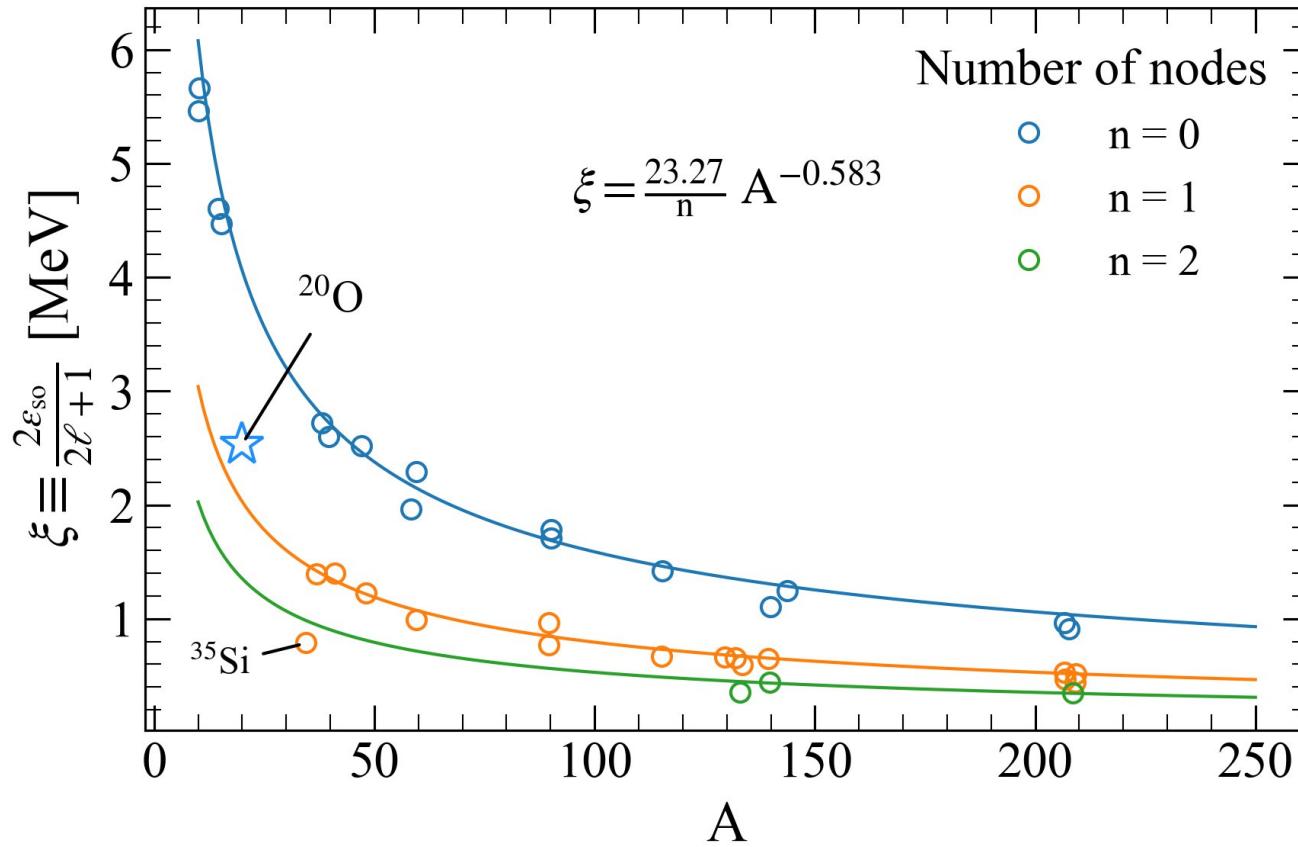
- $^{16}\text{O}(\text{d},\text{t})$: *K. H. Purser et al. NPA 132 (1969)*. No need to reanalyze xs bc there is only one state per nlj; just take the Ex
- $^{16}\text{O}(\text{d},\text{p})$: Alleged state $3/2^-$ is not *single-particle* but j-forbidden stripping. See *K. Hosono JPSP 25 (1968) Table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



We are lacking theo calculations for ^{16}O and ^{18}O

Conclusions

- To be determined



A window to the analysis

