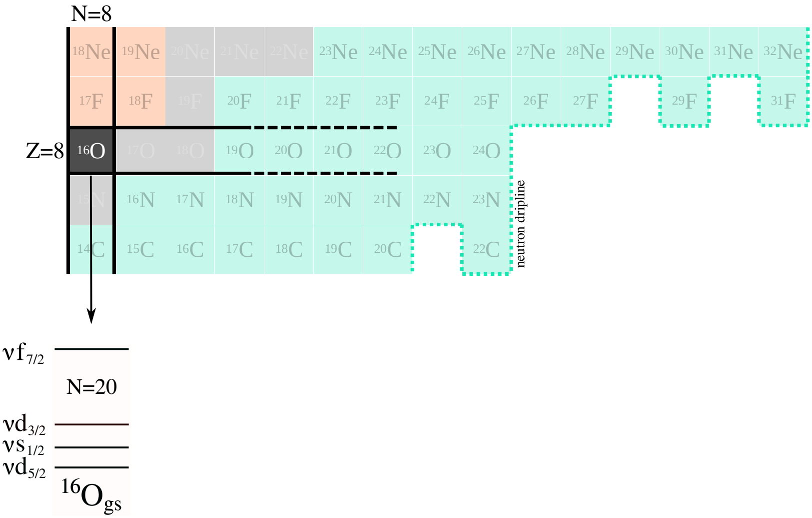
Shell evolution in oxygen probed through unbound states in $^{19}O(d,p\gamma)$

Charlie J. Paxman, Irene Zanon, Emmanuel Clement
+ *the e775s collaboration*

GANIL Colloque, 2026
Bussang, France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Z=8
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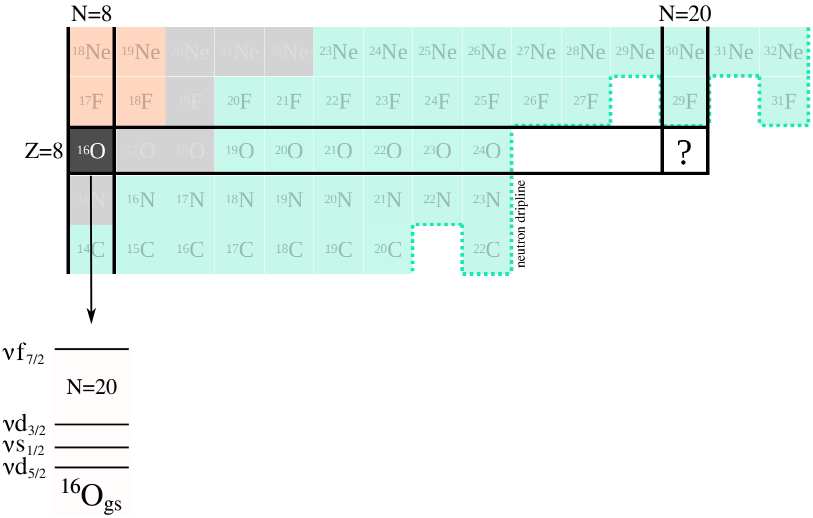
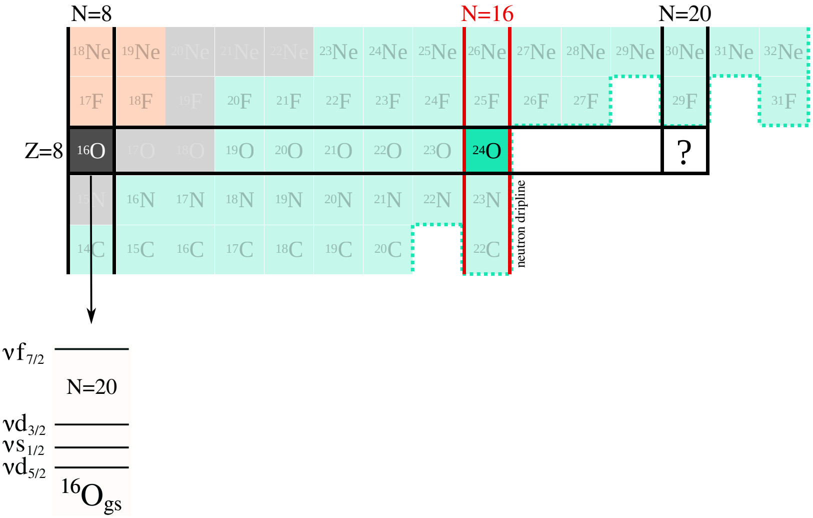
17F 18F 19F 20F 21F 22F 23F 24F 25F 26F 27F 29F 31F
16O 17O 18O 19O 20O 21O 22O 23O 24O
15N 16N 17N 18N 19N 20N 21N 22N 23N
14C 15C 16C 17C 18C 19C 20C 22C
neutron dripline
νf7/2
N=20
νd3/2
νs1/2
νd5/2
16Ogs


N=8
N=20
Z=8
18Ne 19Ne 20Ne 21Ne 22Ne 23Ne 24Ne 25Ne 26Ne 27Ne 28Ne 29Ne 30Ne 31Ne 32Ne
17F 18F 19F 20F 21F 22F 23F 24F 25F 26F 27F 29F 31F
16O 17O 18O 19O 20O 21O 22O 23O 24O
?
15N 16N 17N 18N 19N 20N 21N 22N 23N
14C 15C 16C 17C 18C 19C 20C 22C
neutron dripline
$\nu f_{7/2}$
N=20
$\nu d_{3/2}$
$\nu s_{1/2}$
$\nu d_{5/2}$
$^{16}O_{gs}$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N=16
N=20
18Ne 19Ne 20Ne 21Ne 22Ne 23Ne 24Ne 25Ne 26Ne 27Ne 28Ne 29Ne 30Ne 31Ne 32Ne
17F 18F 19F 20F 21F 22F 23F 24F 25F 26F 27F 29F 31F
Z=8
16O 17O 18O 19O 20O 21O 22O 23O 24O
?
15N 16N 17N 18N 19N 20N 21N 22N 23N
14C 15C 16C 17C 18C 19C 20C 22C
neutron dripline
νf7/2
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νd3/2
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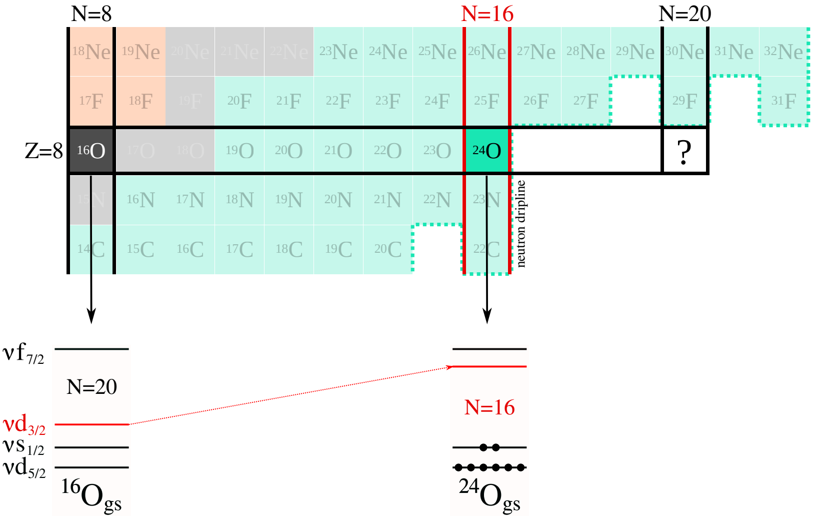
N=8
N=16
N=20
Z=8
18Ne 19Ne 20Ne 21Ne 22Ne 23Ne 24Ne 25Ne 26Ne 27Ne 28Ne 29Ne 30Ne 31Ne 32Ne
17F 18F 19F 20F 21F 22F 23F 24F 25F 26F 27F 29F 31F
16O 17O 18O 19O 20O 21O 22O 23O 24O
?
15N 16N 17N 18N 19N 20N 21N 22N 23N
14C 15C 16C 17C 18C 19C 20C 22C
neutron dripline
νf7/2
N=20
νd3/2
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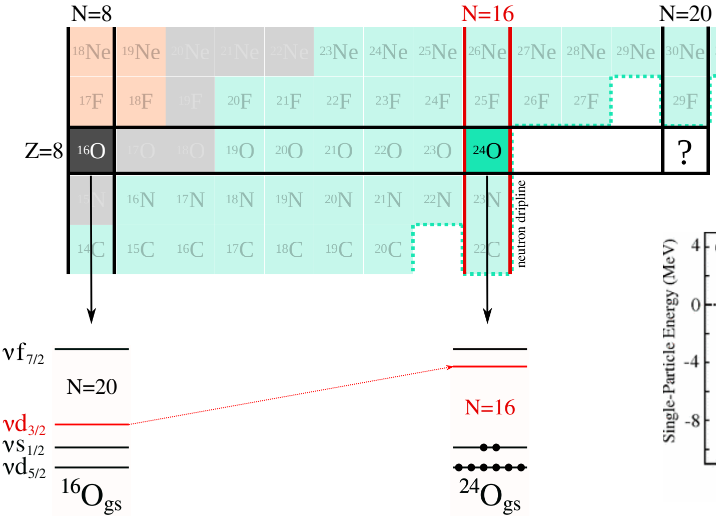
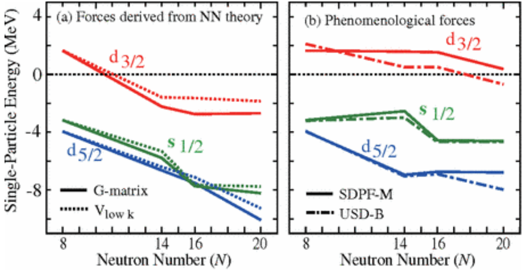
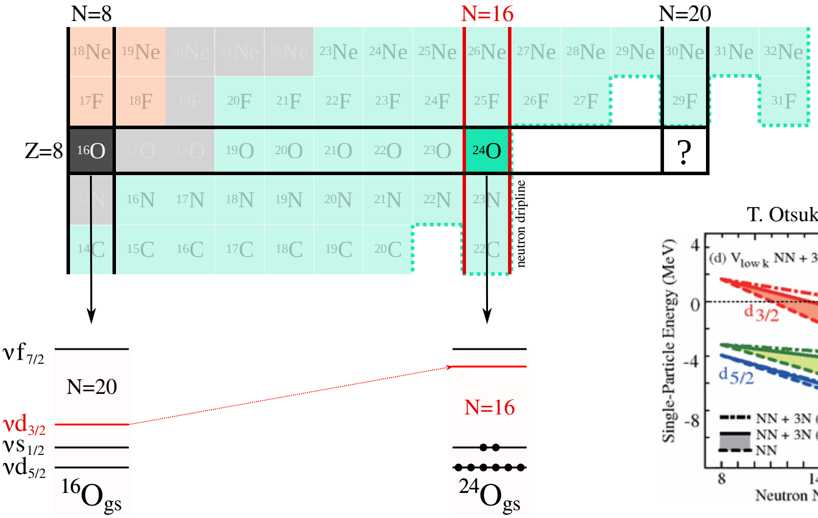
16Ogs
N=16
24Ogs



T. Otsuka *et al.* PRL **105,** 032501 (2010)



NN cannot replicate phenomenology...



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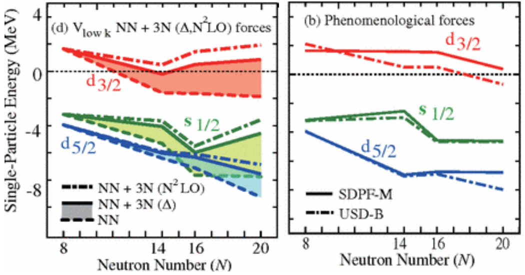
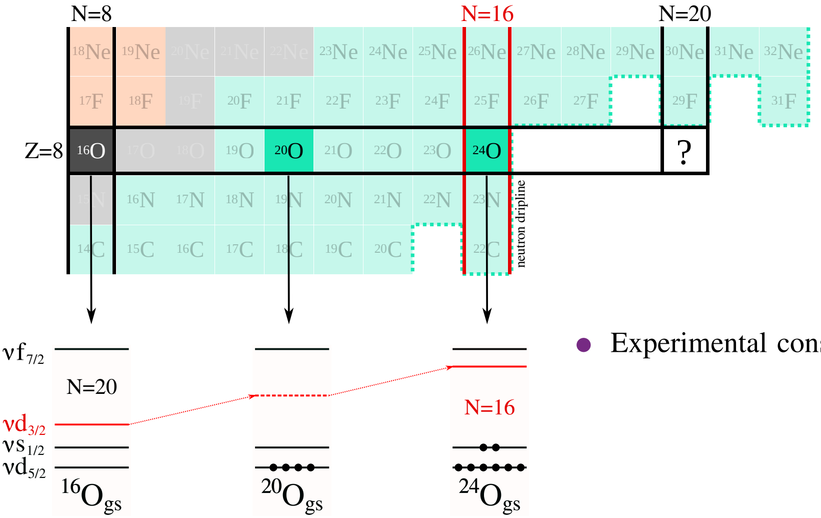
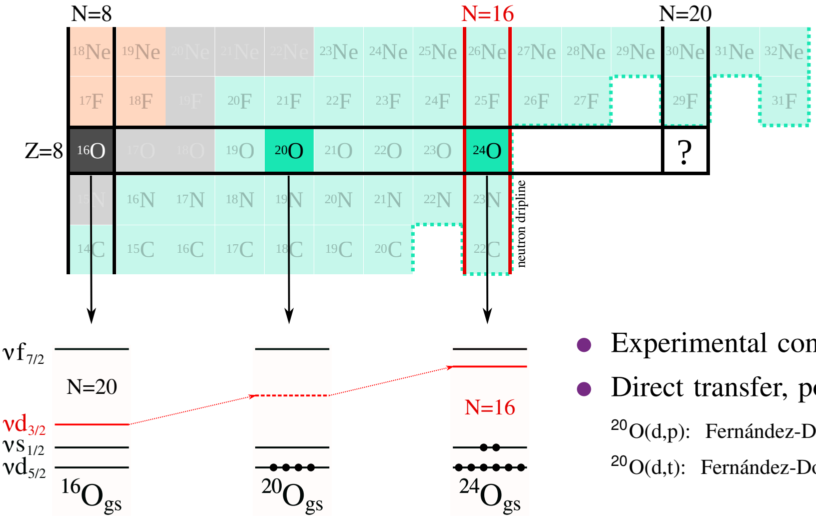


... requires chiral 3N forces!



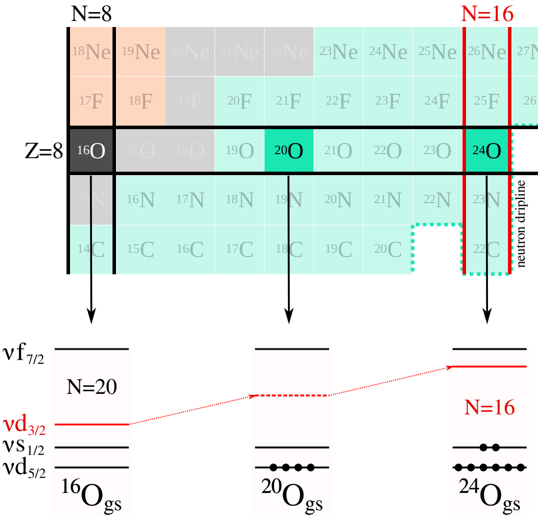
- Experimental constraints for evolution of $d_{3/2}$

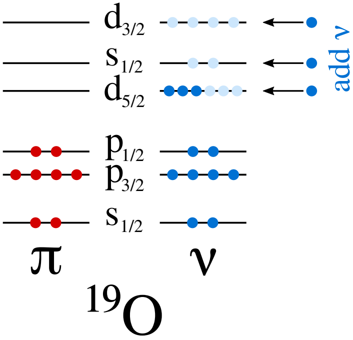


- Experimental constraints for evolution of $d_{3/2}$
- Direct transfer, populate single-particle-like

^{20}O(d,p): Fernández-Domínguez *et al.* PRC **84** 029902 (2011)

^{20}O(d,t): Fernández-Domínguez, Thursday





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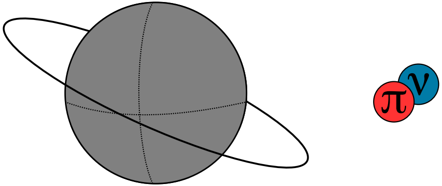
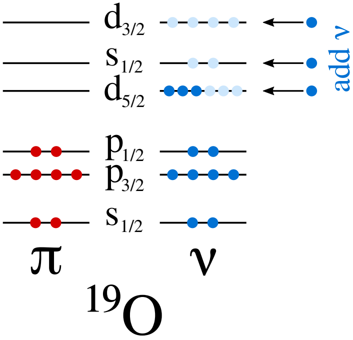
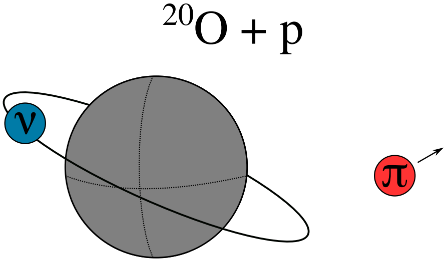
  ^{20}O(d,p): Fernández-Domínguez *et al.* PRC **84** 029902 (2011)

  ^{20}O(d,t): Fernández-Domínguez, Thursday
- What about ^{19}O(d,p)^{20}O transfer?

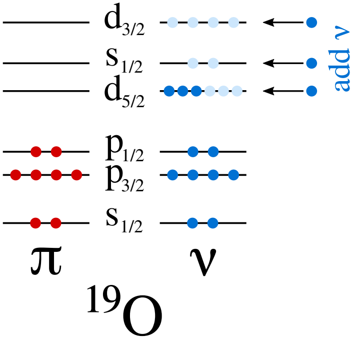
$^{19}O + d$





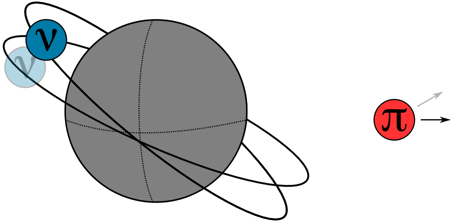


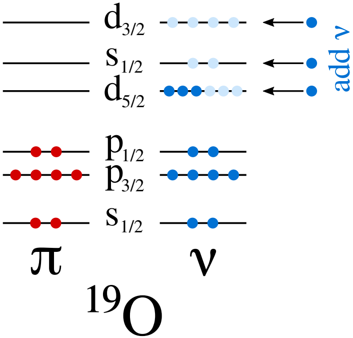
^{20}O + p
ν
π

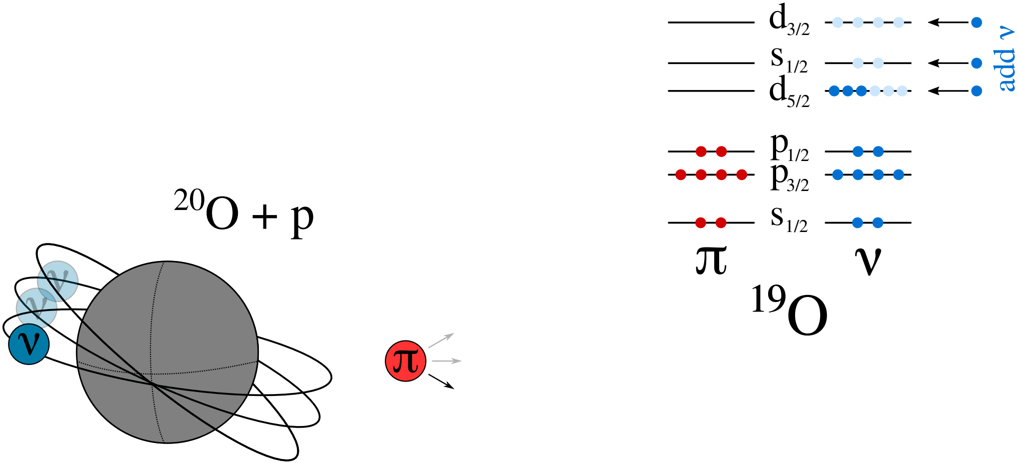


d$_{3/2}$
s$_{1/2}$
d$_{5/2}$
p$_{1/2}$
p$_{3/2}$
s$_{1/2}$
add ν
π
ν
^{19}O

$^{20}O + p$





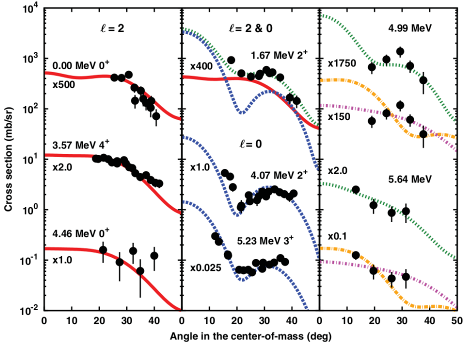


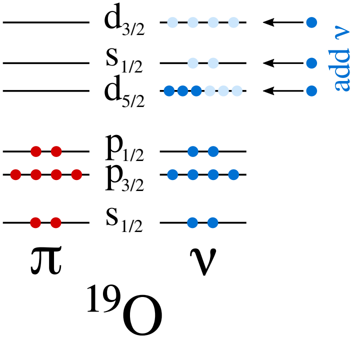
^{20}O + p
ν
ν
ν
π
d3/2
s1/2
d5/2
p1/2
p3/2
s1/2
add ν
π
ν
^{19}O

PHYSICAL REVIEW C **85**, 054318 (2012)

Experimental study of the $^{19}O(d,p)^{20}O$ reaction in inverse kinematics

C. R. Hoffman,[1,*] B. B. Back,[1] B. P. Kay,[1,†] J. P. Schiffer,[1] M. Alcorta,[1] S. I. Baker,[1] S. Bedoor,[2] P. F. Bertone,[1] J. A. Clark,[1] C. M. Deibel,[1,3,‡] B. DiGiovine,[1] S. J. Freeman,[4] J. P. Greene,[1] J. C. Lighthall,[1,2] S. T. Marley,[1,2] R. C. Pardo,[1] K. E. Rehm,[1] A. Rojas,[5,§] D. Santiago-Gonzalez,[5] D. K. Sharp,[4] D. V. Shetty,[2] J. S. Thomas,[4] I. Wiedenhöver,[5] and A. H. Wuosmaa[2]





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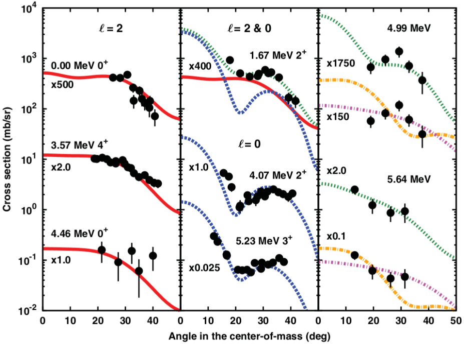

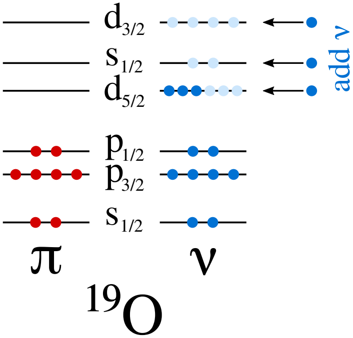

- HELIOS @ Argonne Nat'l Lab
- All $\ell = 2$ strength $\rightarrow d_{5/2}$
- Bound states only!

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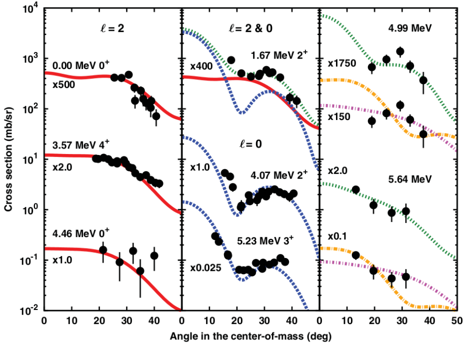

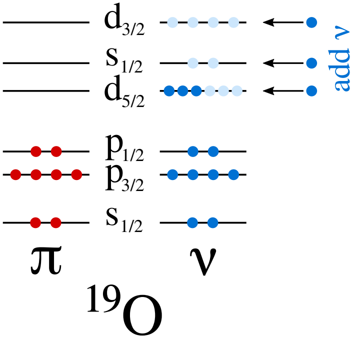

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- All $\ell = 2$ strength $\rightarrow d_{5/2}$
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$d_{3/2}$ strength in unbound states?

PHYSICAL REVIEW LETTERS **131,** 262501 (2023)

High-Precision Spectroscopy of ^{20}O Benchmarking *Ab Initio* Calculations in Light Nuclei

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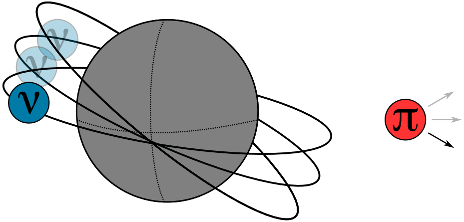
^{20}O + p



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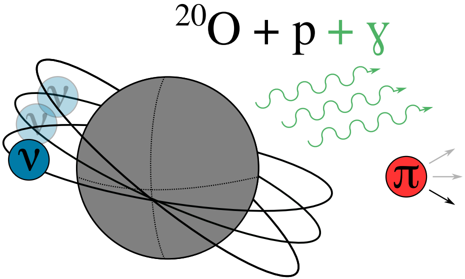

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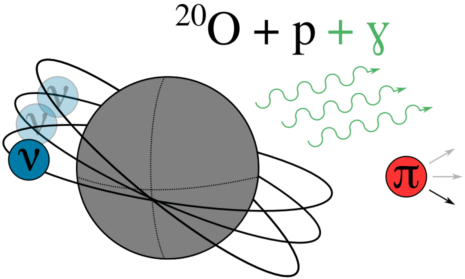
- Focus: lifetimes by DSAM in AGATA



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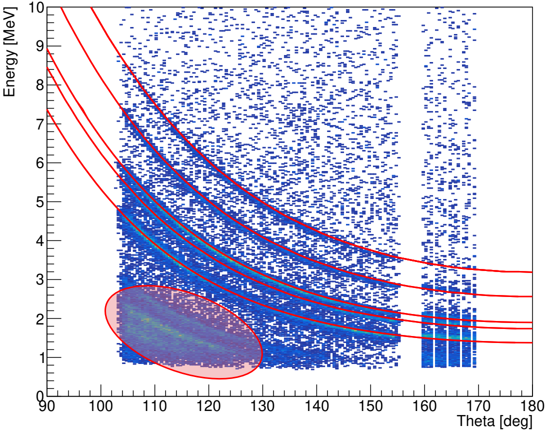
- Focus: lifetimes by DSAM in AGATA
- Possible unbound structure?



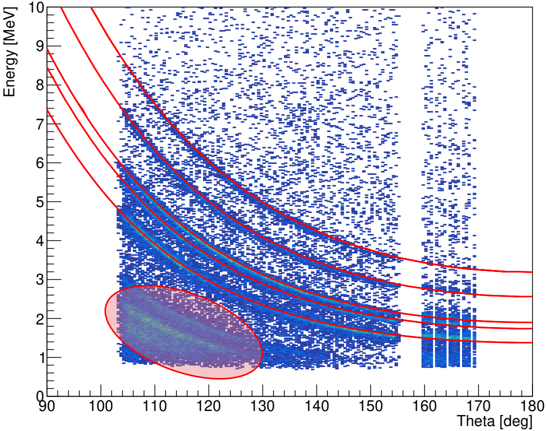
From I. Zanon, Colloque GANIL 2023

PHYSICAL REVIEW LETTERS **131,** 262501 (2023)

High-Precision Spectroscopy of ^{20}O Benchmarking *Ab Initio* Calculations in Light Nuclei

I. Zanon,[1,2,*] E. Clément,[3] A. Goasduff,[1] J. Menéndez,[4] T. Miyagi,[5,6,7] M. Assié,[8] M. Ciemała,[9] F. Flavigny,[10] A. Lemasson,[3] A. Matta,[10] D. Ramos,[3] M. Rejmund,[3] L. Achouri,[10] D. Ackermann,[3] D. Barrientos,[11] D. Beaumel,[8] G. Benzoni,[12] A. J. Boston,[13] H. C. Boston,[13] S. Bottoni,[14,12] A. Bracco,[12,14] D. Brugnara,[1,15] G. de France,[3] N. de Sereville,[8] F. Delaunay,[10] P. Desesquelles,[8] F. Didierjean,[16] C. Domingo-Prato,[17] J. Dudouet,[18] J. Eberth,[19] D. Fernández,[20] C. Fougères,[3] A. Gadea,[17] F. Galtarossa,[8] V. Girard-Alcindor,[3] V. Gonzales,[21] A. Gottardo,[1] F. Hammache,[8] L. J. Harkness-Brennan,[13] H. Hess,[19] D. S. Judson,[13] A. Jungclaus,[22] A. Kaşkaş,[23] Y. H. Kim,[24] A. Kuşoğlu,[25] M. Labiche,[26] S. Leblond,[3] C. Lenain,[10] S. M. Lenzi,[27] S. Leoni,[12] H. Li,[3] J. Ljungvall,[8] J. Lois-Fuentes,[20] A. Lopez-Martens,[8] A. Maj,[28] R. Menegazzo,[27] D. Mengoni,[15,27] C. Michelagnoli,[3,24] B. Million,[12] D. R. Napoli,[1] J. Nyberg,[29] G. Pasqualato,[15,27] Zs. Podolyak,[30] A. Pullia,[12] B. Quintana,[31] F. Recchia,[15,27] D. Regueira-Castro,[20] P. Reiter,[19] K. Rezynkina,[32] J. S. Rojo,[33] M. D. Salsac,[34] E. Sanchis,[21] M. Şenyiğit,[23] M. Siciliano,[34,35] D. Sohler,[36] O. Stezowski,[18] Ch. Theisen,[34] A. Utepov,[3,10] J. J. Valiente-Dobón,[1] D. Verney,[8] and M. Zielinska[34]

- MUGAST-AGATA-VAMOS@GANIL
- Focus: lifetimes by DSAM in AGATA
- Possible unbound structure?
- This work: particle-focused analysis!



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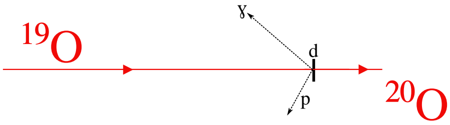
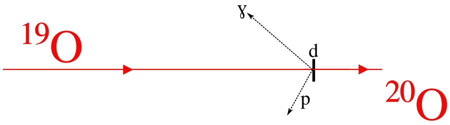


Beam

- ISOL RIB of ^{19}O
- SPIRAL1, GANIL
- 8 MeV/u (= Hoffman *et al.*)
- 4×10^5 pps intensity



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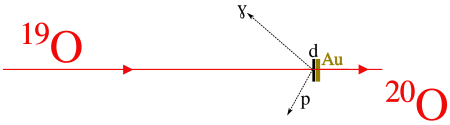
Target(s)

- 0.3 mg/cm^2 CD_2

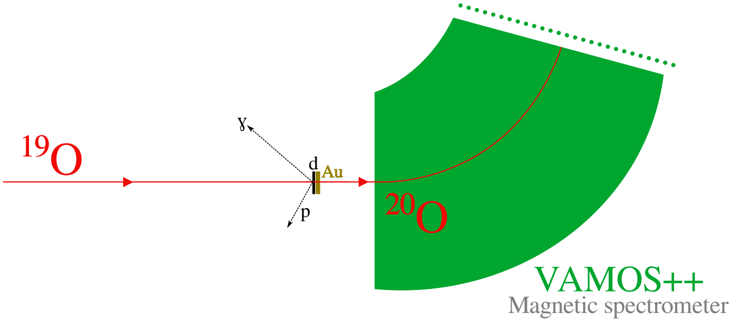


Beam

- ISOL RIB of ^{19}O
- SPIRAL1, GANIL
- 8 MeV/u (= Hoffman *et al.*)
- 4×10^5 pps intensity

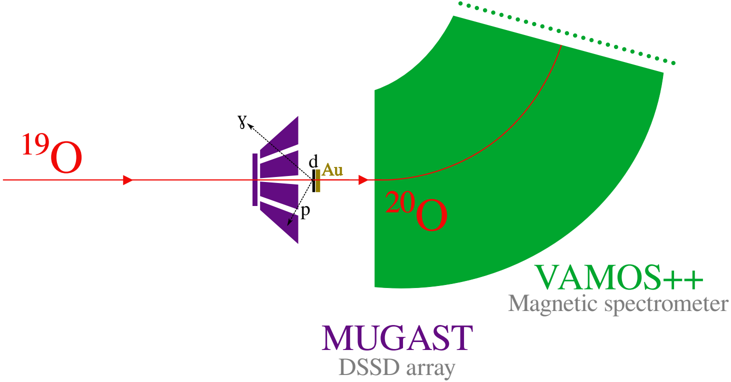
Target(s)

- 0.3 mg/cm^2 CD_2
- 0.3 mg/cm^2 CD_2
  + 24 mg/cm^2 Au
- No effect on proton detection



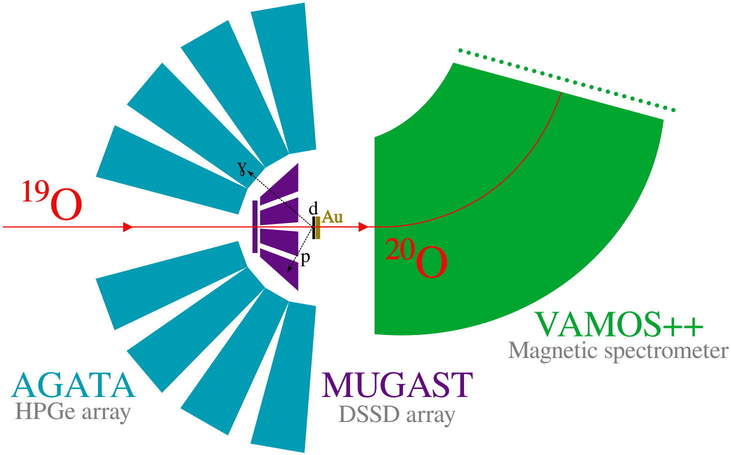
VAMOS++

- ^{20}O at focal plane
- Zero-degree arrangement
- Crucial background rejection
  - No background with CD_2
  - Small bg with CD_2+Au



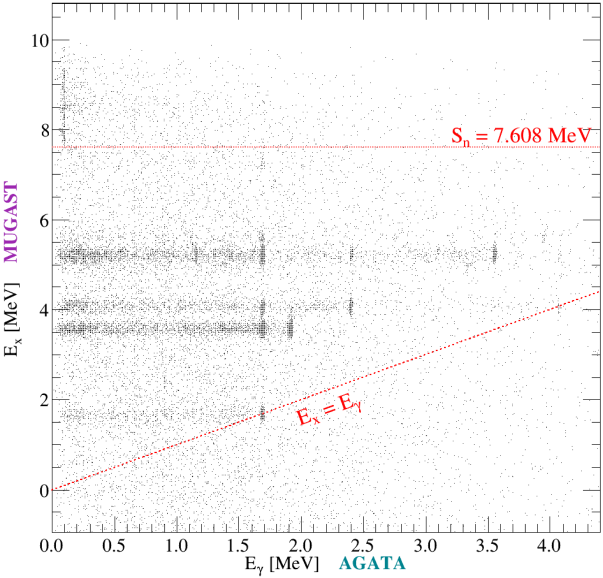
MUGAST

- Detection of proton
- 7 trapezoidal DSSDs
- One annular DSSD
- 215 keV FWHM
  - ~40 keV more than Hoffman *et al.*
  - Dominated by target thickness

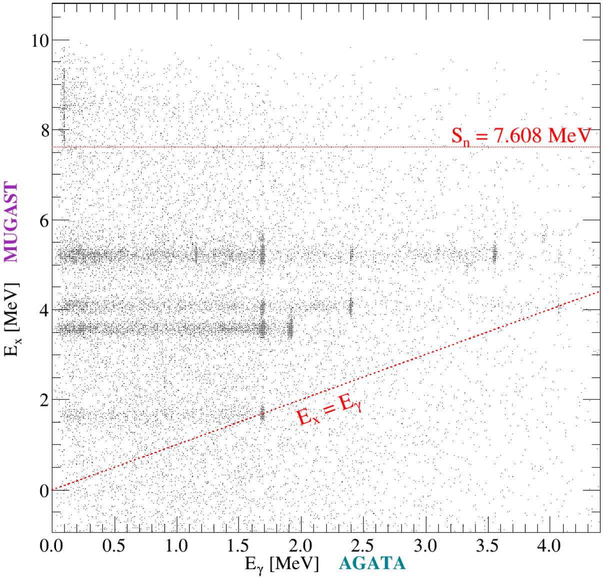


AGATA

- Prompt γ-ray emissions
- State-of-the-art γ-ray tracking
- 12 triple clusters at 18 cm
- 7.7 keV FWHM at 1.67 MeV
- Event-by-event Dopp. corr.
  - β @ mid-CD_2
  - β @ post-Au



- Strength: particle-γ coincidence!
  - Excitation energy to keV-precision
  - Build decay schemes for each level



- Strength: particle-γ coincidence!
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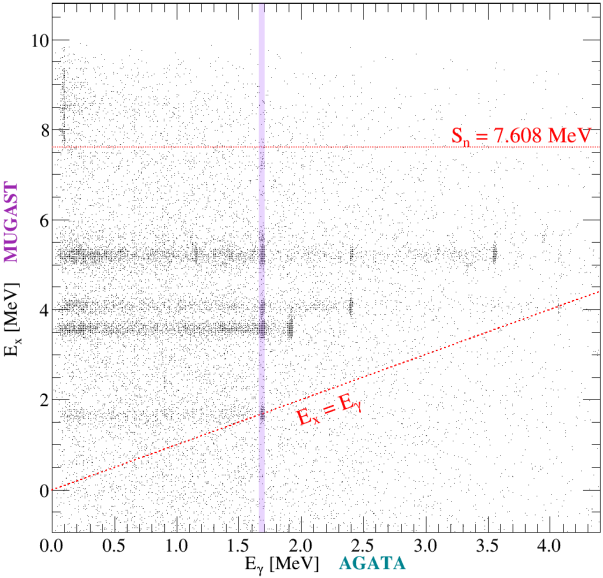
- Two key γ-ray transitions:



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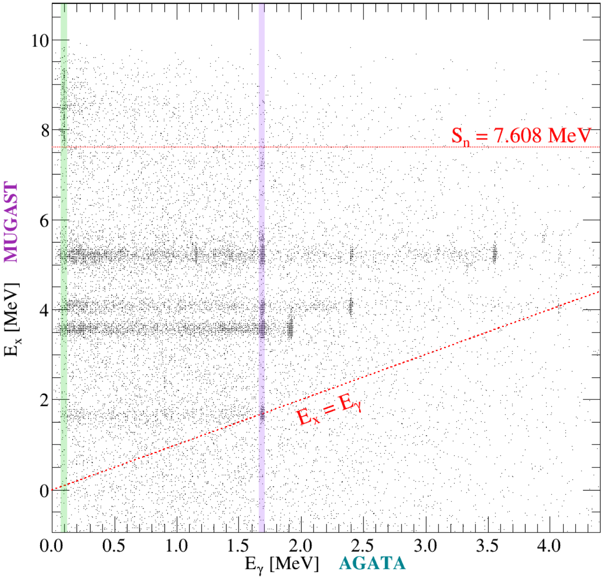
  1674 keV: ^{20}O, 1st ex. $\rightarrow$ g.s.



- Strength: particle-γ coincidence!
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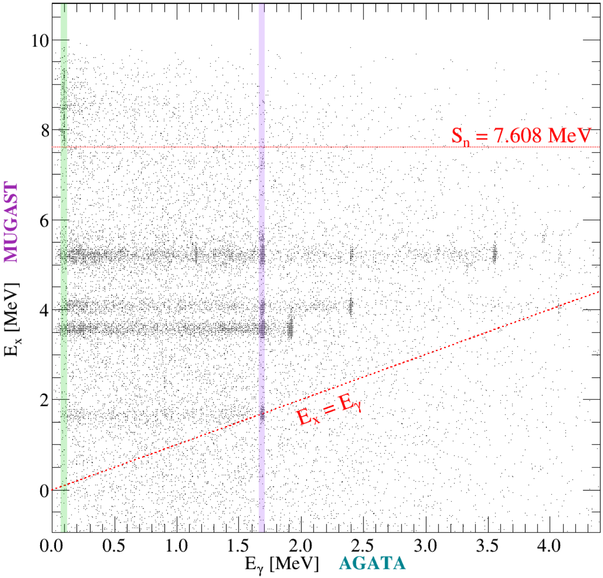
- Two key γ-ray transitions:

  1674 keV: ^{20}O, 1st ex. $\rightarrow$ g.s.

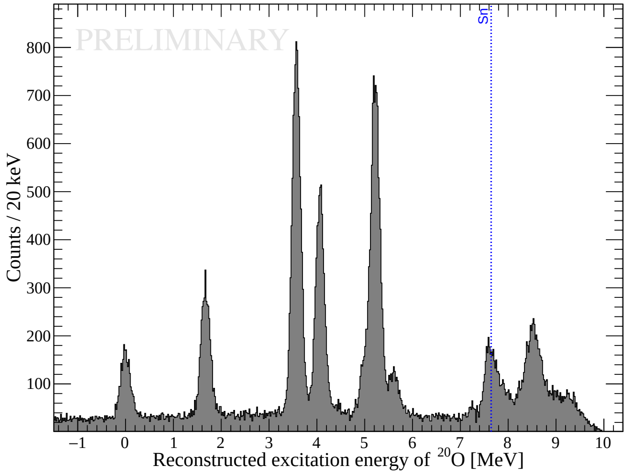
  96 keV: ^{19}O, 1st ex. $\rightarrow$ g.s.

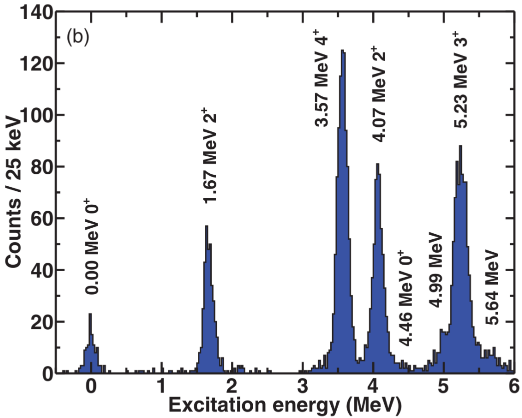


- Strength: particle-γ coincidence!
  - Excitation energy to keV-precision
  - Build decay schemes for each level
- Two key γ-ray transitions:

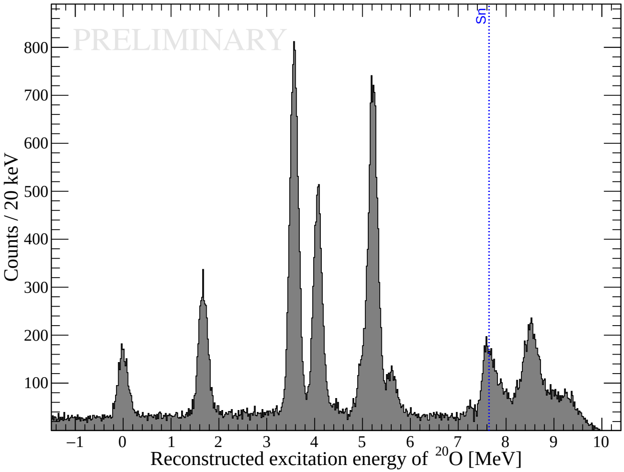
  1674 keV: ^{20}O, 1st ex. $\longrightarrow$ g.s.

  96 keV: ^{19}O, 1st ex. $\longrightarrow$ g.s.
- Unbound, no γ cascade for energy...
- E_x accuracy is critical!

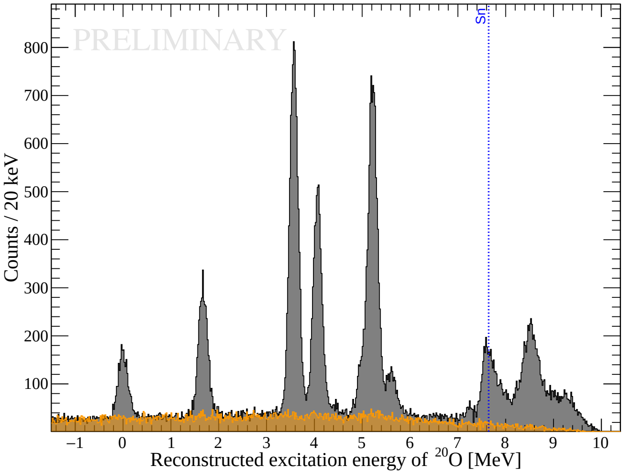




C. R. Hoffman *et al.* PRC **85**, 054318 (2012)

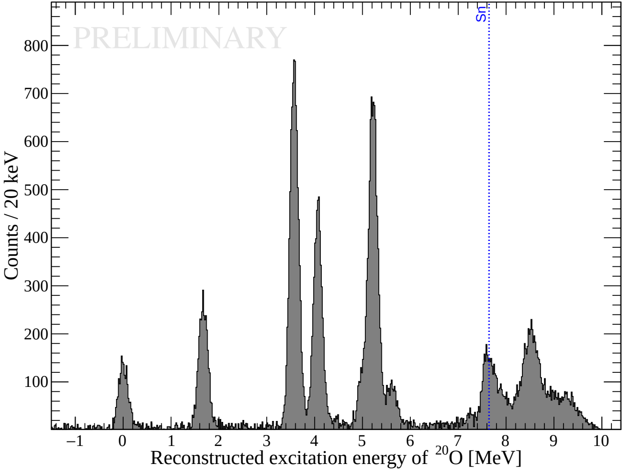


Background contributions



Background contributions

- Off-coincidence gate for **Au background**



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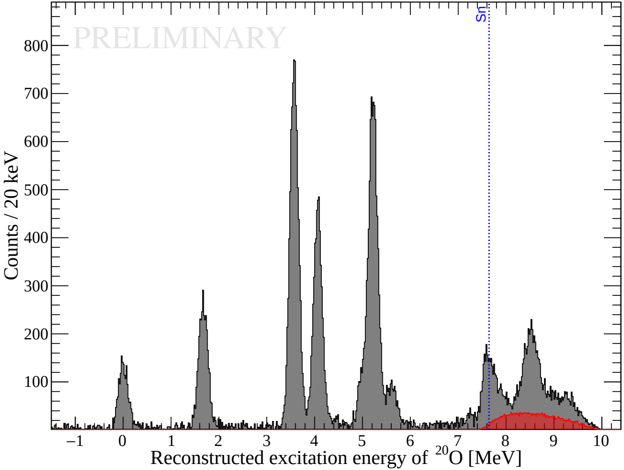
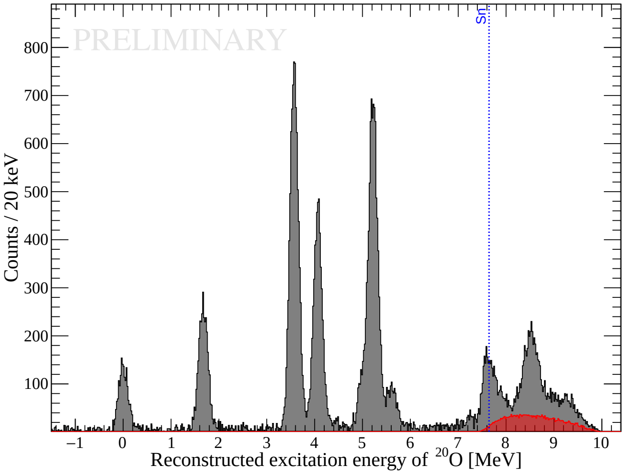


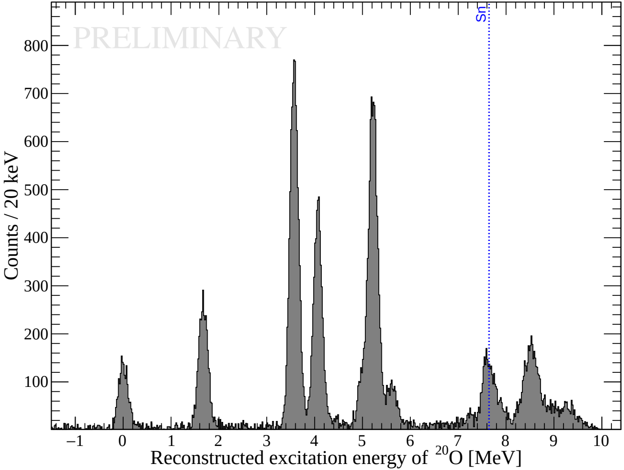
Background contributions

- Off-coincidence gate for Au background
- Above S_n, **deuteron breakup**



Background contributions

- Off-coincidence gate for Au background
- Above S_n, **deuteron breakup**
  - Simulated with GEANT4 & nptool
    (WARNING: flat cross section!)
  - Scaled in 2D, E_x:θ_{lab}, subtract max
  - Soon: realistic cross-section (G. Potel)



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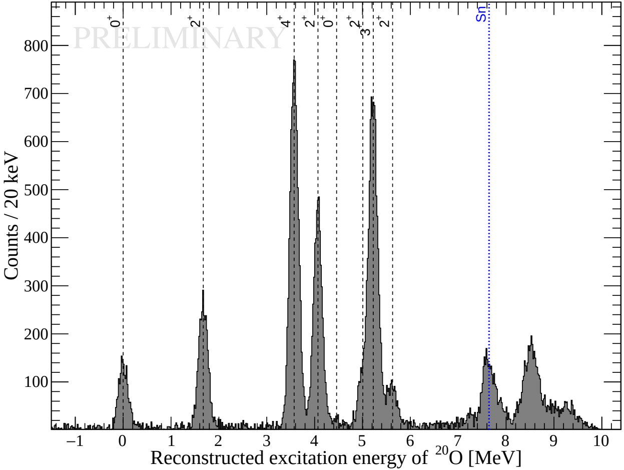

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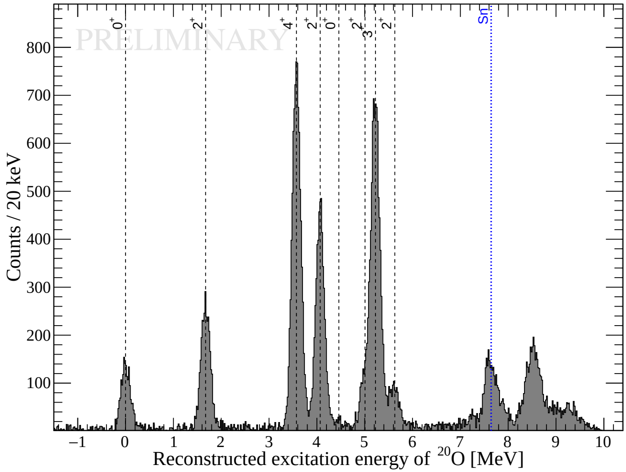
Accuracy of energy without γ-rays

- Accurate to within 10's of keV
- Confident extrapolating to unb. region



Background contributions

- Off-coincidence gate for Au background
- Above S_n, deuteron breakup
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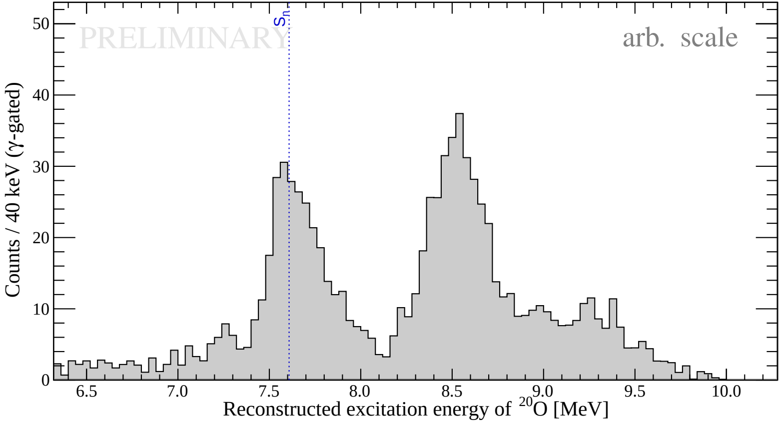
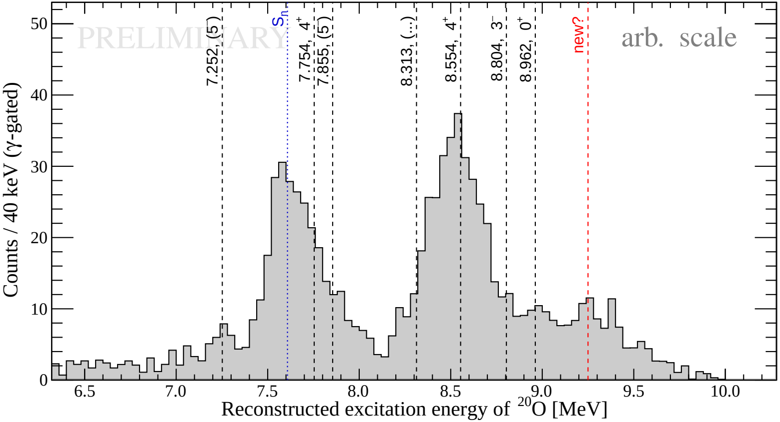
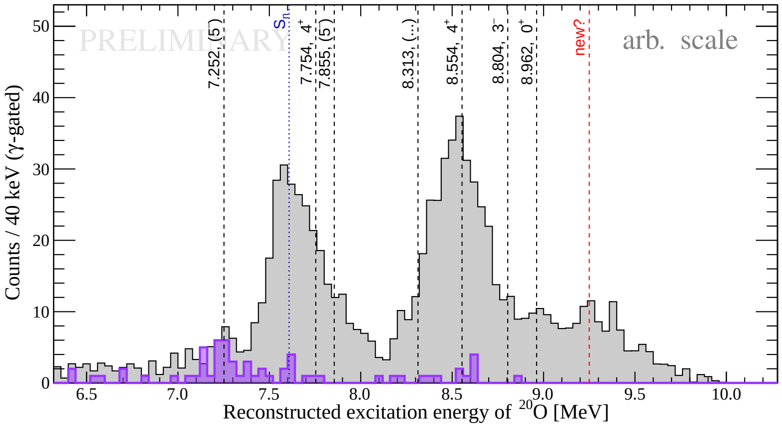
So, what is populated in the unbound region?

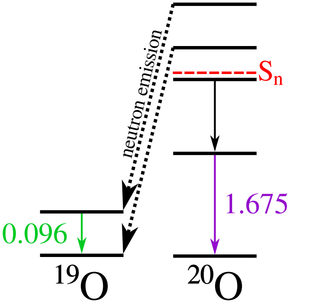

PRELIMINARY
arb. scale
S_n
Counts / 40 keV (γ-gated)
0
10
20
30
40
50
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
Reconstructed excitation energy of ^{20}O [MeV]



Bohlen *et al.* EPJA **47** 44 (2011)
Tilley *et al.* NPA **636** 249 (1998)
LaFrance *et al.* PRC **20** 5 (1979)

- All states narrow in literature, except 8.554 MeV (Γ = 220 keV)





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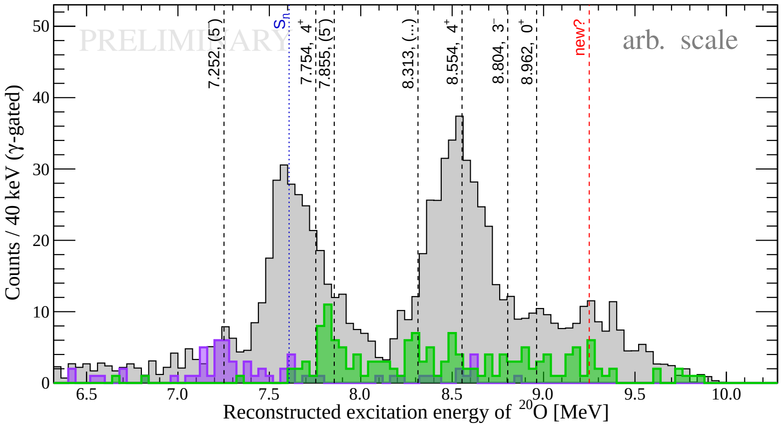

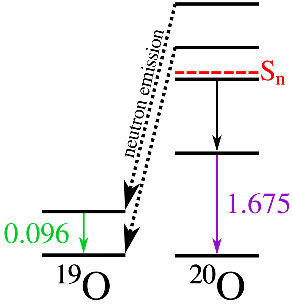

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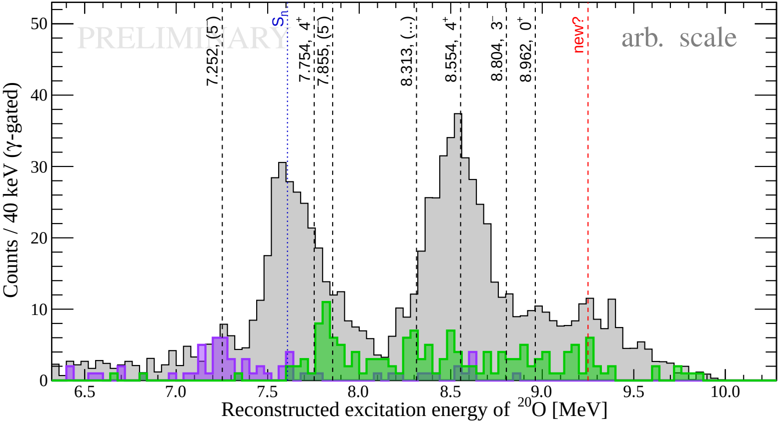

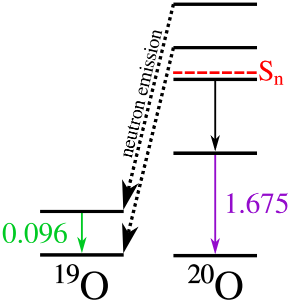

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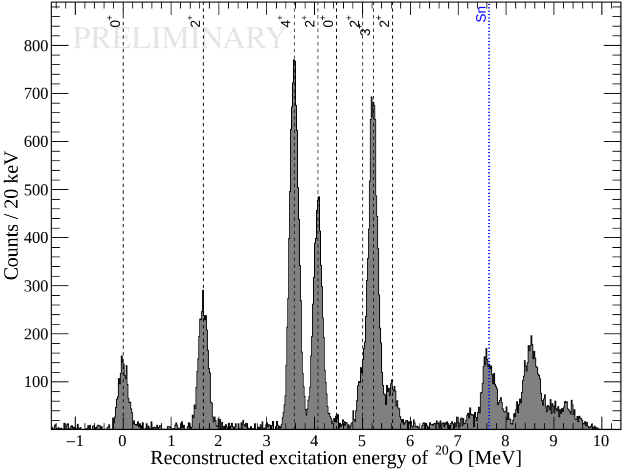
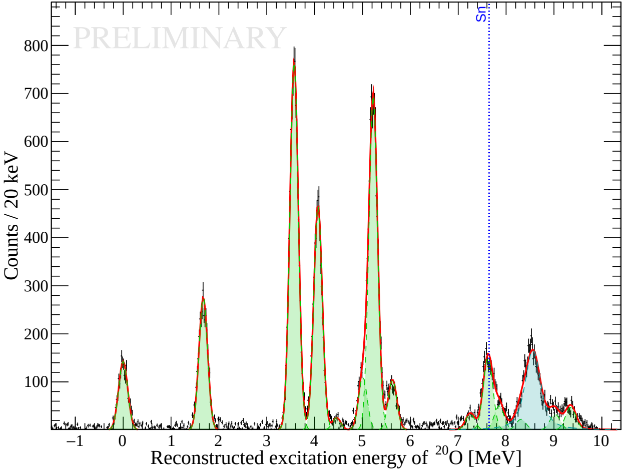
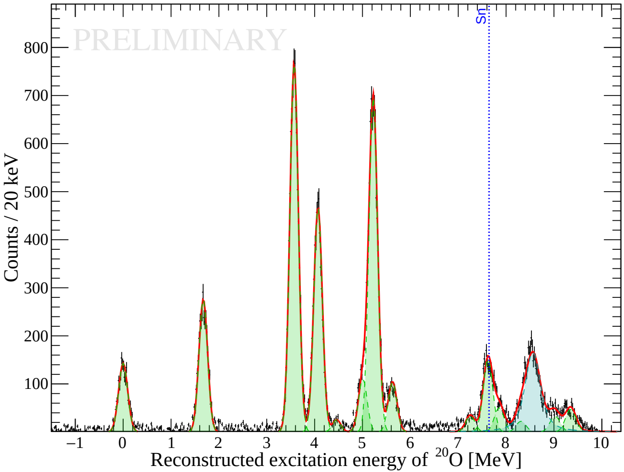
- All states narrow in literature, except 8.554 MeV (Γ = 220 keV)
- Not trivial to populate 5^- states! Expect positive parity; $s_{1/2}$, 2^+, 3^+ or $d_{3/2}$, 1^+–4^+
- Reassign spin-parity? Shell model calculations may provide clarity


PRELIMINARY
0+
2+
4+
2+
0+
2+
3-
2+
Sn
Counts / 20 keV
800
700
600
500
400
300
200
100
−1
0
1
2
3
4
5
6
7
8
9
10
Reconstructed excitation energy of 20O [MeV]



- Fit full spectrum with **Gauss** & **Voigt** with fixed E, σ and Γ
- Fit across θ, then correct for solid angle
- Extract experimental diff. cross sections!

$$\frac{d\sigma}{d\Omega}_{\text{exp}} = S\frac{d\sigma}{d\Omega}_{\text{thr}}$$



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$$\frac{d\sigma}{d\Omega}_{\text{exp}} = S\frac{d\sigma}{d\Omega}_{\text{thr}}$$

Need reaction theory to compare...

Koning-Delaroche Uncertainty Qualified (KDUQ)

- KDUQ integrated into FRONT code for TWOFNR!
  - Huge thanks to Chloë Hebborn
- Calculate ADWA potential in FRONT...
- ... but TWOFNR can't handle unbound states!

Pruitt, Escher and Rahman, PRC **107** 014602 (2023)
Hebborn and Nunes, Front. Phys. **13** 1525170 (2025)

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- KDUQ integrated into FRONT code for TWOFNR!
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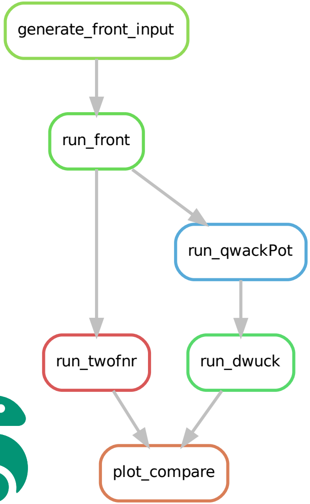
- Calculate ADWA potential in FRONT...
- ... but TWOFNR can't handle unbound states!

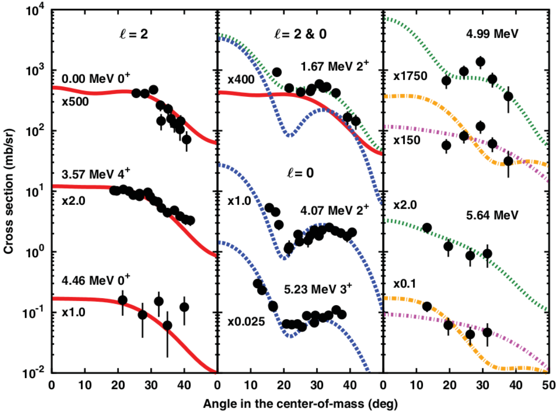
Read ADWA into DWUCK4, Vincent & Fortune method!

- Do this 416 times for one UQ output (10^5 total!)
- Confirm by comparing TWOFNR to DWUCK4



Pruitt, Escher and Rahman, PRC **107** 014602 (2023)
Hebborn and Nunes, Front. Phys. **13** 1525170 (2025)

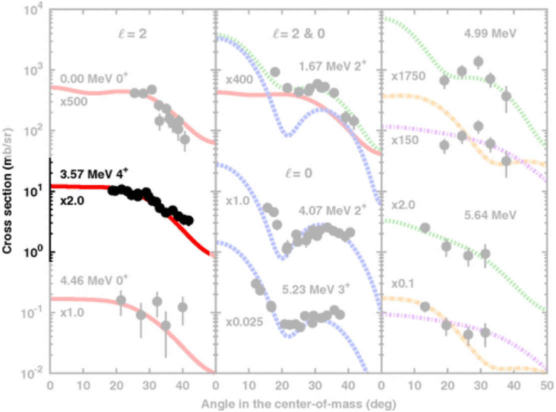
Compare bound states to literature



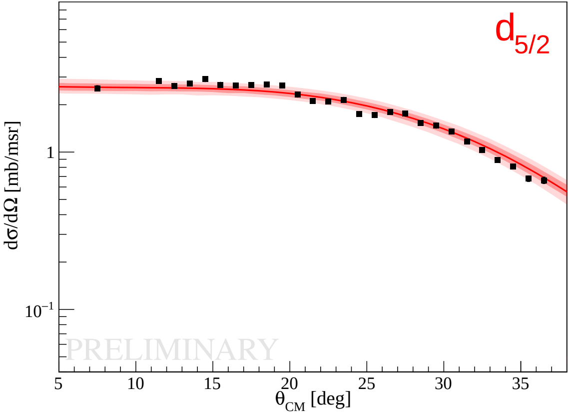
C. R. Hoffman *et al.* PRC **85**, 054318 (2012)

Compare bound states to literature

3.572 MeV, $\ell = 2 \longrightarrow$ Agree!

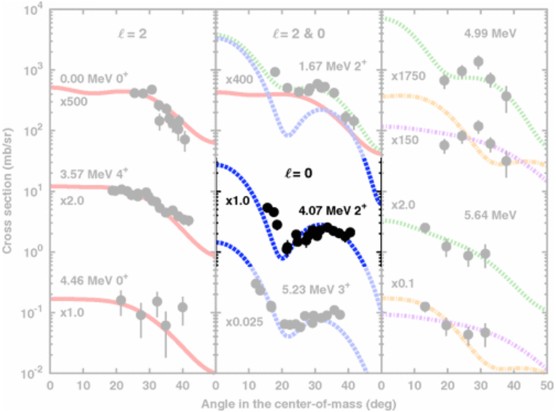


C. R. Hoffman *et al.* PRC **85**, 054318 (2012)

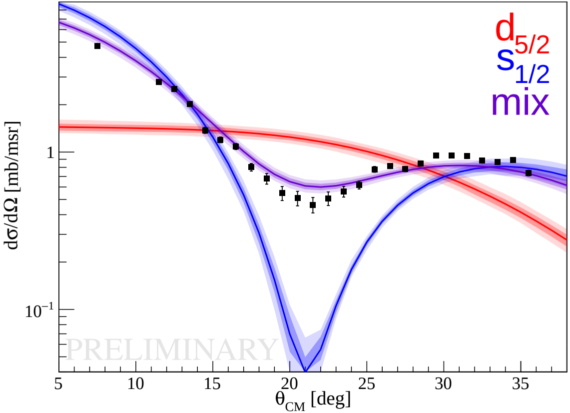


Compare bound states to literature

4.070 MeV, $\ell = 0 + 2 \rightarrow$ Small d-wave component?

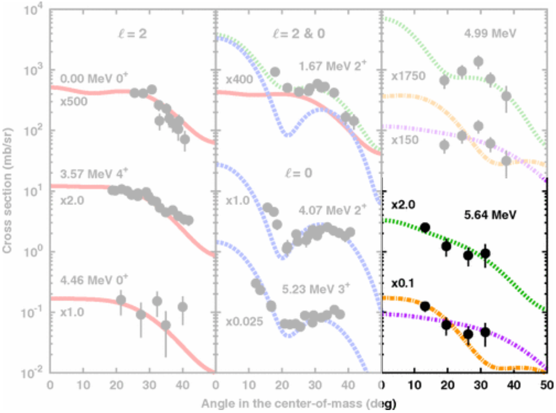


C. R. Hoffman *et al.* PRC **85**, 054318 (2012)

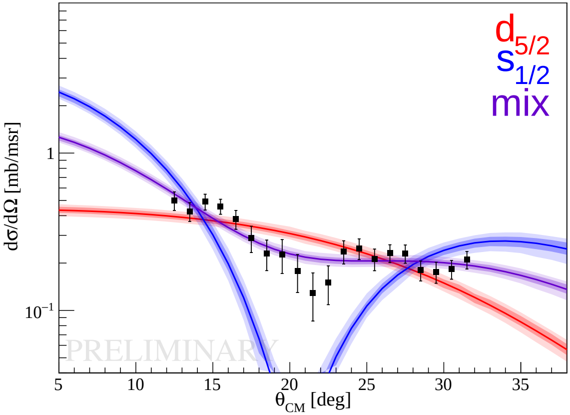


Compare bound states to literature

5.628 MeV, $\ell = 0 + 2 \rightarrow$ Better constrain weak states



C. R. Hoffman *et al.* PRC **85**, 054318 (2012)

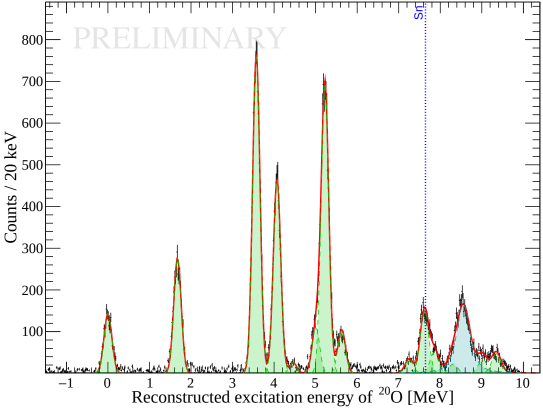


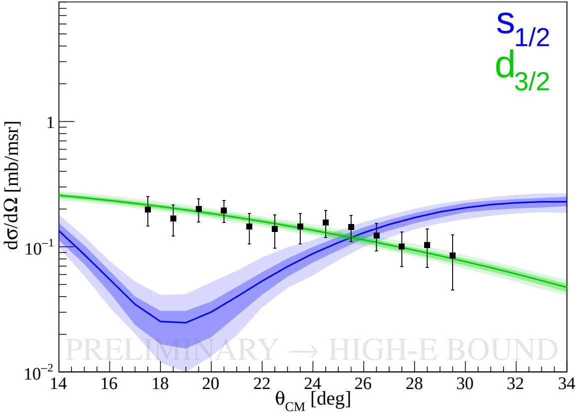
Search for $d_{3/2}$ at high-energy

C. R. Hoffman *et al.* PRC **85**, 054318 (2012)

Search for $d_{3/2}$ at high-energy

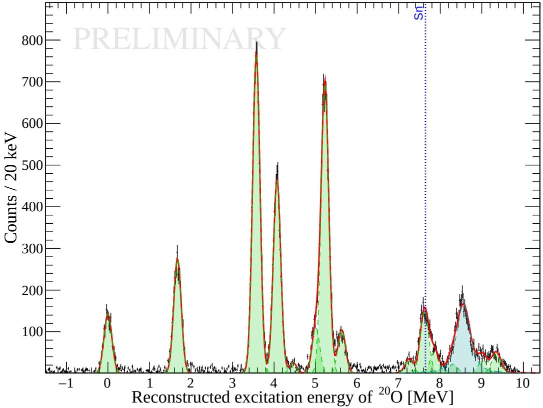
7.252 MeV, $\ell = 2 \rightarrow$ maybe $d_{3/2}$?

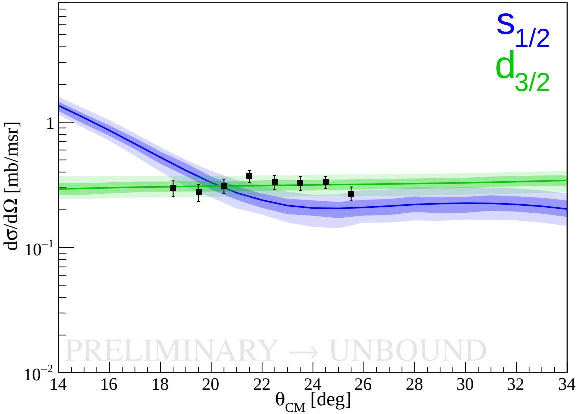




Search for $d_{3/2}$ at high-energy

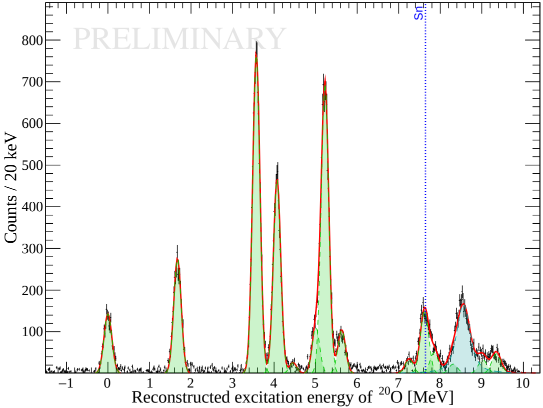
7.855 MeV, $\ell = 2 \rightarrow$ maybe $d_{3/2}$?

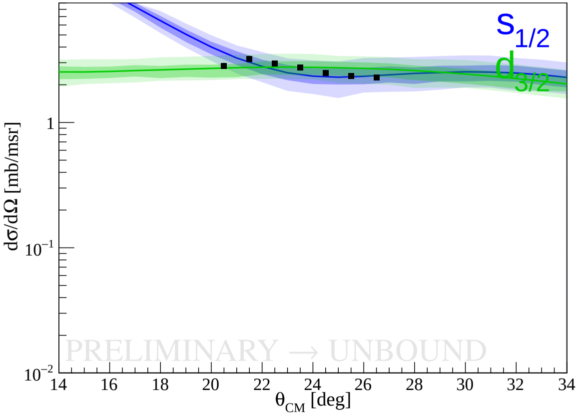




Search for $d_{3/2}$ at high-energy

8.554 MeV, less certain...





Summary:

- Evolution of $\nu d_{3/2}$ orbital towards oxygen dripline, trace emergence of N=16 gap
- ^{19}O(d,p) to search for $d_{3/2}$ strength in *unbound* states of ^{20}O
- Improved constraint on bound states (i.e. mixing)
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  - Compare to shell model calculations (Bhoomika Maheshwari, underway)
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- Are these states $d_{3/2}$? $\longrightarrow$ Shell evolution & $N = 16$ shell gap!

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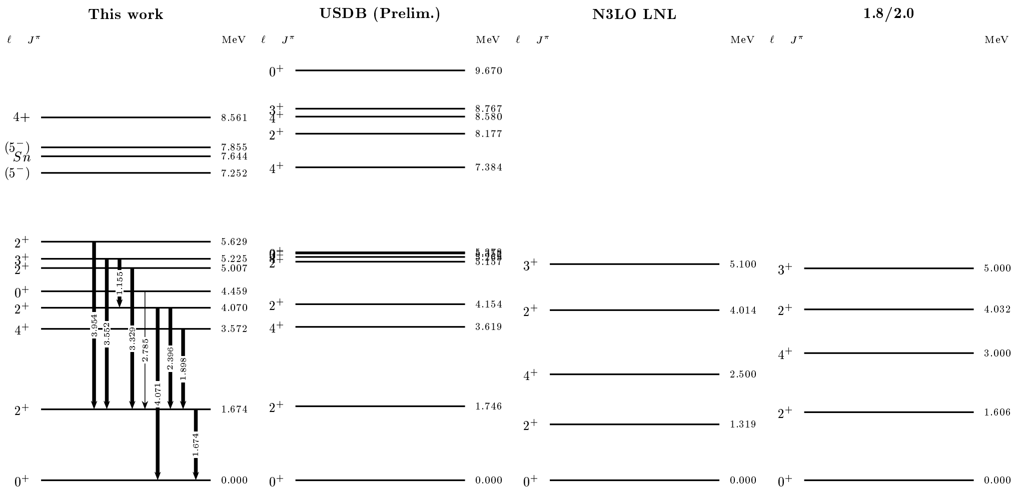
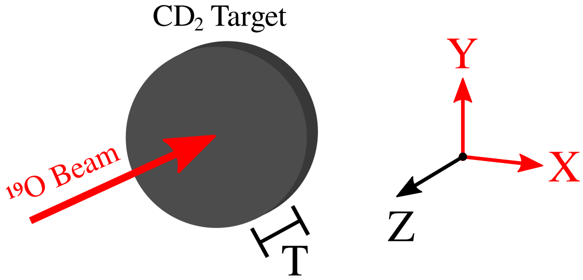
Thank you!

BACKUP SLIDES

Backup - prelim SM calcs from Bhoomika



- Recall, no beam tracking!
- Sensitive to beam spot position
- Numerical minimisation!
- Vary X_b, Y_b, Z_t T_t
- Align by "average" position
- Separated by target



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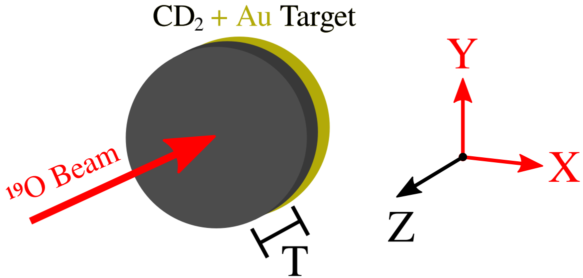
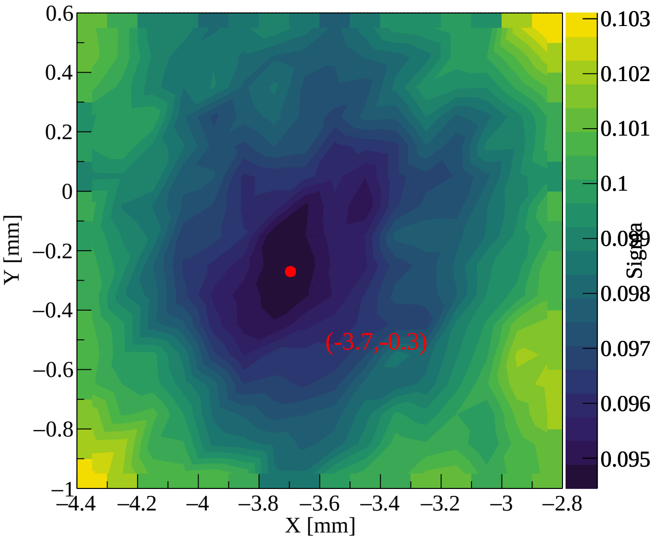


Backup - Minimization example



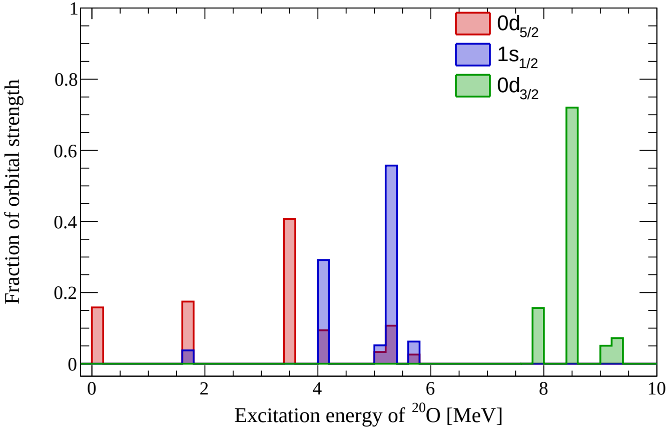
Backup - rotational structures

Table 2. Experimental excitation energies E_x, spin-parities J^π and widths, given for different K^π rotational bands proposed for ^{20}O: the parity doublet bands 0_2^+ and 0_2^-, and the parity doublet bands 0_4^+ and 0_4^-. Assignments, which are made from the $(2J+1)$, may have to be confirmed independently, and are given in brackets.

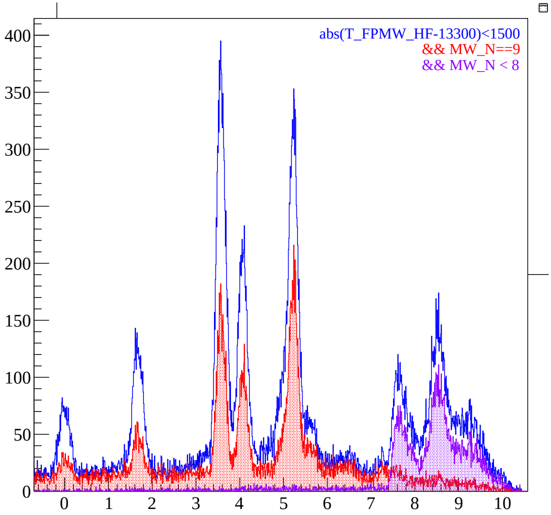
$K^\pi = 0_2^+$			$K^\pi = 0_2^-$			$K^\pi = 0_4^+$			$K^\pi = 0_4^-$		
E_x (MeV)	J^π	Γ (keV)	E_x (MeV)	J^π	Γ (keV)	E_x (MeV)	J^π	Γ (keV)	E_x (MeV)	J^π	Γ (keV)
4.458	0^+		9.918	(1^-)	20	9.768	0^+	20	11.67	(1^-)	100
5.237	2^+		11.95	(3^-)	90	10.11	2^+	5	12.83	(3^-)	100
7.754	4^+		13.96	(5^-)	150	11.39	(4^+)	110	13.44	(5^-)	65
10.93	(6^+)	40	18.46	(7^-)	140	13.60	(6^+)	250	17.35	(7^-)	210
16.36	(8^+)	90				16.63	(8^+)	110			
						18.61	(10^+)	190			

Bohlen *et al.* EPJA **47** 44 (2011)

Backup - Prelim orbital fractions (assuming high-E are d3/2)

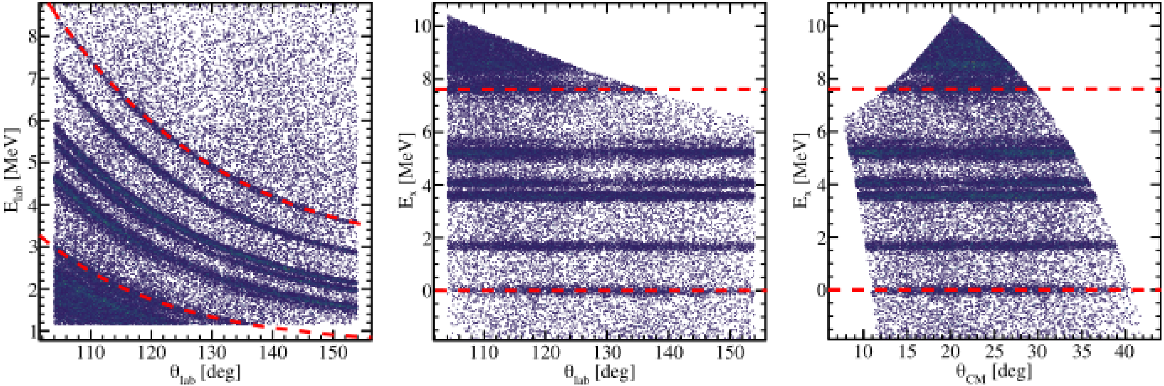


Backup - VAMOS to isolate unbound?



great! but how to normalise...

Backup - Why the unusual edges to the data?



Optical model calculations

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PHYSICAL REVIEW C **107**, 014602 (2023)

Uncertainty-quantified phenomenological optical potentials for single-nucleon scattering

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Front. Phys., 05 June 2025
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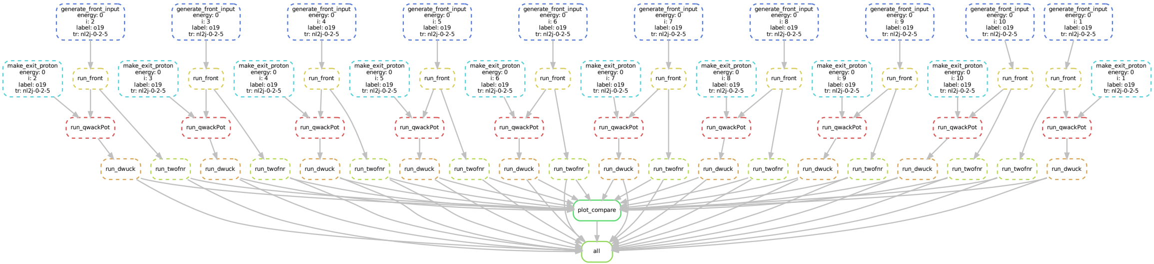
- **Using KDUQ for (un)bound states**

Workflow



1/40th of one calculation...

compare TWOFNR to DWUCK4