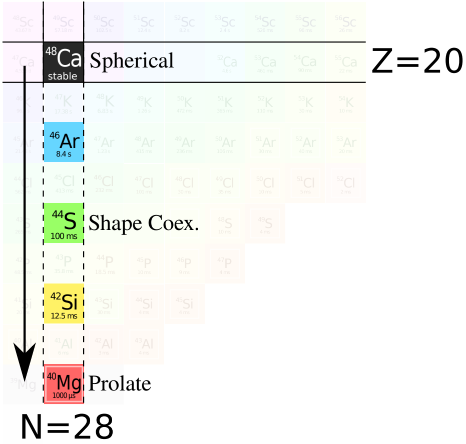
Exotic cross-shell interactions at $N = 28$: Single-neutron transfer on ^{47}K

Charlie J. Paxman (GANIL)

6^{th} European Nuclear Physics Conference – 22/09/25 – Caen, France

Motivation

- Challenge: N=28 "island of inversion"



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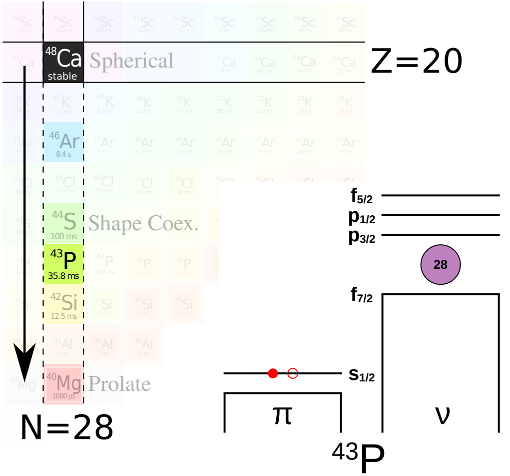

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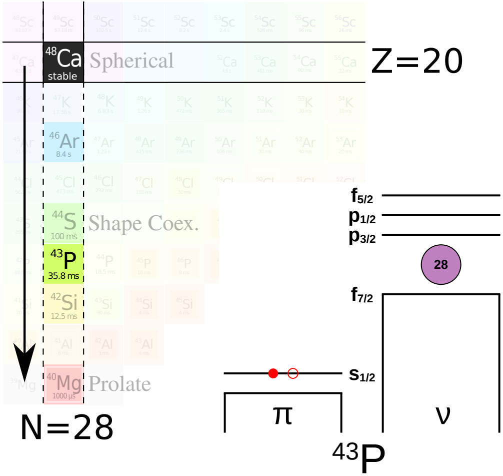

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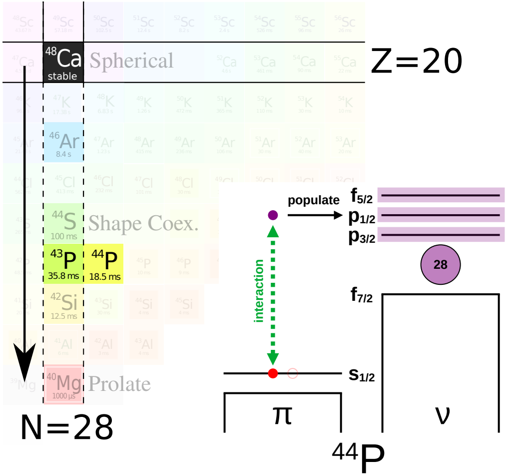

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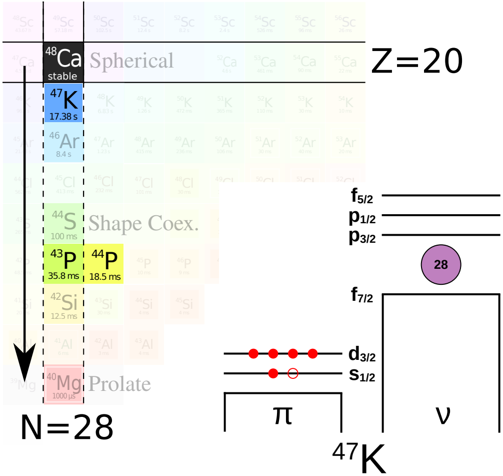
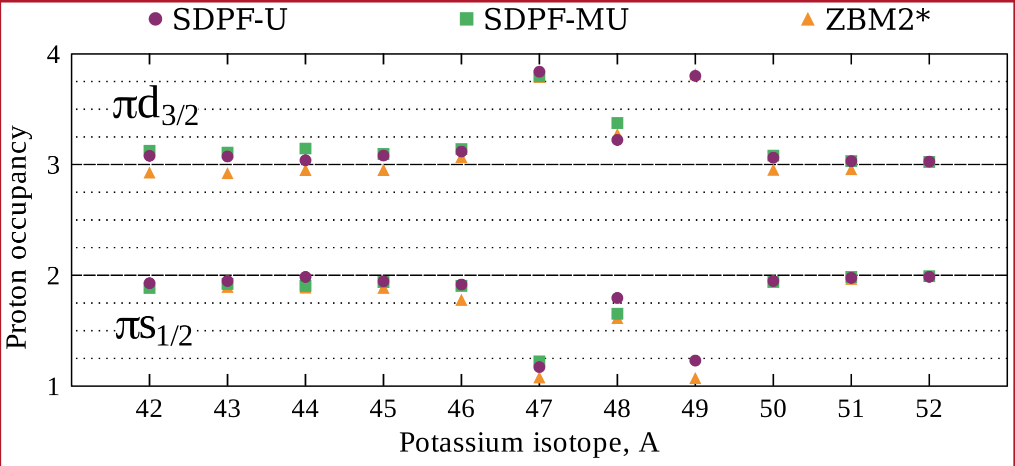
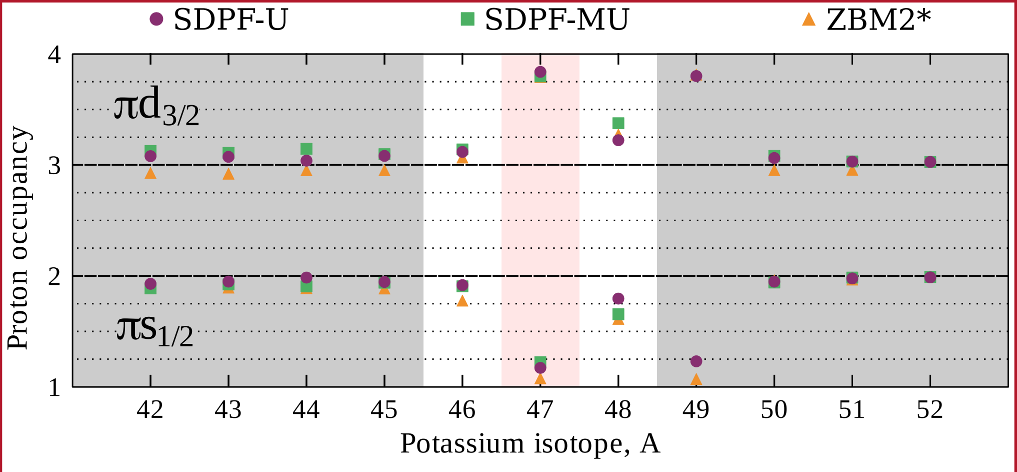




Adapted from J. Papuga et al. Phys. Rev. C 90, 034321 (2014)



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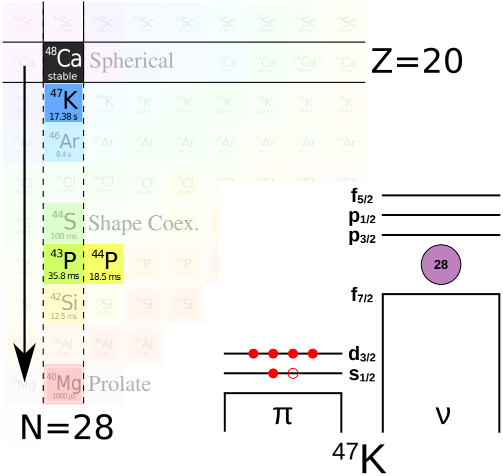

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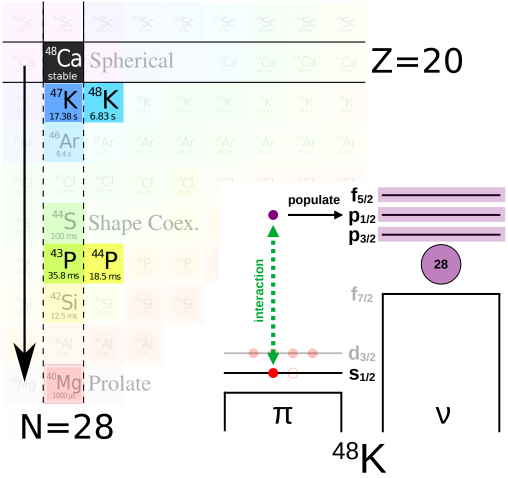
- Add neutron, probe interesting interactions!



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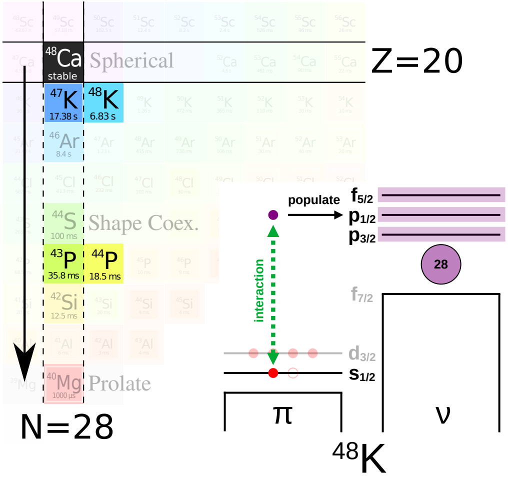
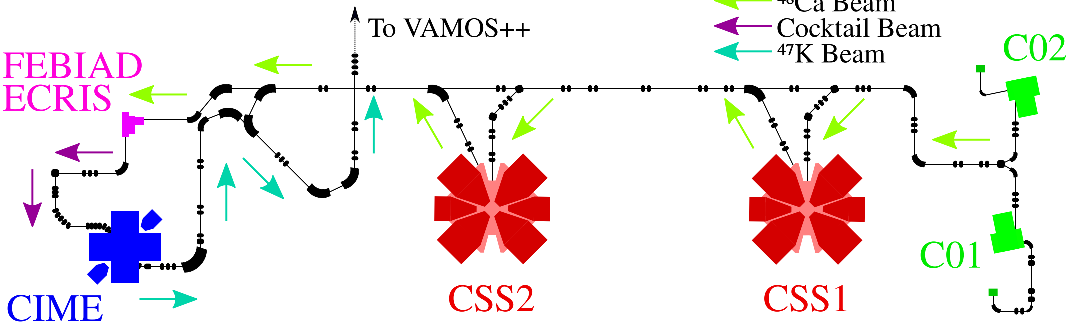


First measurement of exotic $\pi(s^{-1}_{1/2}) \otimes \nu(f_{5/2}p)$ interactions

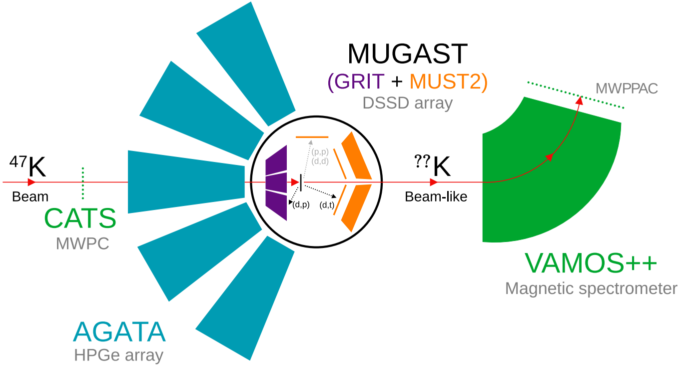
Radioactive Isotope Beam



- ^{47}K RIB @ 7.7 MeV/u.
- Avg. 5×10^5 pps
- 10^{-4} mass res. → pure beam

Experimental Setup

CATS
Target
VAMOS++
MUGAST
AGATA

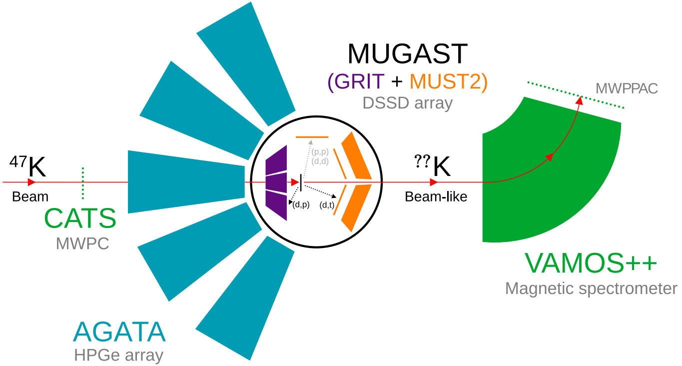


Experimental Setup

CATS

- Beam monitoring
- Timing signal (trigger)

Target
VAMOS++
MUGAST
AGATA



Experimental Setup

CATS

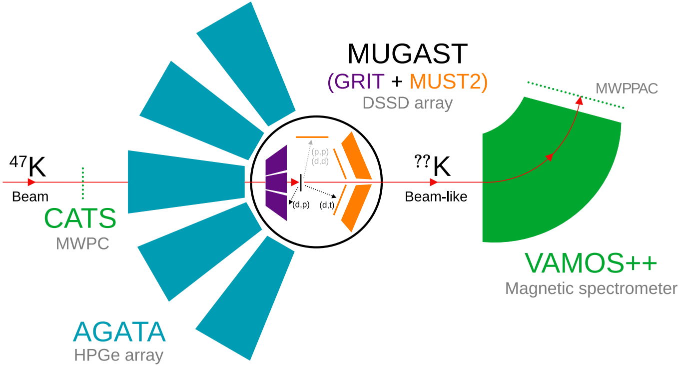
Target

- 0.31(2) mg/cm^2 CD$_2$
- 6% CH$_2$ contamination

VAMOS++

MUGAST

AGATA



Experimental Setup

CATS

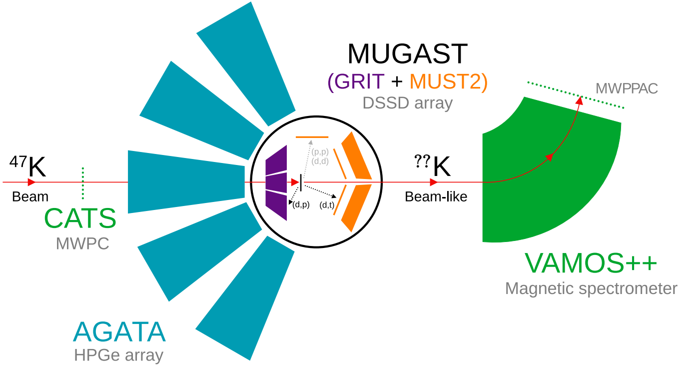
Target

VAMOS++

- Heavy recoil detection
- Zero degree arrangement; receiving full beam
- MWPPAC only
- Recoil timing & reject reactions on carbon

MUGAST

AGATA

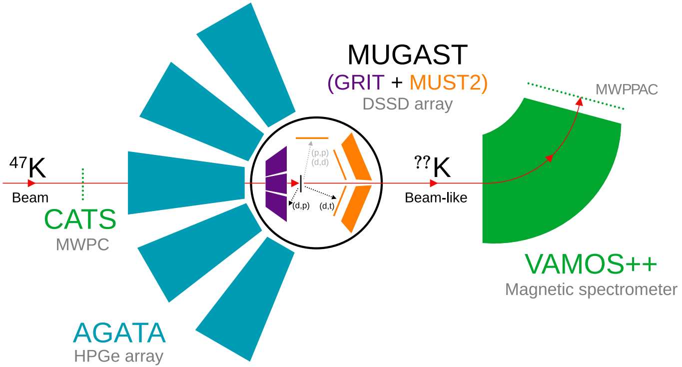


Experimental Setup

CATS
Target
VAMOS++
MUGAST

- Light ejectile detection
- 6 x GRIT trapez. DSSD
  1 x MUST2 DSSD
  4 x MUST2 DSSD+CsI
- FWHM = 330 keV in ^{48}K
- FWHM = 420 keV in ^{46}K

AGATA



Experimental Setup

CATS
Target
VAMOS++
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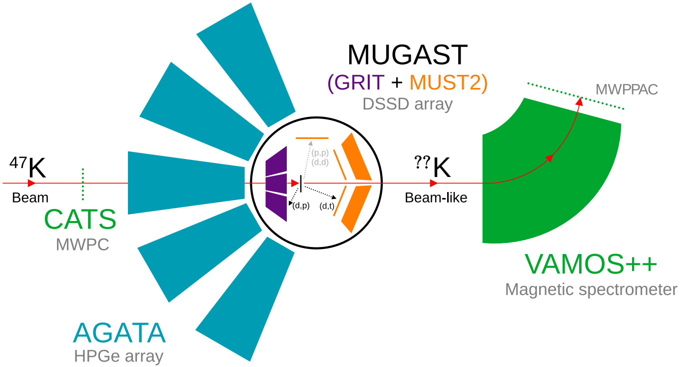
- Prompt γ-ray emissions
- 36 crystals @ 18 cm
- PSA & add-back online, DC with light ejectile
- FWHM = 7 keV @ 1.8 MeV; $\beta = 0.16$



Experimental Setup

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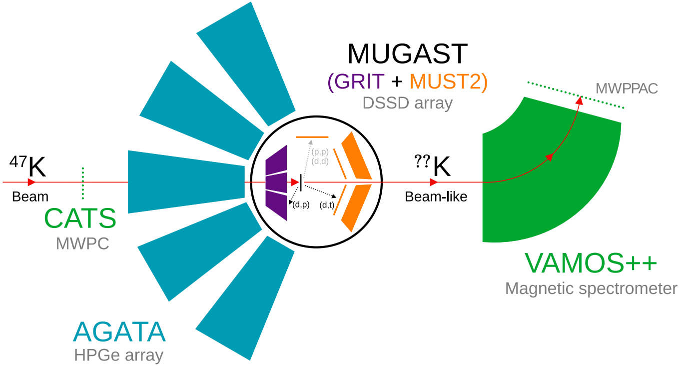
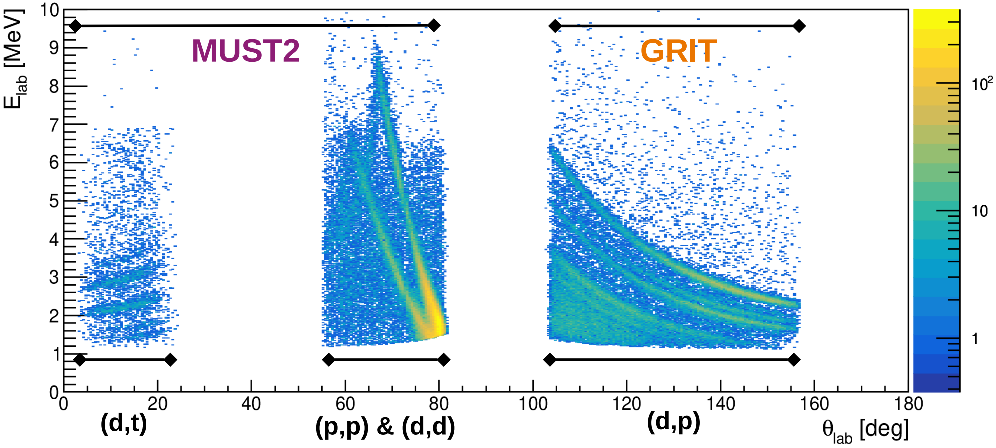
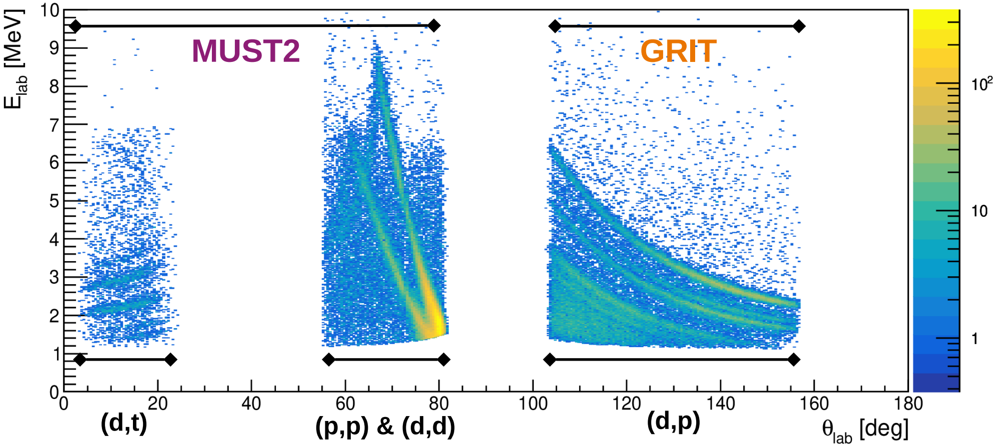
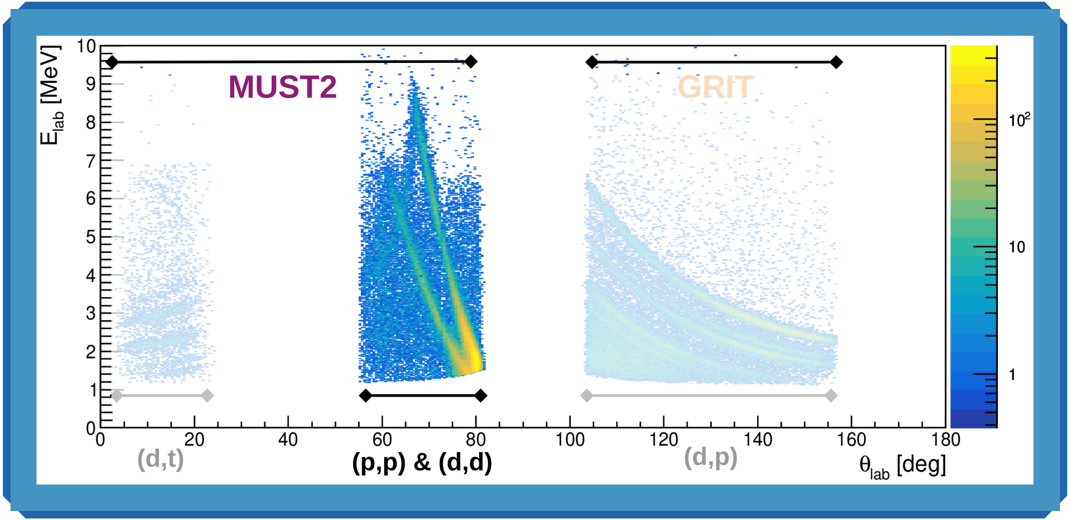


Triple-coincidence critical!

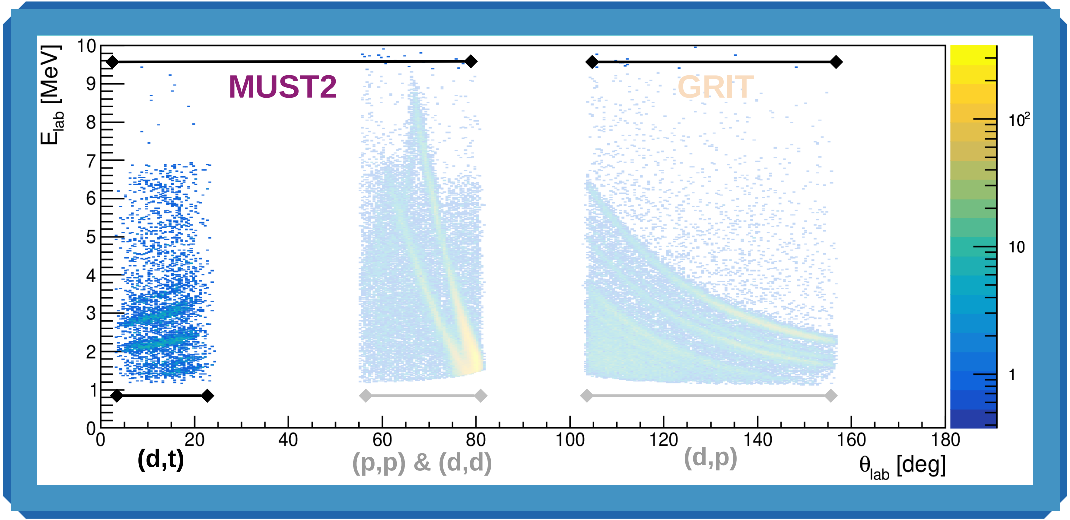

MUST2
GRIT
E_lab [MeV]
θ_lab [deg]
(d,t)
(p,p) & (d,d)
(d,p)
0
1
2
3
4
5
6
7
8
9
10
20
40
60
80
100
120
140
160
180
1
10
10^2



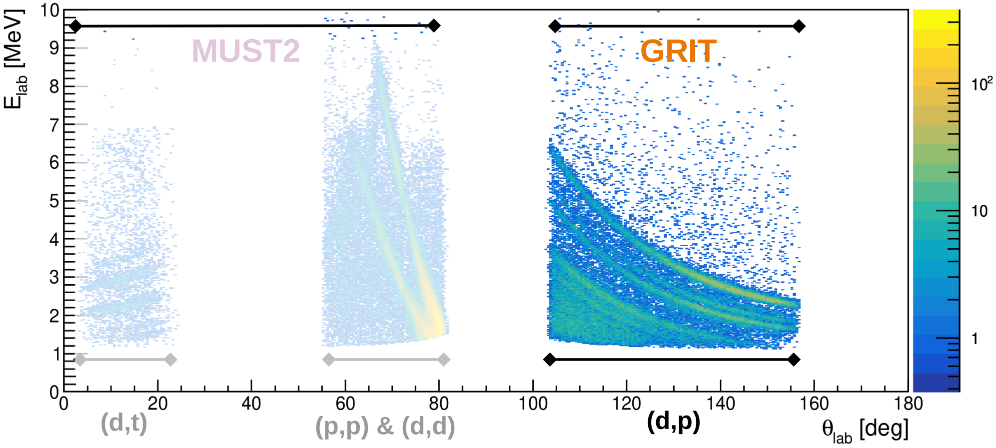
Pure SPIRAL1+ beam & VAMOS++ gating



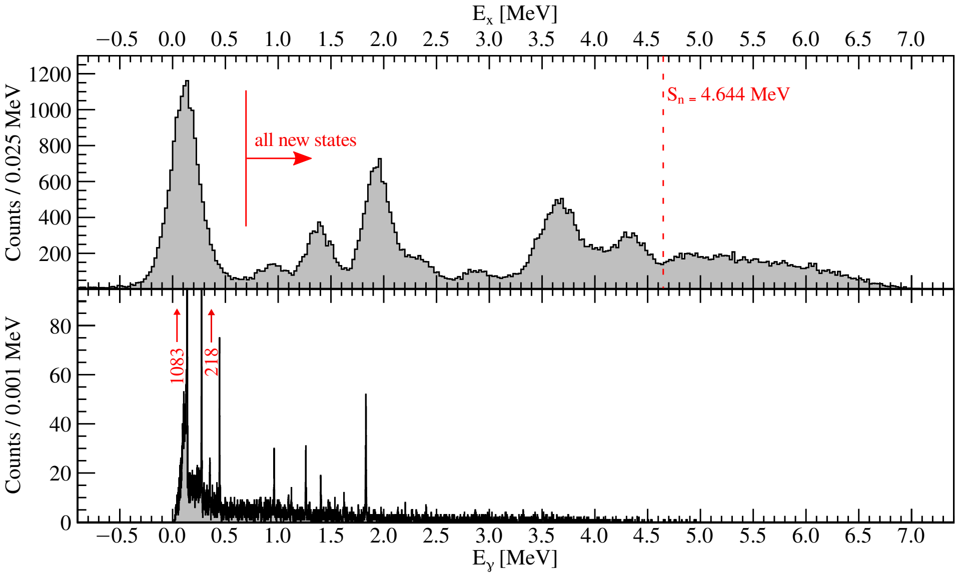
Elastics: Normalisation of beam intensity and target thickness

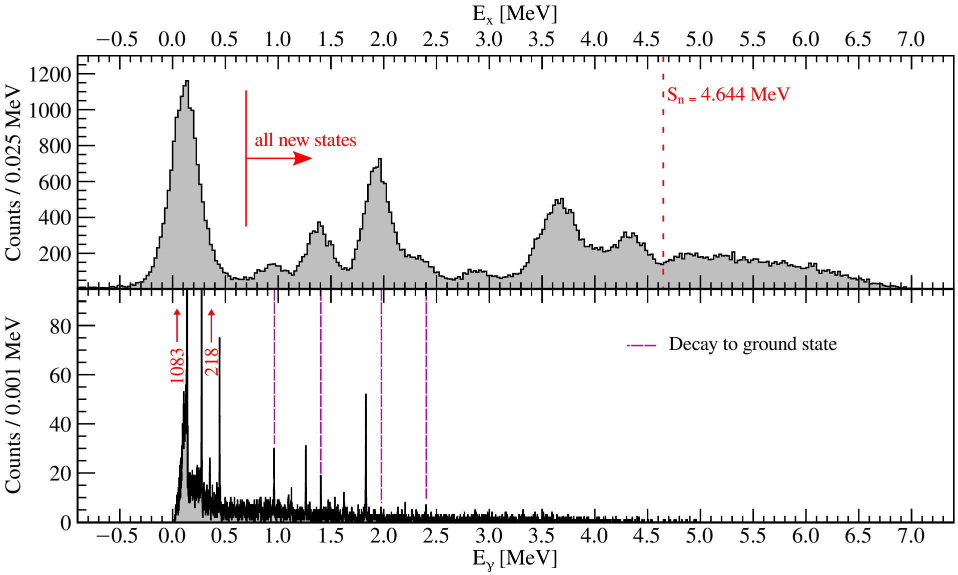


^{47}K(d,t): Simultaneous data set, neutron orbital occupation



^{47}K(d,p): Experimental focus, neutron orbital vacancies


E_x [MeV]
−0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0
Counts / 0.025 MeV
1200 1000 800 600 400 200
all new states
S_n = 4.644 MeV
Counts / 0.001 MeV
80 60 40 20 0
1083
218
E_γ [MeV]


E_x [MeV]
−0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0
Counts / 0.025 MeV
1200
1000
800
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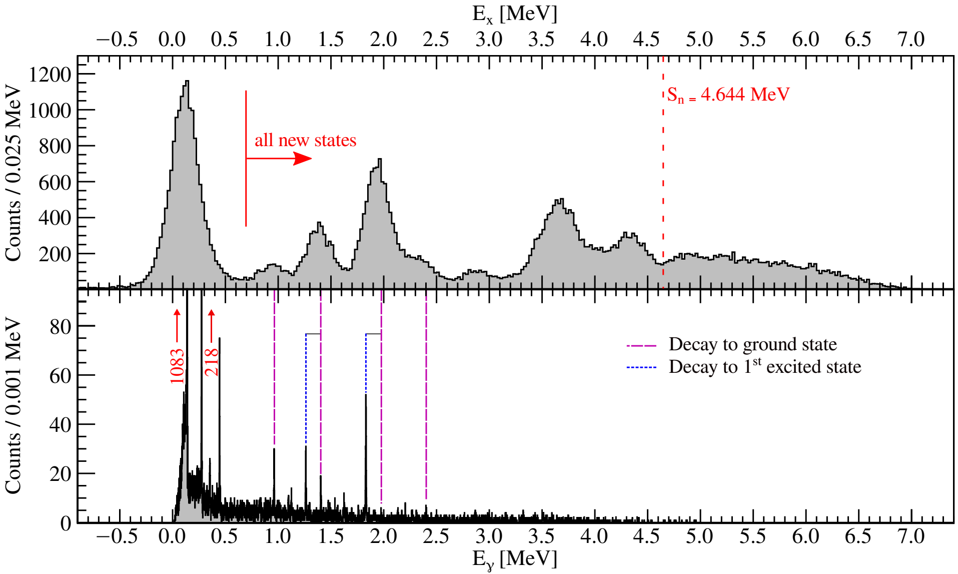
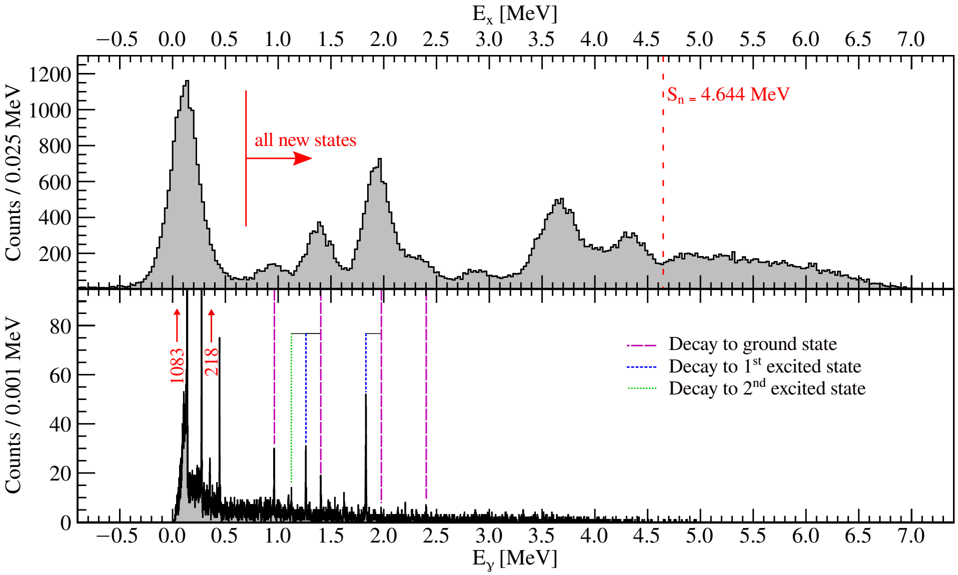
80
60
40
20
0
1083
218
Decay to ground state
−0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0
E_γ [MeV]


E_x [MeV]
Counts / 0.025 MeV
all new states
S_n = 4.644 MeV
Counts / 0.001 MeV
1083
218
Decay to ground state
Decay to 1st excited state
E_γ [MeV]


E$_x$ [MeV]
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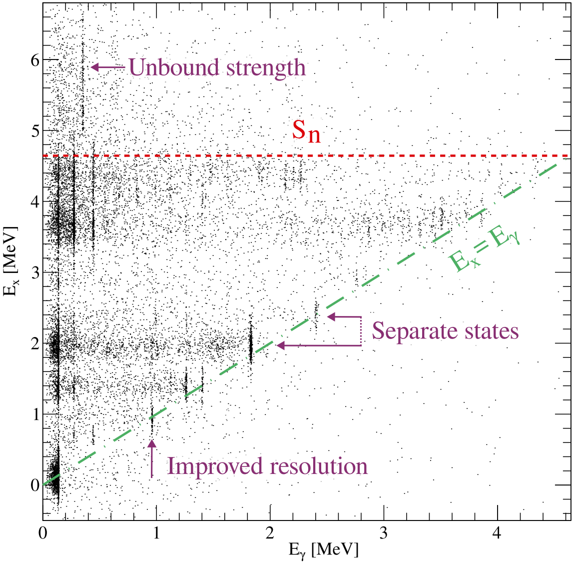
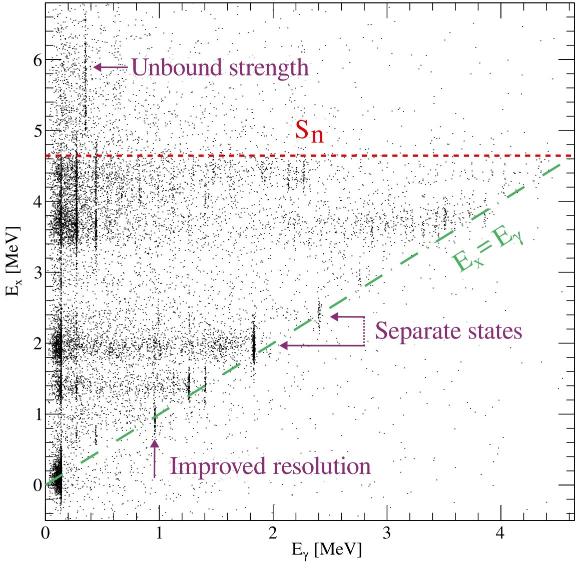
Counts / 0.025 MeV
1200 1000 800 600 400 200
all new states
S$_n$ = 4.644 MeV
Counts / 0.001 MeV
80 60 40 20 0
1083
218
Decay to ground state
Decay to 1st excited state
Decay to 2nd excited state
E$_\gamma$ [MeV]



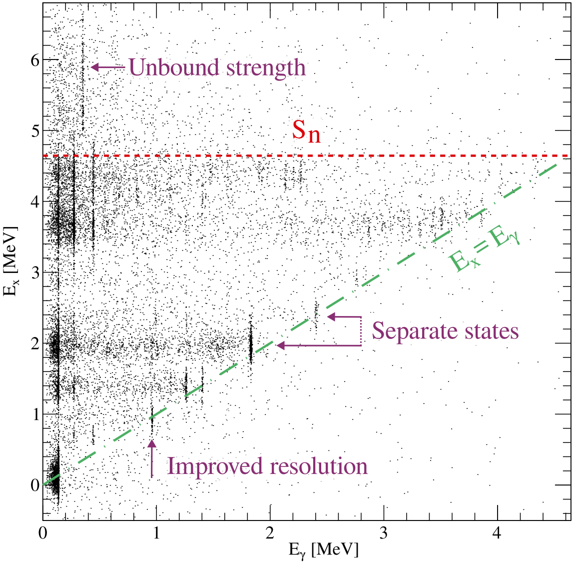
p-γ

- Strength is in 2D analysis



p-γ

- Strength is in 2D analysis
- Determine E_x to keV precision



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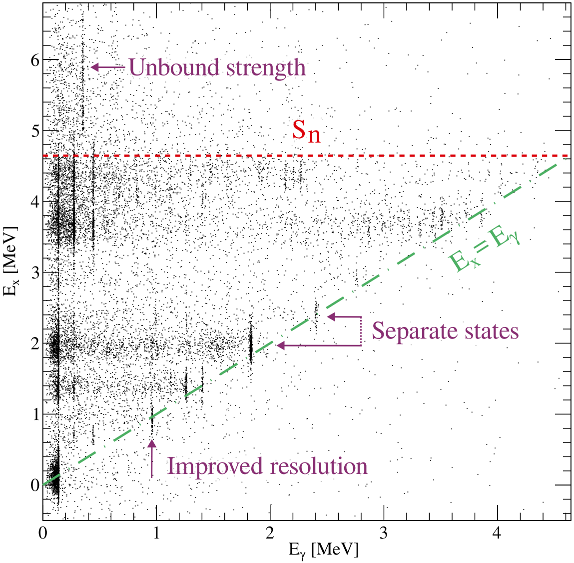
- Isolation of unresolved states



p-γ

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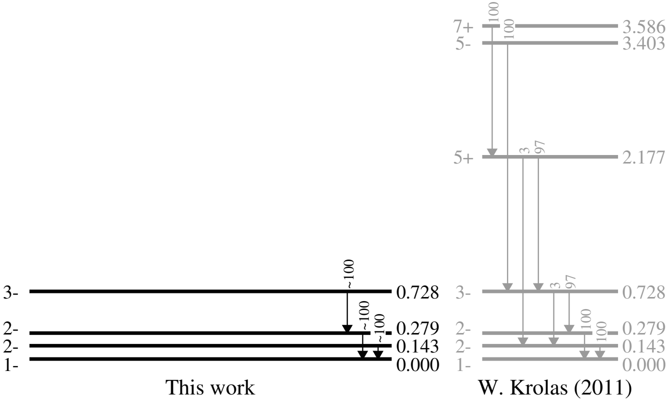
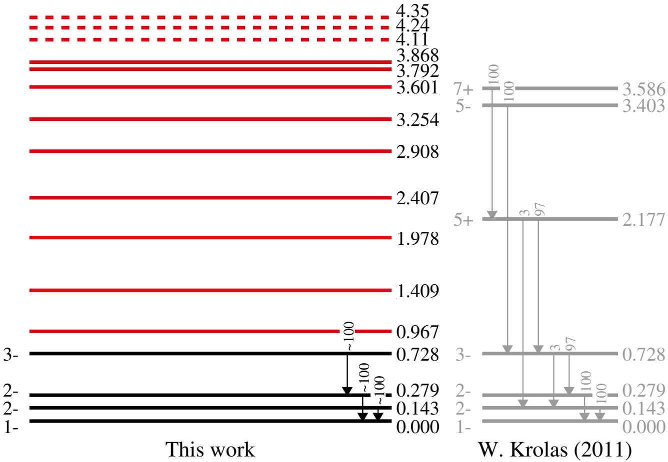
- Determine E_x to keV precision
- Isolation of unresolved states
- Clear unbound strength!


100
100
7+
3.586
5-
3.403
5+
2.177
3
97
3-
0.728
~100
3
97
2-
0.279
~100
~100
100
100
2-
0.143
1-
0.000
This work
W. Krolas (2011)


4.35
4.24
4.11
3.868
3.792
3.601
3.254
2.908
2.407
1.978
1.409
0.967
3- 0.728
2- 0.279
2- 0.143
1- 0.000
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~100
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7+ 3.586
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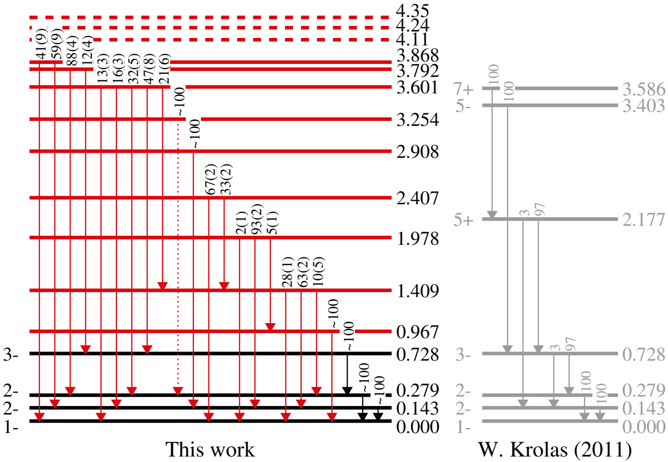
4.35
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2.908
2.407
1.978
1.409
0.967
0.728
0.279
0.143
0.000
3-
2-
2-
1-
41(9)
59(9)
88(4)
12(4)
13(3)
16(3)
32(5)
47(8)
21(6)
~100
~100
67(2)
33(2)
2(1)
93(2)
5(1)
28(1)
63(2)
10(5)
~100
~100
~100
~100
This work
7+
5-
5+
3-
2-
2-
1-
3.586
3.403
2.177
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0.279
0.143
0.000
100
100
3
97
3
97
100
100
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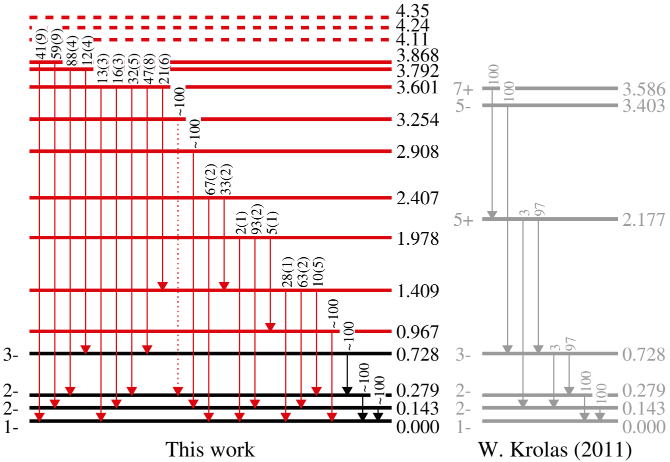
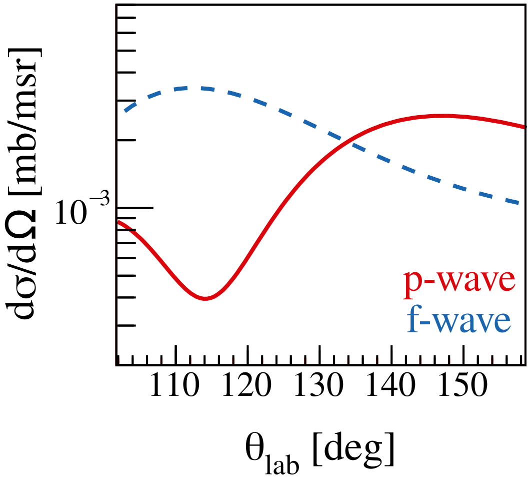
Spins and structure?



Angular Distributions

- Theoretical DCS from TWOFNR
  - Johns.-Tandy & Kon.-Delar.



Angular Distributions

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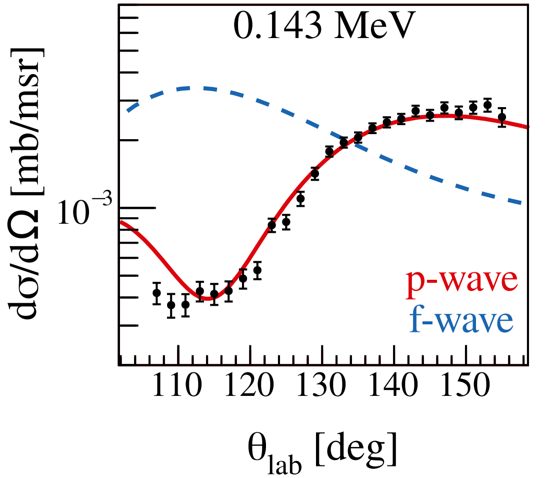
- Unambiguous **p-wave** or **f-wave**
  - Angular resolution of GRIT
  - Efficiency from realistic simul.



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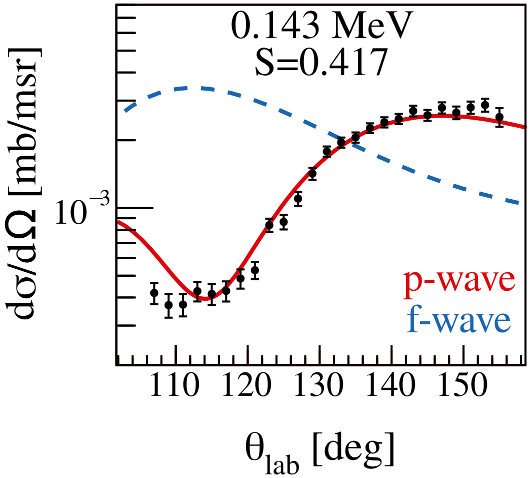
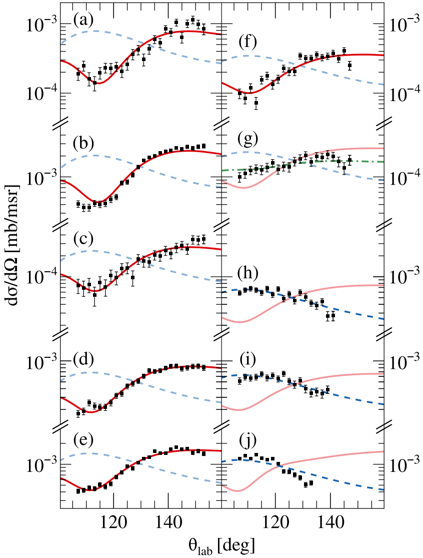
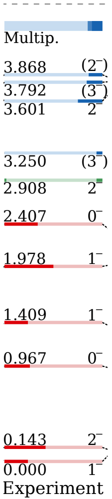
- Unambiguous **p-wave** or **f-wave**
  - Angular resolution of GRIT
  - Efficiency from realistic simul.
- Scaling → spectroscopic factor!

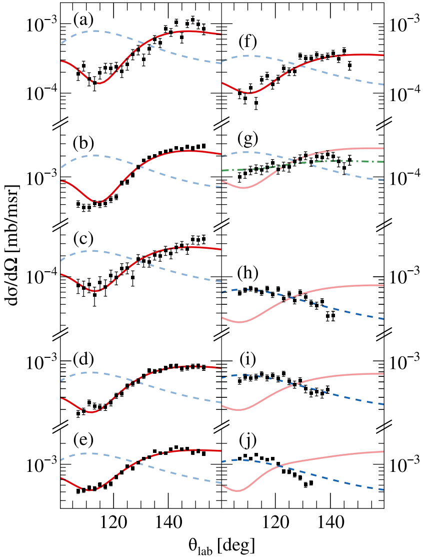




^{48}K Exp. Results

- Nine novel states "complete"





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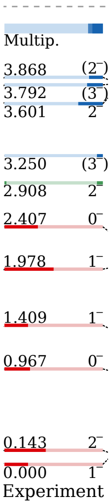

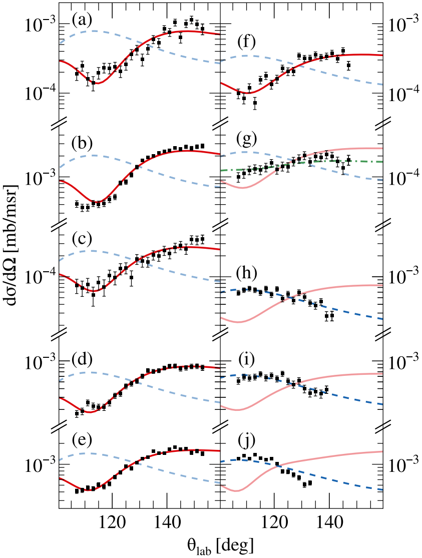

^{48}K Exp. Results

- Nine novel states "complete"
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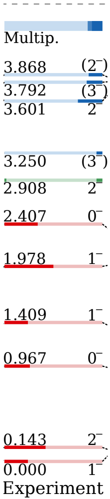
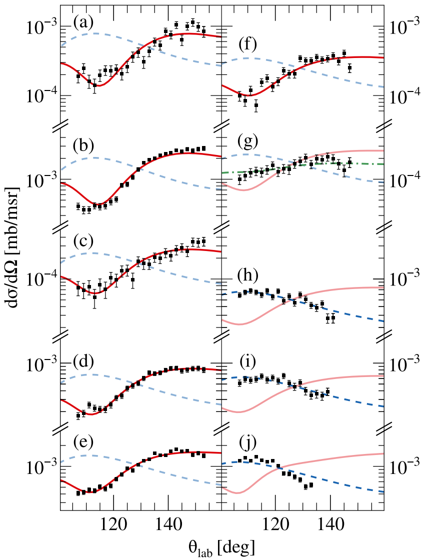
- High-quality diff. cross sec.





^{48}K Exp. Results

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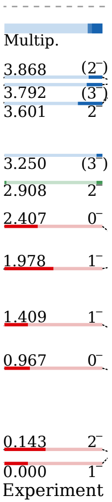
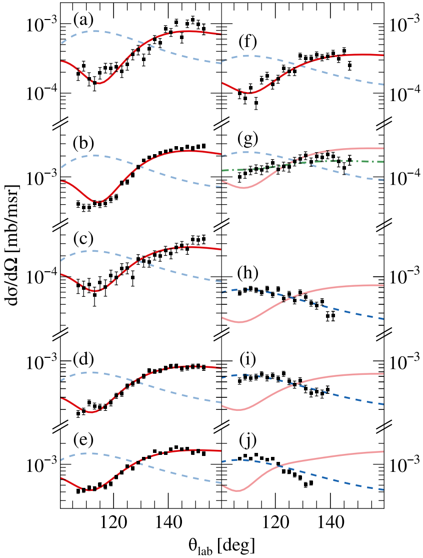
- High-quality diff. cross sec.
- Distinct regions of p-/f-wave





^{48}K Exp. Results

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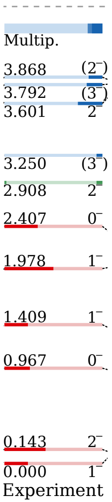
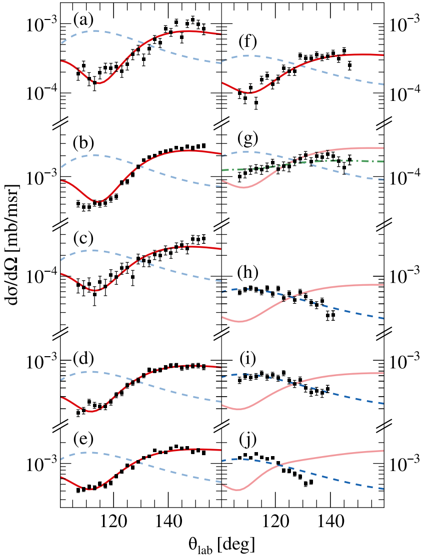
- + high-E bound (3 states)
- High-quality diff. cross sec.
- Distinct regions of p-/f-wave
- One mixed state in between





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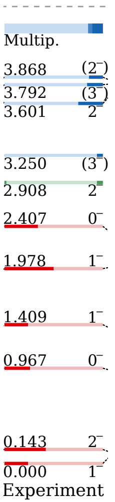
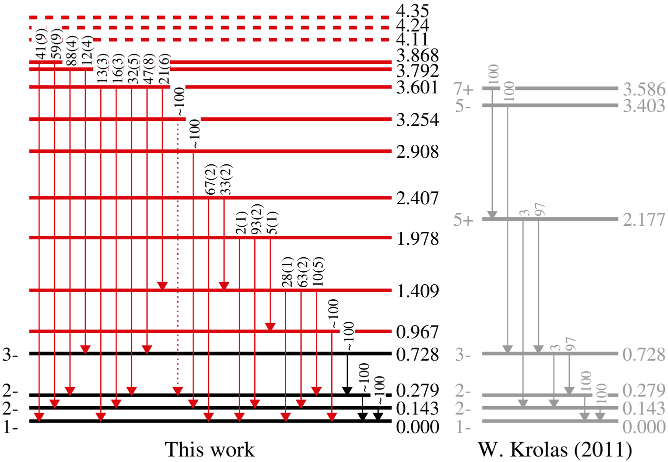
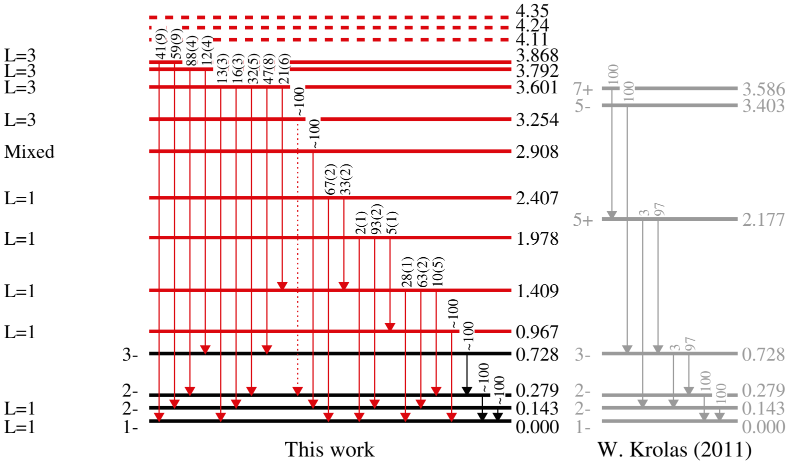
- One mixed state in between
- Adding this to the picture...



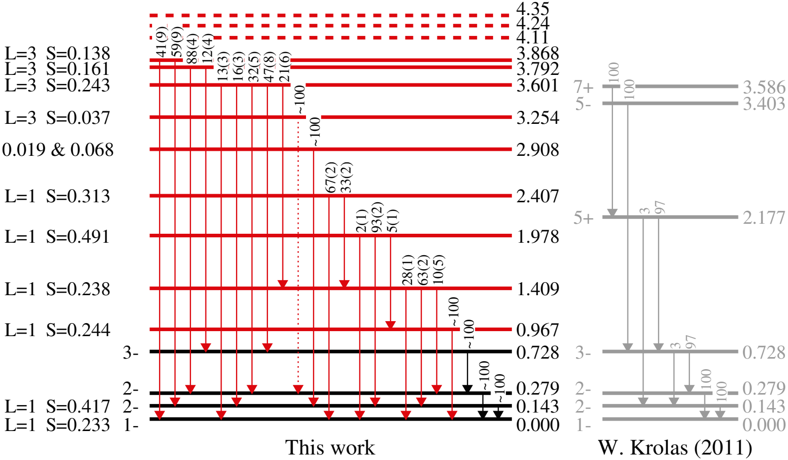
γ-ray transitions



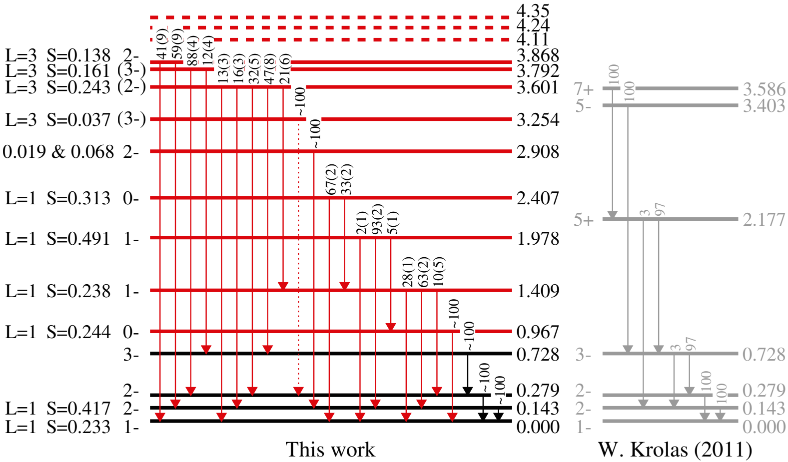
γ-ray transitions + ℓ-wave



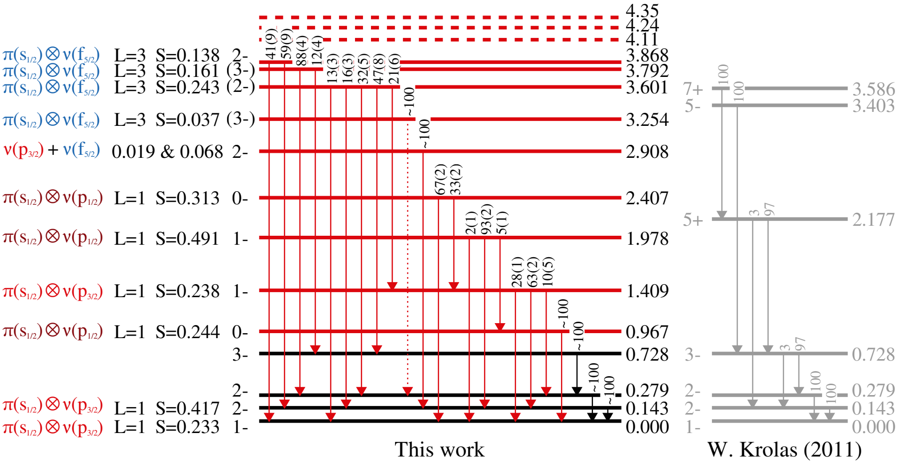
γ-ray transitions + ℓ-wave + spectroscopic factors

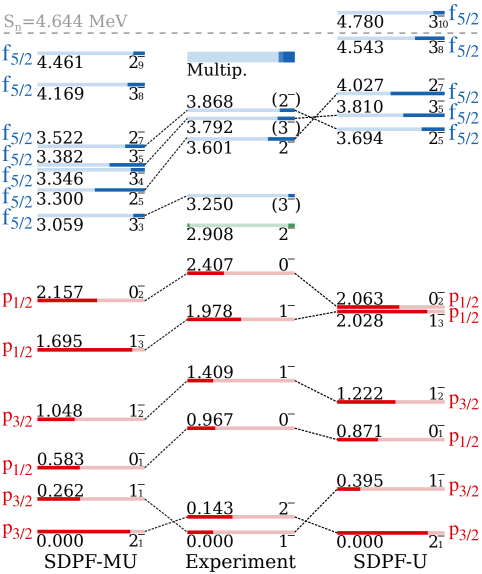


γ-ray transitions + ℓ-wave + spectroscopic factors = state spin (J^{π})

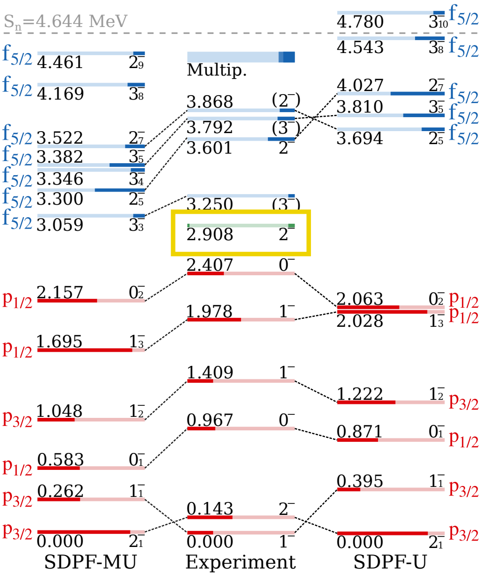


γ-ray transitions + ℓ-wave + spectroscopic factors = state spin (J^π) + structure



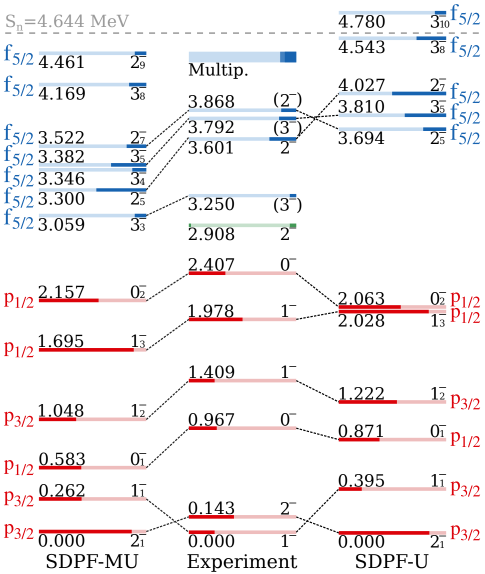


Observations



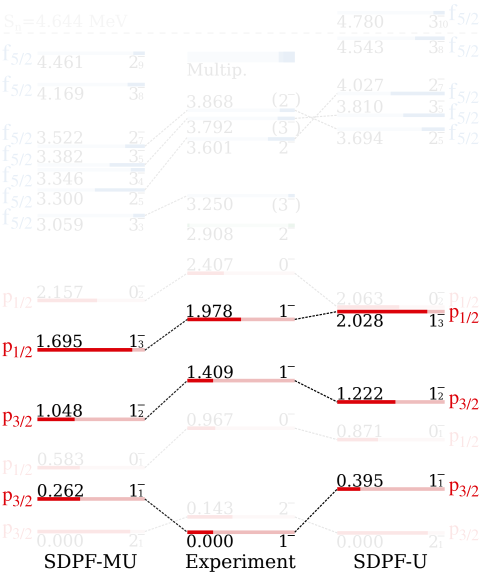
Observations

- Neither SM accounts for mixed state
  - Challenge for shell model theorists



Observations

- Neither SM accounts for mixed state
  - Challenge for shell model theorists
- Spectroscopic factors are **small**
  - ^{47}K(d,t): no unexpected population
  - Suspect proton config. mixing



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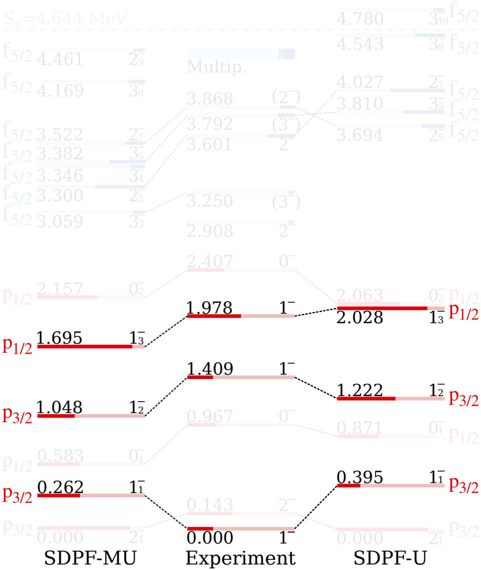
- Failure to predict known 1^- g.s.
  - First observation of other 1^- states
  - Specific matrix elements:

$$\langle p_{3/2}s_{1/2}|V_{int}|p_{3/2}d_{3/2}\rangle_{J=2,T=0}$$
$$\langle p_{3/2}s_{1/2}|V_{int}|p_{3/2}s_{1/2}\rangle_{J=1,T=0}$$



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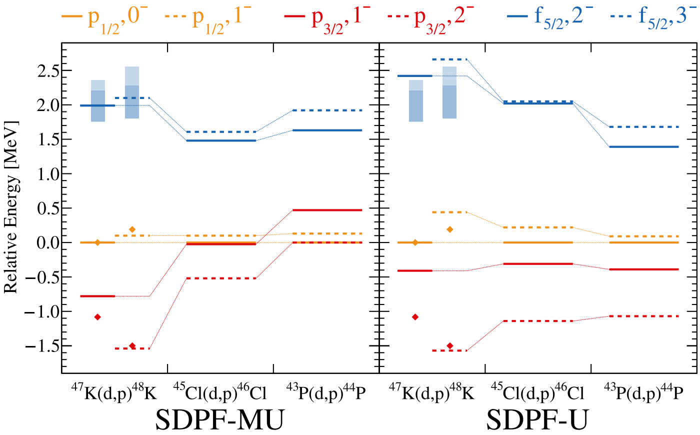
    $\langle p_{3/2}s_{1/2}|V_{int}|p_{3/2}s_{1/2}\rangle_{J=1,T=0}$
  - Implications down $N = 28$ chain...

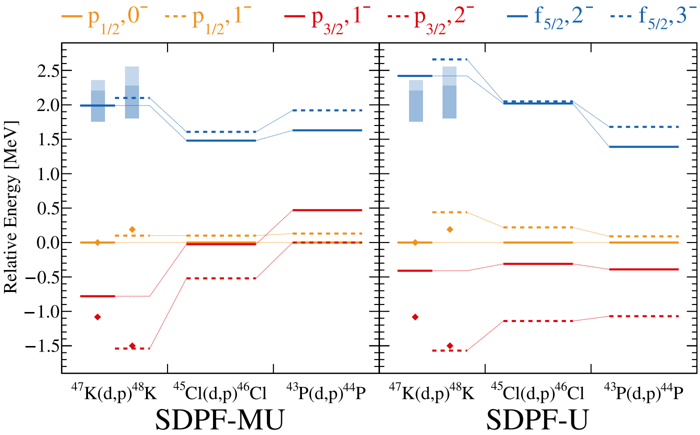
Extrapolation

- SF-weight. energy of ν, J^{π}



Extrapolation

- SF-weight. energy of ν, J^{π}
- Shell models diverge!



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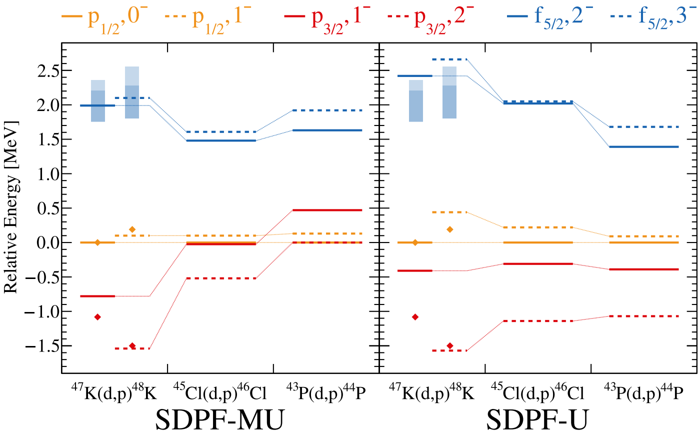

Extrapolation

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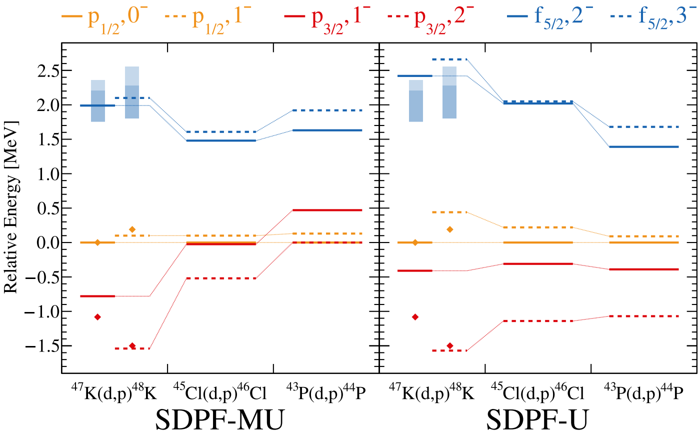

- SF-v
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- Our i
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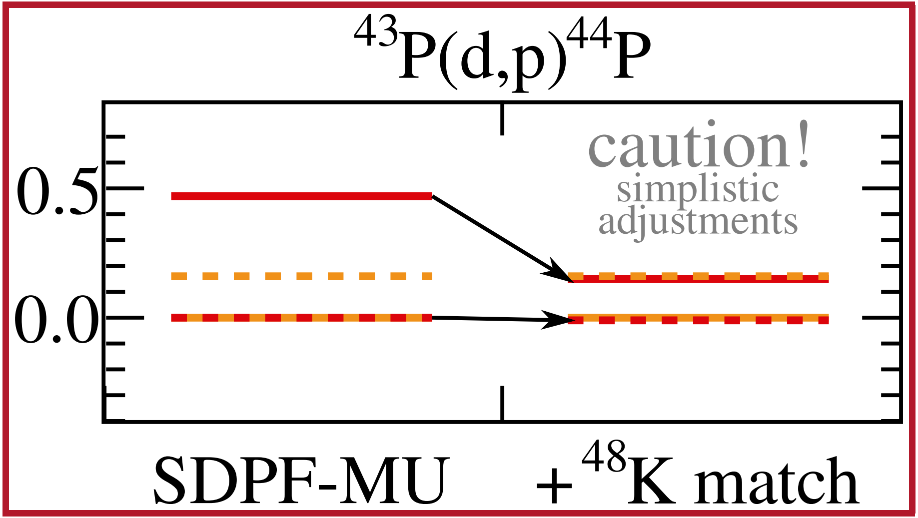

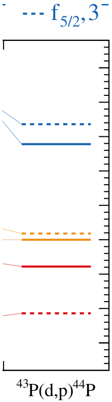

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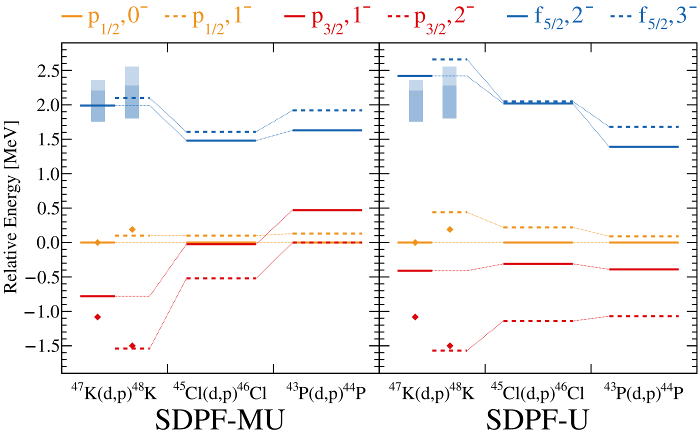

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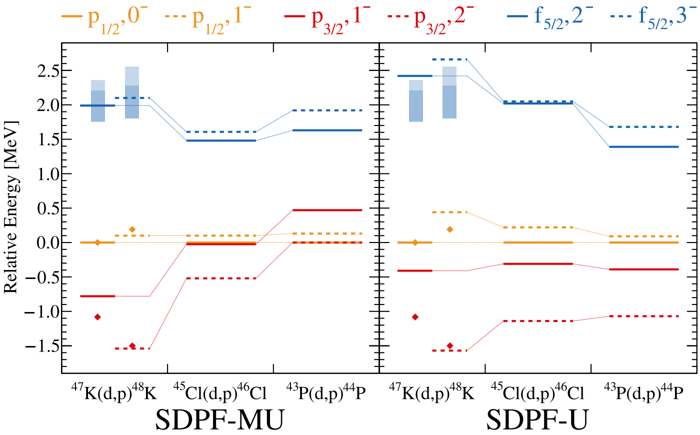
  - Increased collectivity?



Extrapolation

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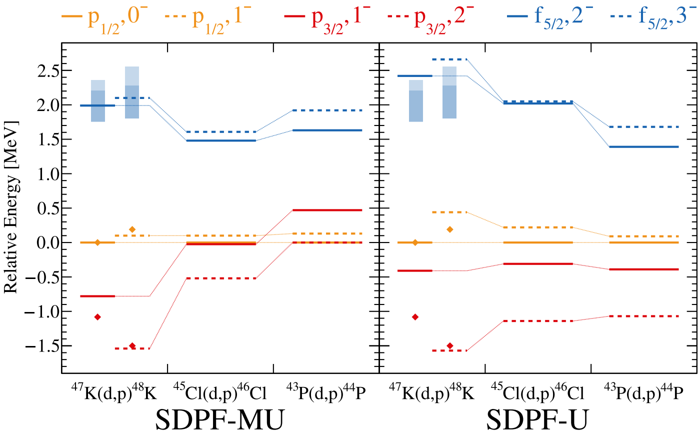
- Next: ^{45}Cl(d,p)? ^{43}P(d,p)?



Summary

- **First experimental measurement** of exotic $\pi s_{1/2}^{-1} \otimes \nu fp$ interaction
- **^{47}K(d,p)** & ^{47}K(d,t) using MUGAST-AGATA-VAMOS@GANIL
- Range of ***p*-wave and *f*-wave states identified**, with J^{π} & S.F.
- Comparison with shell model reveals **key markers**:
  - Relative energies of 1^{-} states in ^{48}K $\rightarrow$ **increased degeneracy** in ^{44}P?
  - Neither accounts for mixed state $\rightarrow$ **anchor for $\nu f_{5/2}$**?
  - Small spectroscopic factor tied to **proton mixing?**
- Next step down odd-Z, $N = 28 \rightarrow$ **^{45}Cl(d,p)?**

^{47}K(d,p): Phys. Rev. Lett. **134**, 162504 (2025)

^{47}K(d,t): Manuscript in preparation

Thank you for your attention!

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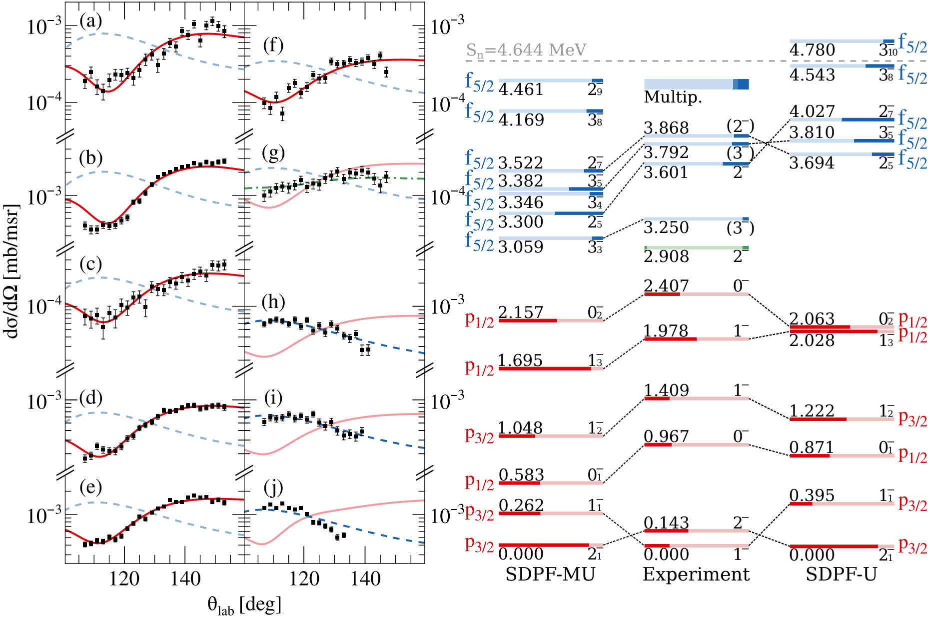
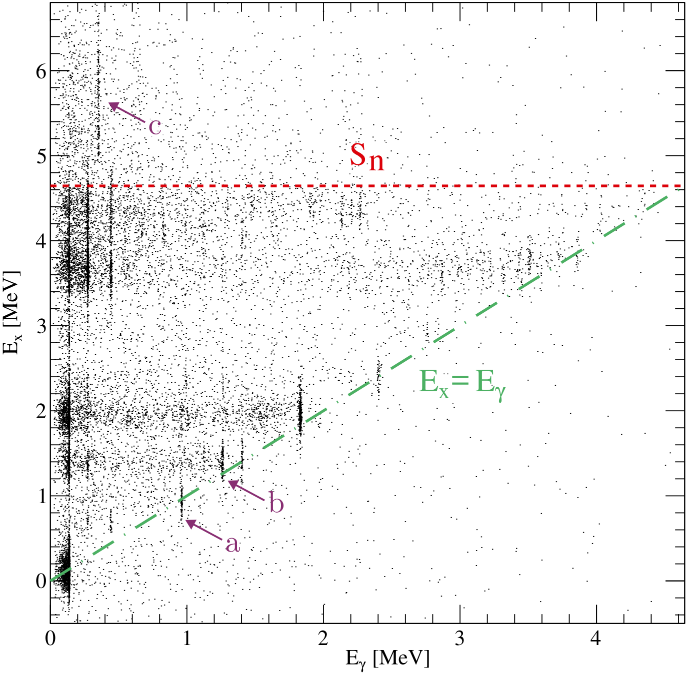
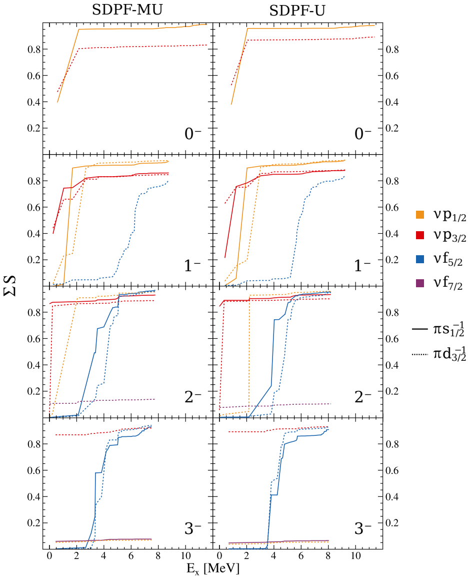
BACKUP SLIDES



(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
dσ/dΩ [mb/msr]
θlab [deg]
120
140
Sn=4.644 MeV
Multip.
SDPF-MU
Experiment
SDPF-U
f5/2
p1/2
p3/2
4.461
4.169
3.522
3.382
3.346
3.300
3.059
2.157
1.695
1.048
0.583
0.262
0.000
3.868 (2−)
3.792 (3−)
3.601 2−
3.250 (3−)
2.908 2−
2.407 0−
1.978 1−
1.409 1−
0.967 0−
0.143 2−
0.000 1−
4.780
4.543
4.027
3.810
3.694
2.063
2.028
1.222
0.871
0.395
0.000



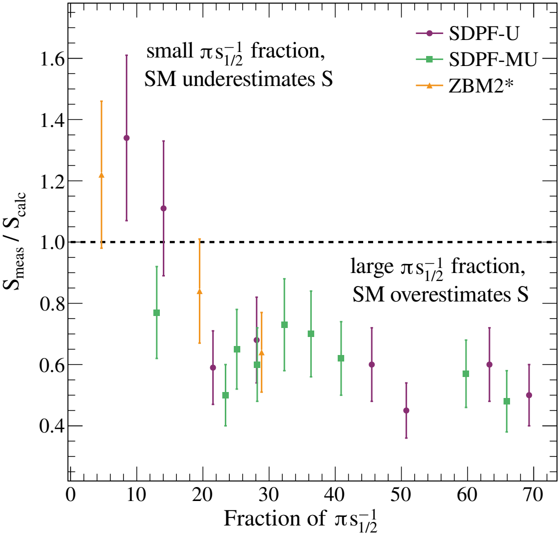
S_n
E_x = E_γ
a
b
c
E_x [MeV]
E_γ [MeV]
0
1
2
3
4
5
6



SDPF-MU
SDPF-U
0⁻
1⁻
2⁻
3⁻
ΣS
E_x [MeV]
$\nu p_{1/2}$
$\nu p_{3/2}$
$\nu f_{5/2}$
$\nu f_{7/2}$
$\pi s_{1/2}^{-1}$
$\pi d_{3/2}^{-1}$

Shell model 'accuracy'

- Taking only simple states...
- An (unexpected) relationship?
- Poor understanding of π mixing?



$$\frac{d\sigma}{d\Omega}\left[\frac{mb}{msr}\right] = \frac{N_{count}}{\Delta\Omega}\left[\frac{1}{msr}\right] * B\ [mb]$$

$$\frac{d\sigma}{d\Omega}\left[\frac{mb}{msr}\right] = \frac{N_{count}}{\Delta\Omega}\left[\frac{1}{msr}\right] * \frac{1000A * 10^{27}}{N_{beam}N_{A}T}\ [mb]$$

Analytical

- Same normalisation factor for (d,p), (d,t) and (d,d)

$$\frac{d\sigma}{d\Omega}\left[\frac{mb}{msr}\right] = \frac{N_{count}}{\Delta\Omega}\left[\frac{1}{msr}\right] * B\ [mb]$$

$$\frac{d\sigma}{d\Omega}\left[\frac{mb}{msr}\right] = \frac{N_{count}}{\Delta\Omega}\left[\frac{1}{msr}\right] * \frac{1000A * 10^{27}}{N_{beam} N_A T}\ [mb]$$

Analytical

- Same normalisation factor for (d,p), (d,t) and (d,d)
- Includes beam intensity and target thickness.

$$\frac{d\sigma}{d\Omega}\left[\frac{mb}{msr}\right] = \frac{N_{count}}{\Delta\Omega}\left[\frac{1}{msr}\right] * B\ [mb]$$

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Analytical

- Same normalisation factor for (d,p), (d,t) and (d,d)
- Includes beam intensity and target thickness.
- N_{beam} monitored with CATS.

$$\frac{d\sigma}{d\Omega}\left[\frac{mb}{msr}\right] = \frac{N_{count}}{\Delta\Omega}\left[\frac{1}{msr}\right] * B\ [mb]$$

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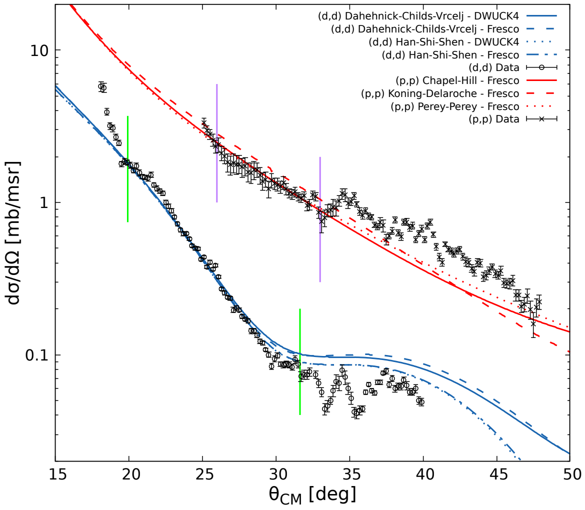
- N_{beam} monitored with CATS.
- Therefore can find B, extract T:



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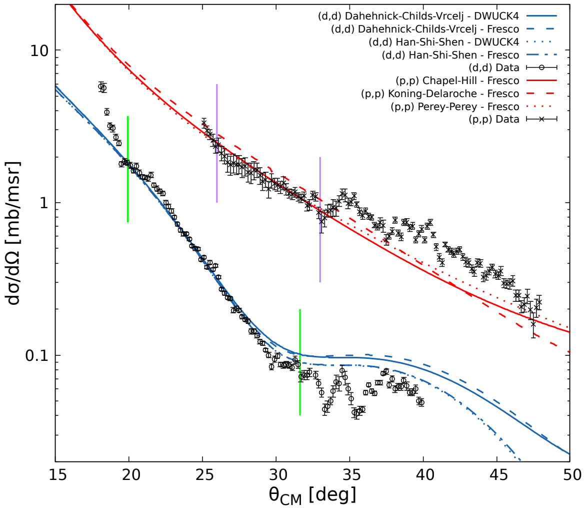
  - 0.31(2) mg/cm^2 CD_2
  - 0.02(1) mg/cm^2 CH_2



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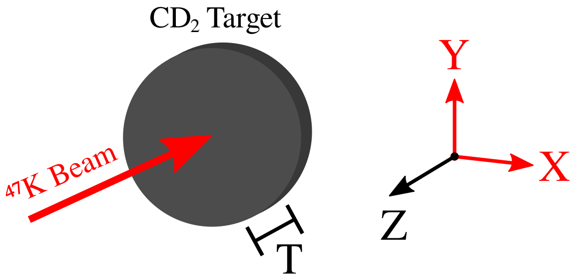
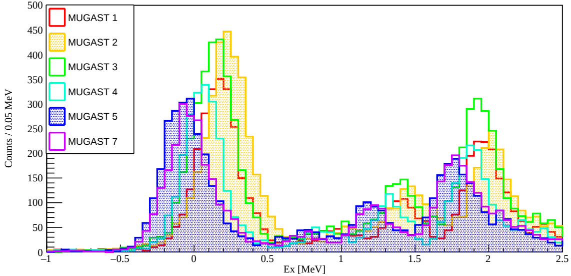
- Use range as limits on numerical method...



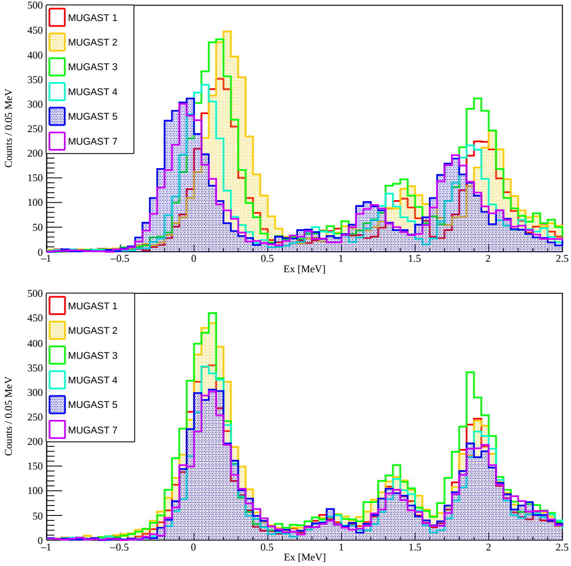
Numerical

- Vary X_{beam}, Y_{beam}, Z_{target} and T_{target} during kinematic reconstruction of (d,p) data.



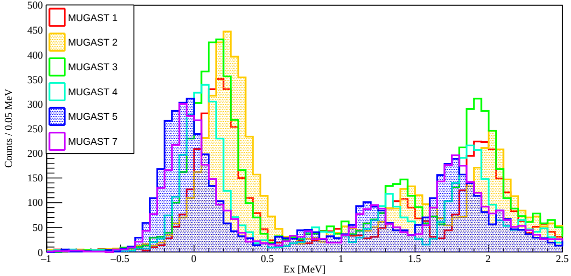
Numerical

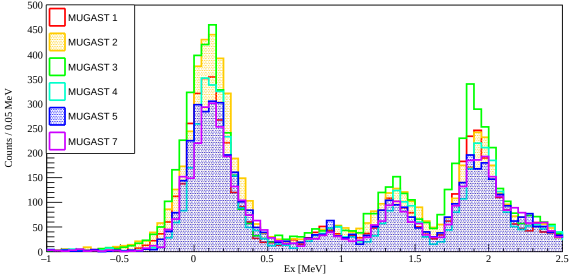
- Vary X_{beam}, Y_{beam}, Z_{target} and T_{target} during kinematic reconstruction of (d,p) data.
- Affects the accuracy of energy and peak width of excitation peaks.



Numerical

- Vary X_{beam}, Y_{beam}, Z_{target} and T_{target} during kinematic reconstruction of (d,p) data.
- Affects the accuracy of energy and peak width of excitation peaks.
- Minimisation, with restricted T from analytical method.





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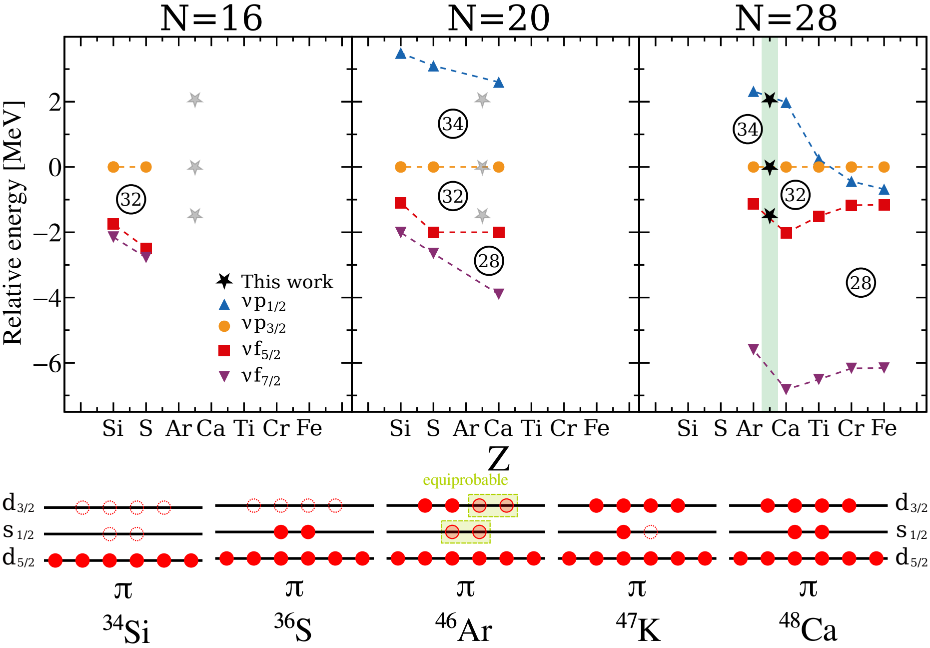
- Affects the accuracy of energy and peak width of excitation peaks.
- Minimisation, with restricted T from analytical method.

X = -4.15 mm Y = 0.47 mm
Z = +0.22 mm T = 3.25μm



N=16
N=20
N=28
Relative energy [MeV]
2
0
−2
−4
−6
32
34
28
This work
νp1/2
νp3/2
νf5/2
νf7/2
Si S Ar Ca Ti Cr Fe
Z
equiprobable
d3/2
s1/2
d5/2
π
34Si
36S
46Ar
47K
48Ca

Ex (EXP)	Number	Core proton s1/2				Core proton hole d3/2		
	¿							
		WC p3/2	SM p3/2	EXP p3/2		WC p3/2	SM p3/2	EXP p3/2
0.000	1	0	0.40	0.24		1	0.44	*
1.409	2	1	0.35	0.24		0	0.22	*
		WC p1/2	SM p1/2	EXP p1/2		WC p1/2	SM p1/2	EXP p1/2
1.978	3	1	0.88	0.50		0	0.02	*
-	4	0	0.01	-		1	0.65	*

We can see that the experimental spectroscopic factors are **low** with respect to the shell model predictions, comparing the two columns highlighted in blue. A simple way to resolve this problem is to shift the excess in the spectroscopic factor for the shell model across to the yellow column so that it becomes 0.60, 0.33 and 0.40. The ground state is thus closer to the pure configuration with a proton(d3/2) core than the shell model predicts, whereas the second state is less purely a proton(s1/2) core than predicted.

The mixing that involves the two lowest energy configurations is certainly not a simple two-level mixing. A better approximation is to consider the four lowest levels as being a mixture of a neutron in either p3/2 or p1/2 coupled to a proton hole in either d3/2 or s1/2. Using the orbital codes of p3, p1, d3 and s1 respectively, the four basis states can then be labelled as p3/d3, p3/s1, p1/s1 and p1/d3. With this basis, the matrices describing the weak coupling states is:

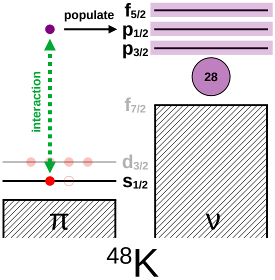
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

and the shell model states and the experimental measurements are[1] :

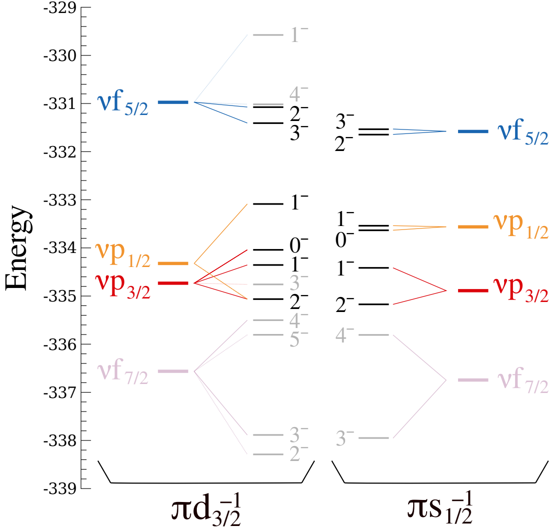
$$\begin{pmatrix} 0.44 & 0.40 & 0.00 & 0.02 \\ 0.22 & 0.35 & 0.01 & 0.21 \\ 0.00 & 0.00 & 0.88 & 0.02 \\ 0.15 & 0.07 & 0.01 & 0.65 \end{pmatrix} \wedge \begin{pmatrix} 0.24 & \text{¿} \\ 0.24 & \text{¿} \\ 0.50 & \text{¿} \end{pmatrix}$$

where it’s only possible experimentally to access the two central columns because these correspond to the proton hole in s1/2 that dominates the ground state of 47K.

Clearly there is plenty of scope for the “missing” strength represented by the experimental numbers to be redistributed across the other configurations.



- $\pi s_{1/2}^{-1}$ and $\pi d_{3/2}^{-1}$ degenerate
- Two $\nu p_{3/2}$ 1^- states close in energy
- States **pushed apart** by mixing
- Wrong spacing implies **proton config. mixing** is poorly estimated!



‘Weak coupling’ model, no mixing