

Probing exotic cross-shell interactions at $N = 28$ with single-neutron transfer on ^{47}K

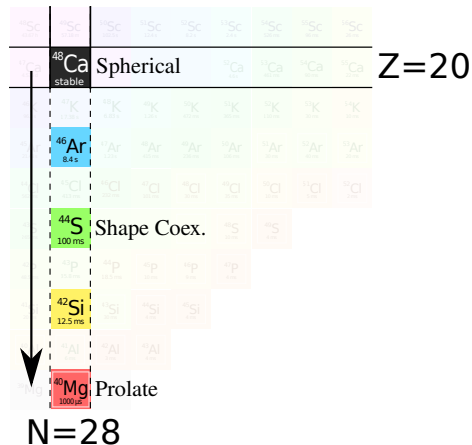
Charlie J. Paxman (GANIL)

29th International Nuclear Physics Conference – 30/05/25 – Daejeon, Korea



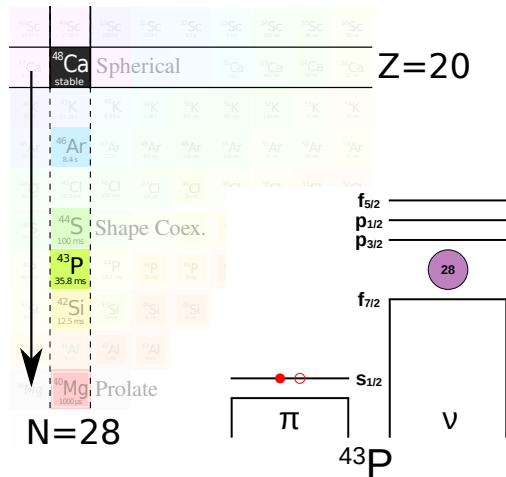
Motivation

- Challenge: $N=28$ "island of inversion"



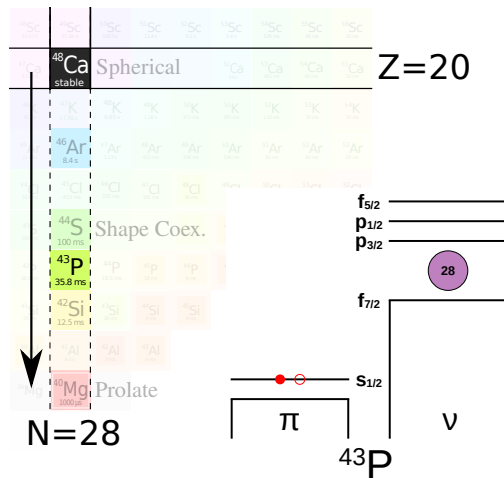
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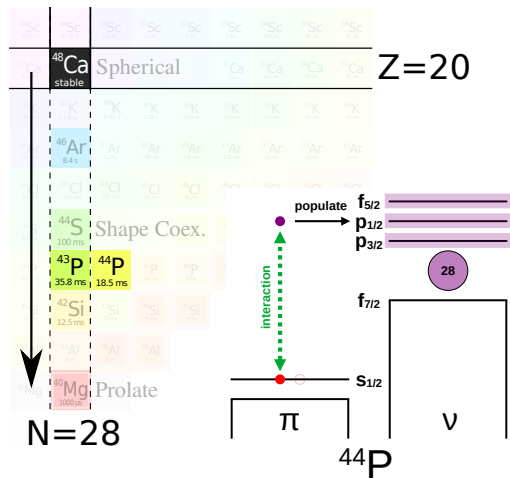
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- Need $\pi(s_{1/2})\nu(p_{3/1}p_{1/2}f_{5/2})$ elements



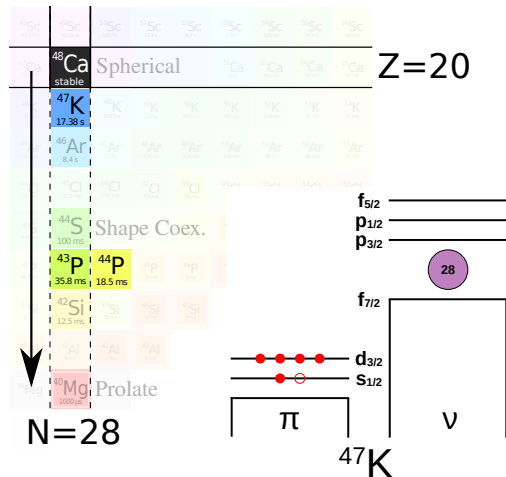
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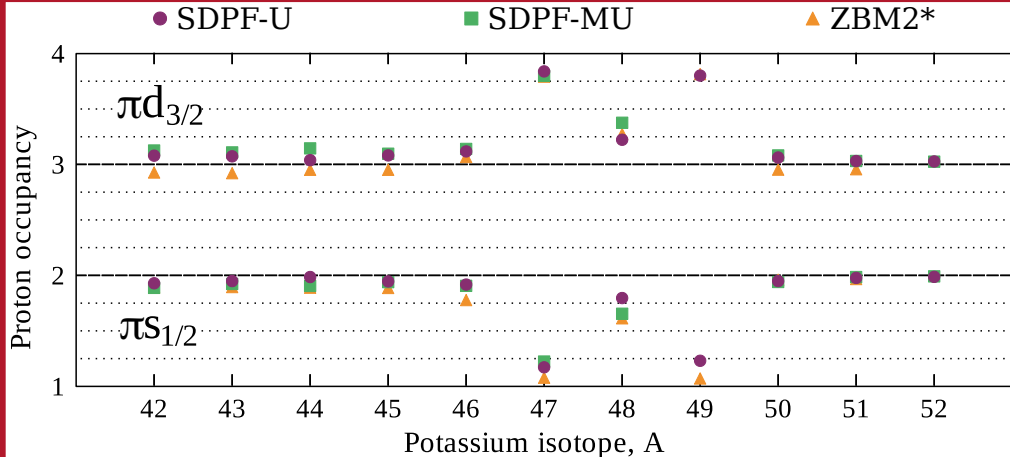
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- In a perfect world, $^{43}\text{P}(\text{d},\text{p})$ transfer



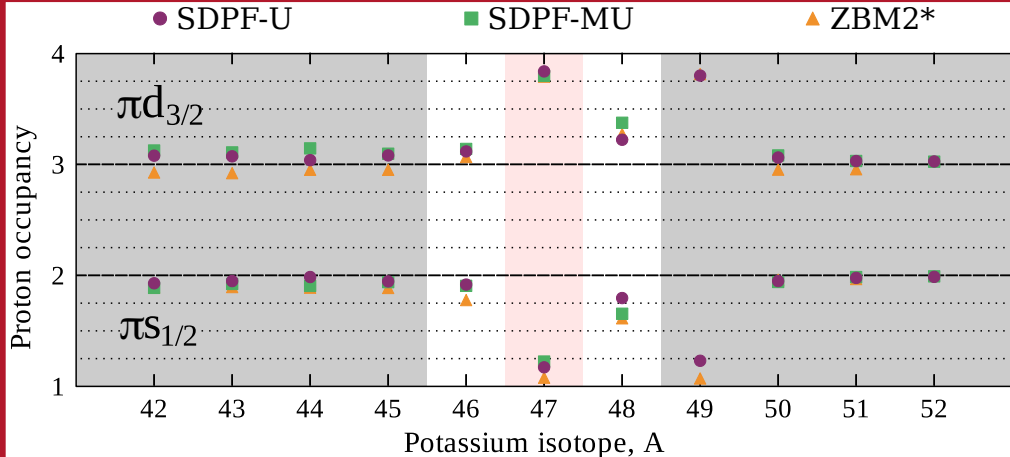
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- Instead, exploit exotic structure of $^{47}\text{K}_{g.s.}$



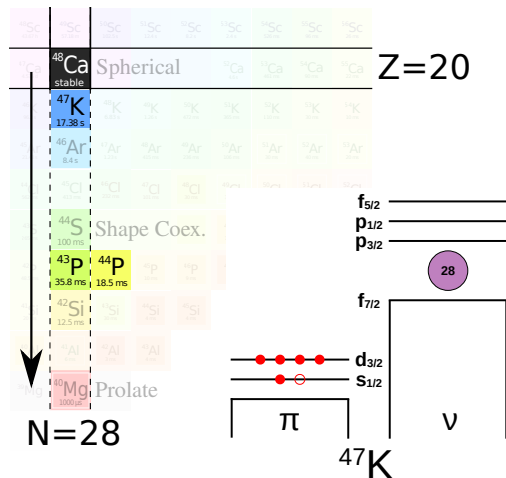


Adapted from J. Papuga et al. Phys. Rev. C 90, 034321 (2014)



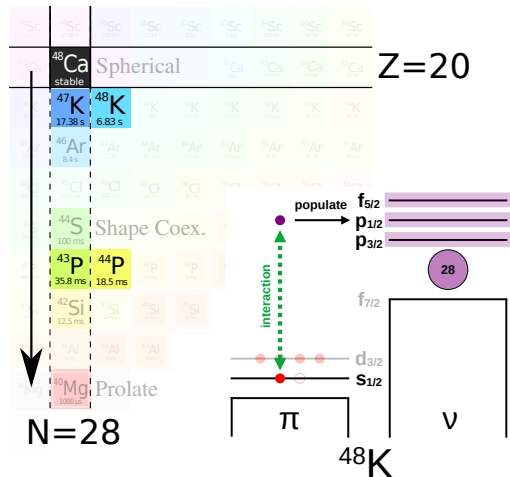
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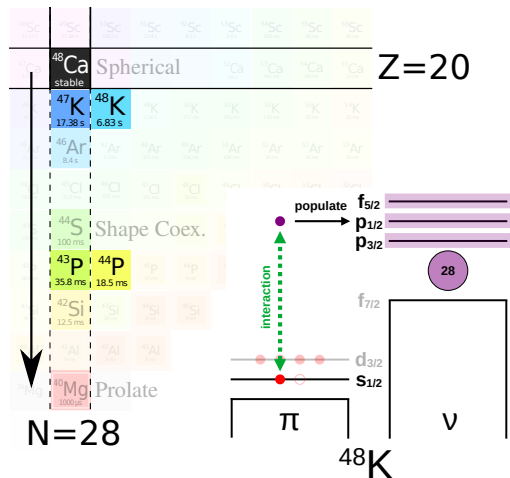
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- Add neutron, probe interesting interactions!



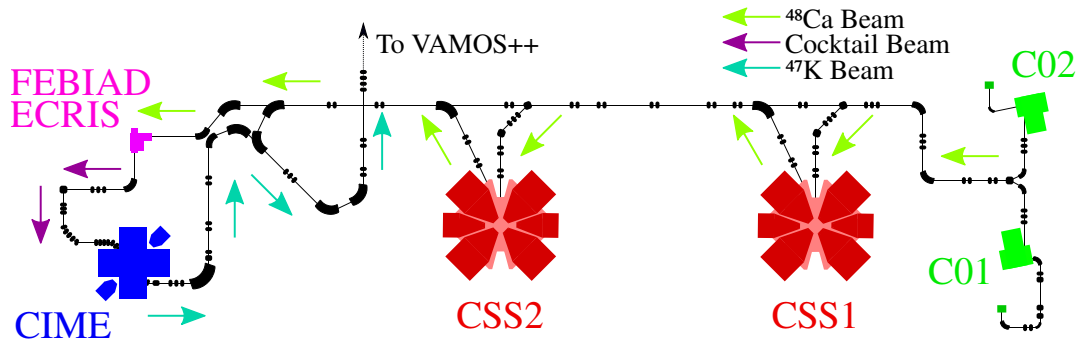
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**First measurement of exotic
 $\pi(s_{1/2}^{-1}) \otimes \nu(f_{5/2}p)$ interactions**



Radioactive Isotope Beam



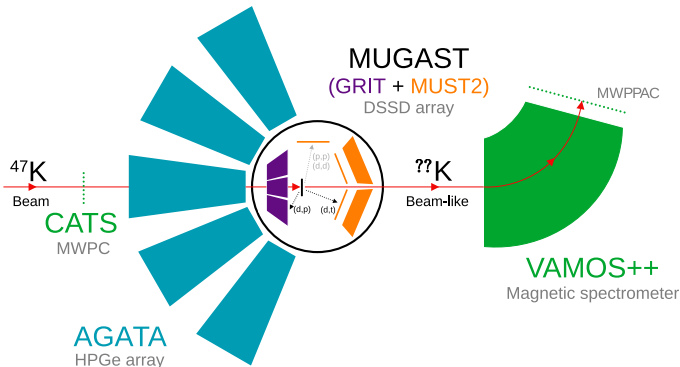
○ ^{47}K RIB @ 7.7 MeV/u.

○ Avg. 5×10^5 pps

○ 10^{-4} mass res. $\rightarrow$ pure beam

Experimental Setup

CATS
Target
VAMOS++
MUGAST
AGATA



Experimental Setup

CATS

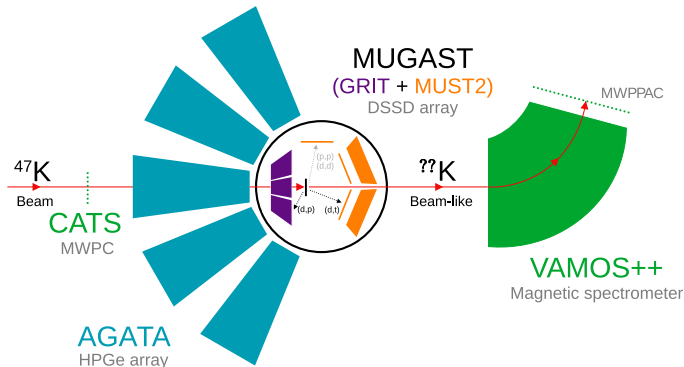
- Beam monitoring
- Timing signal (trigger)

Target

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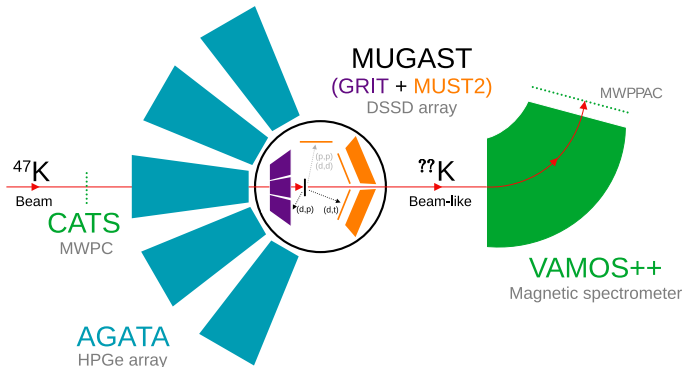
Target

- $0.31(2) \text{ mg/cm}^2 \text{ CD}_2$
- 6% CH_2 contamination

VAMOS++

MUGAST

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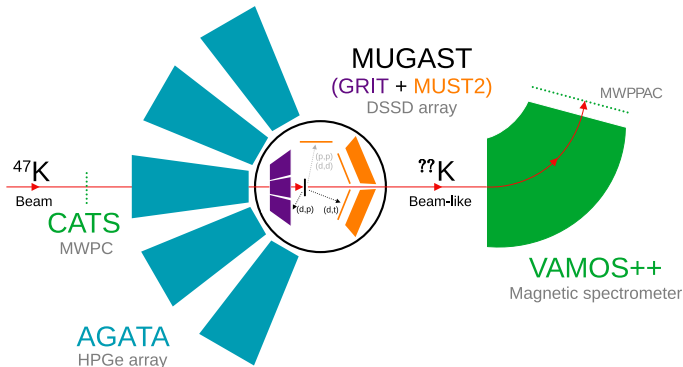
Target

VAMOS++

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

MUGAST

AGATA



Experimental Setup

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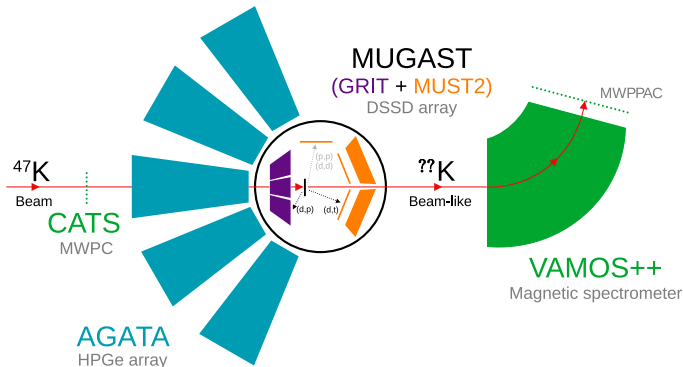
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- Light ejectile detection
- 6 x GRIT trapez. DSSD
- 1 x MUST2 DSSD
- 4 x MUST2 DSSD+CsI
- FWHM = 330 keV in ^{48}K
- FWHM = 420 keV in ^{46}K

AGATA



Experimental Setup

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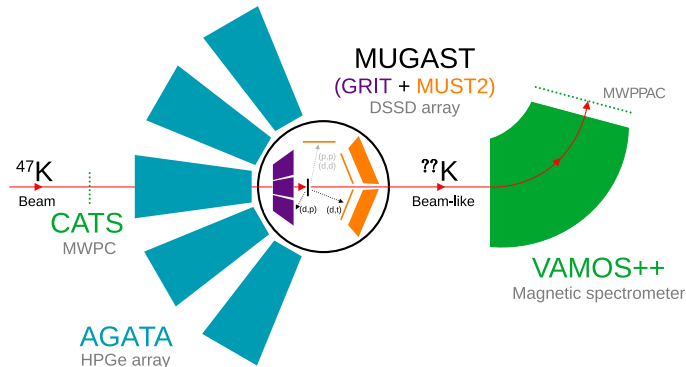
Target

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MUGAST

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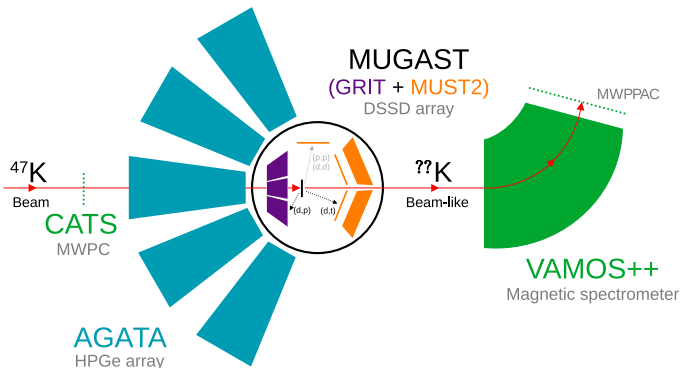
- Prompt γ -ray emissions
- 36 crystals @ 18 cm
- PSA & add-back online, DC with light ejectile
- FWHM = 7 keV @ 1.8 MeV; $\beta = 0.16$

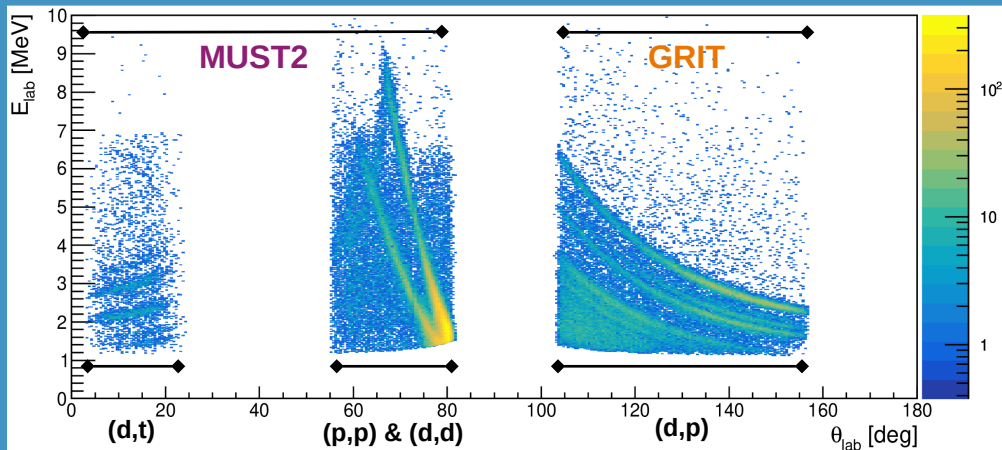


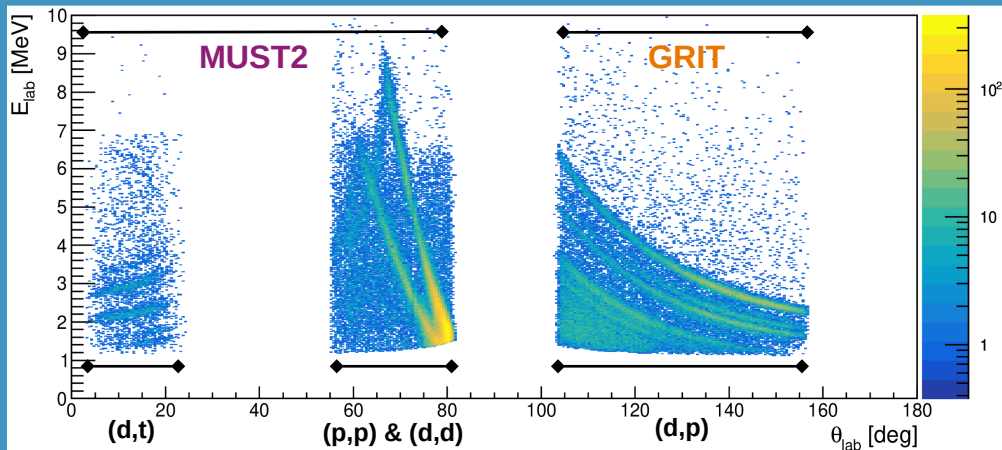
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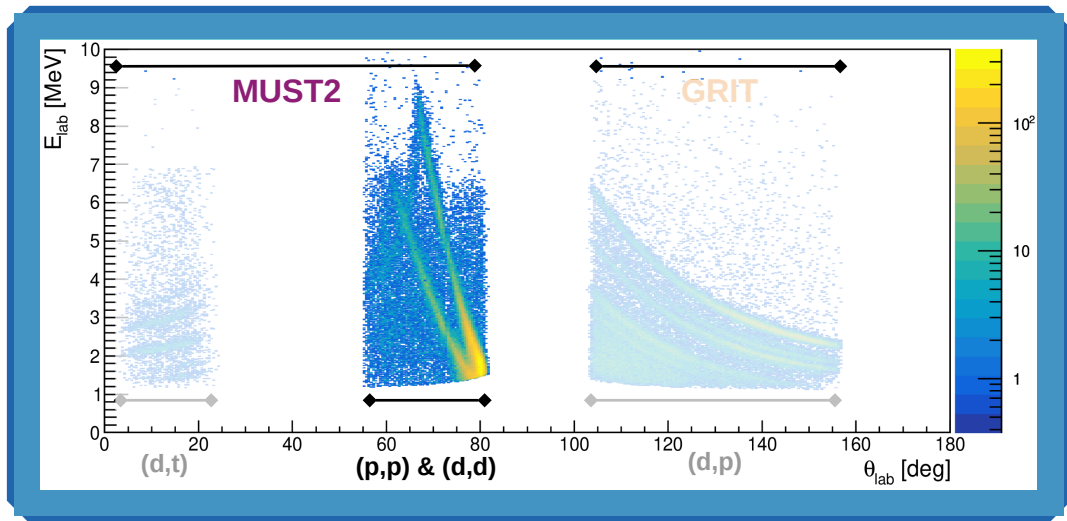
Triple-coincidence critical!



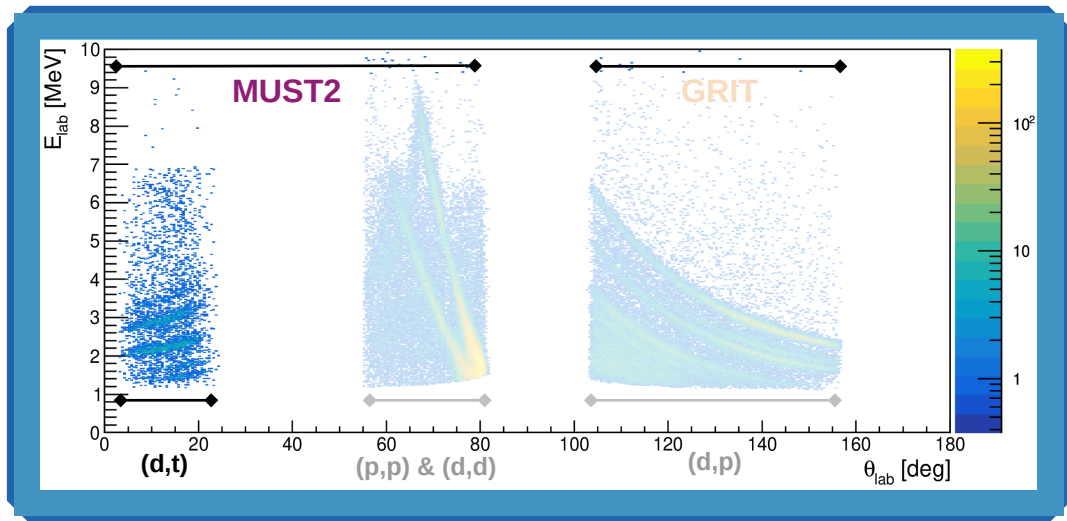




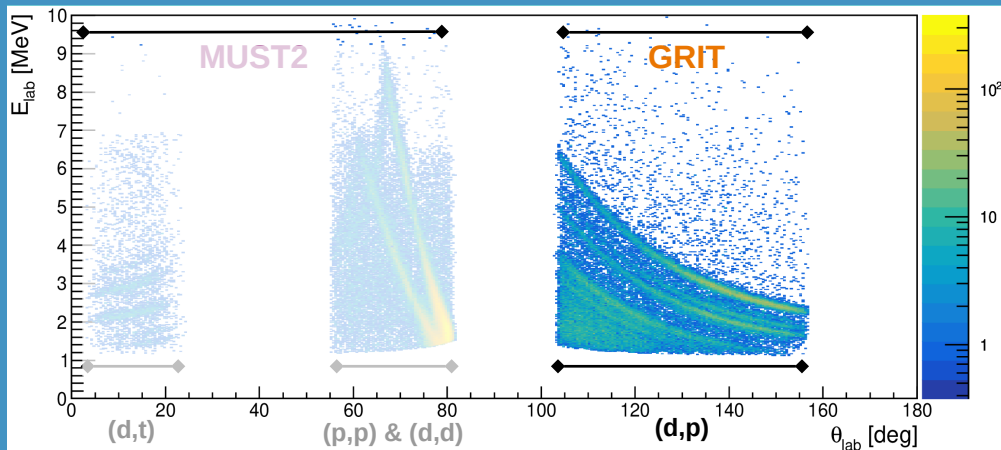
Pure SPIRAL1+ beam & VAMOS++ gating



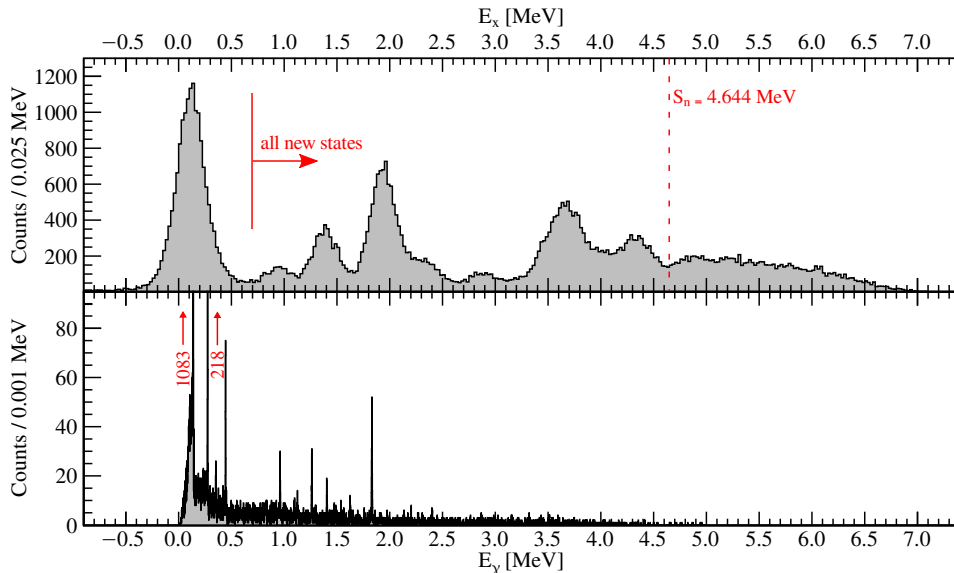
Elastics: Normalisation of beam intensity and target thickness

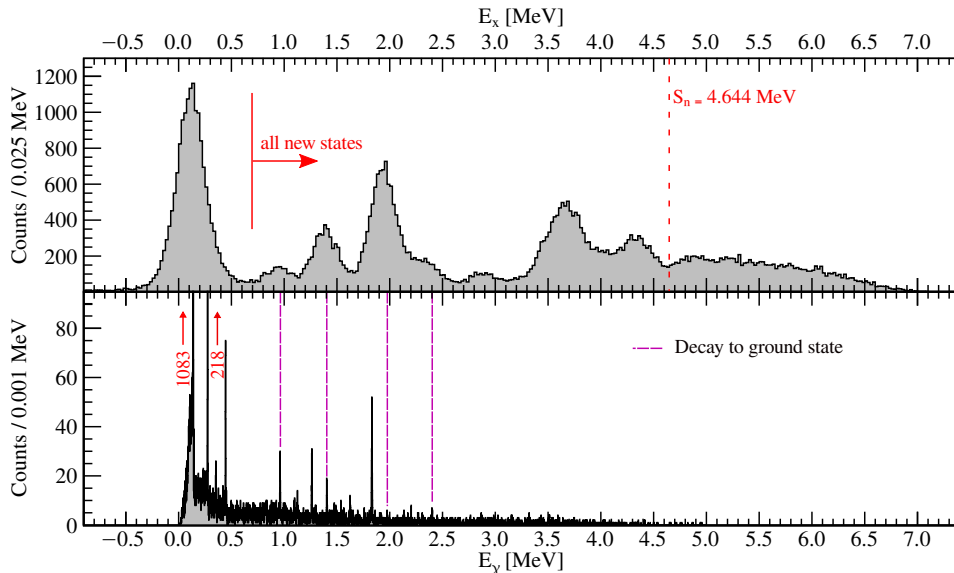


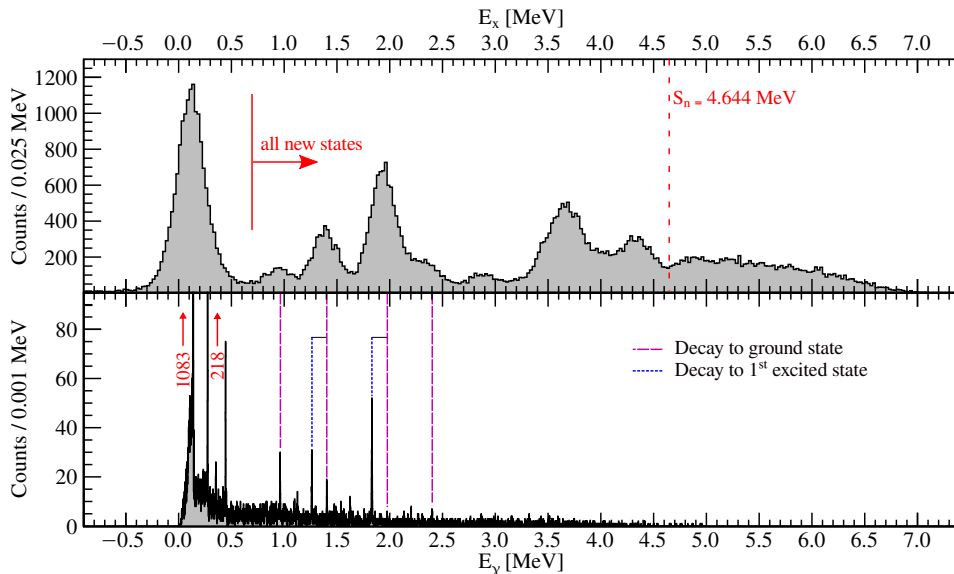
$^{47}\text{K}(\text{d},\text{t})$: Simultaneous data set, neutron orbital occupation

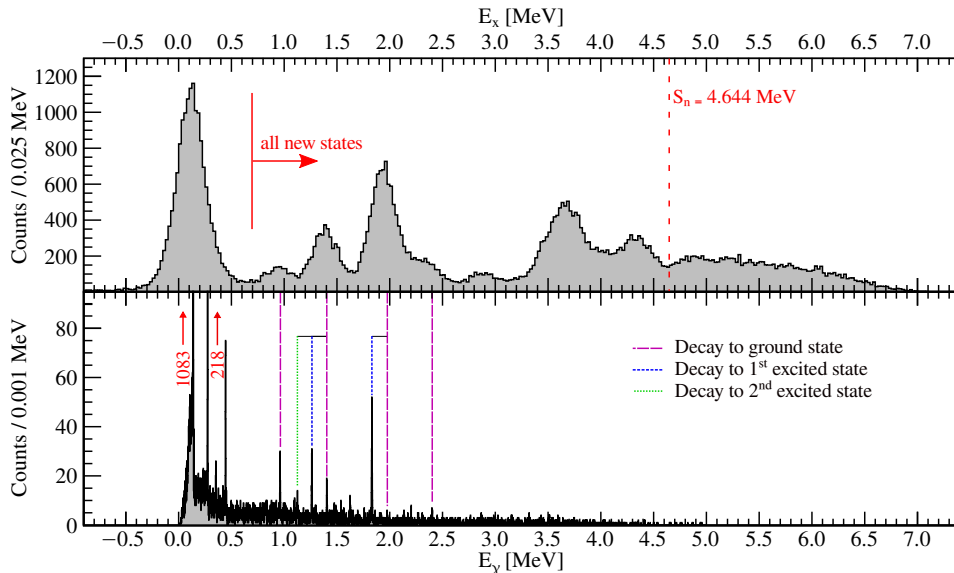


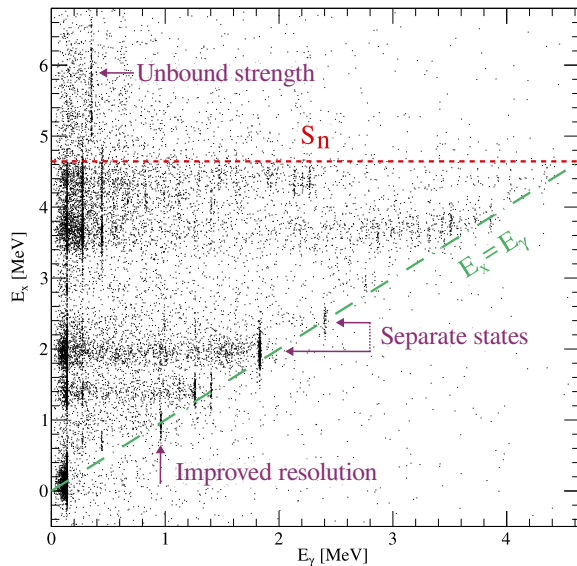
$^{47}\text{K}(d,p)$: Experimental focus, neutron orbital vacancies





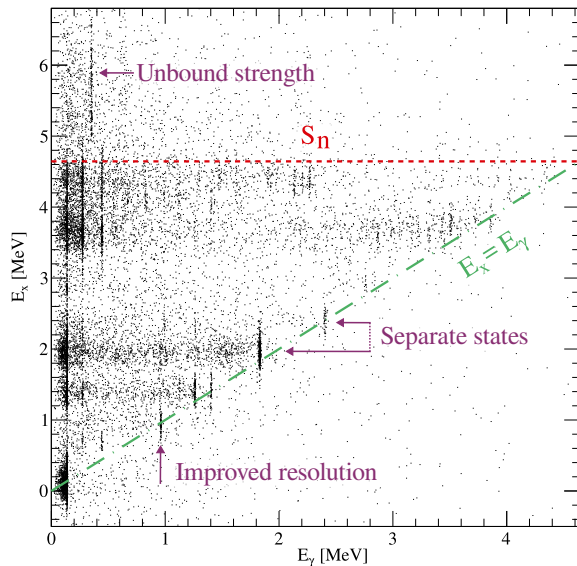






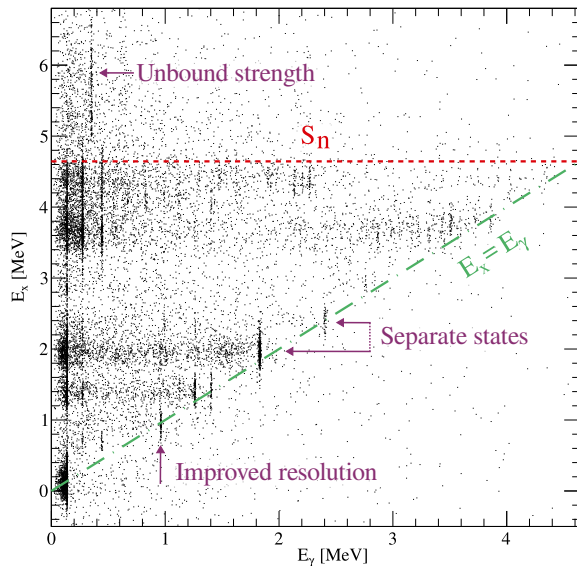
p- γ

- Strength is in 2D analysis

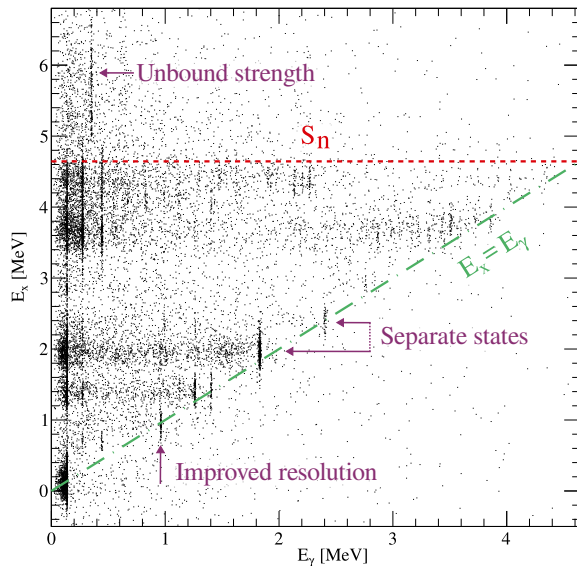


p- γ

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

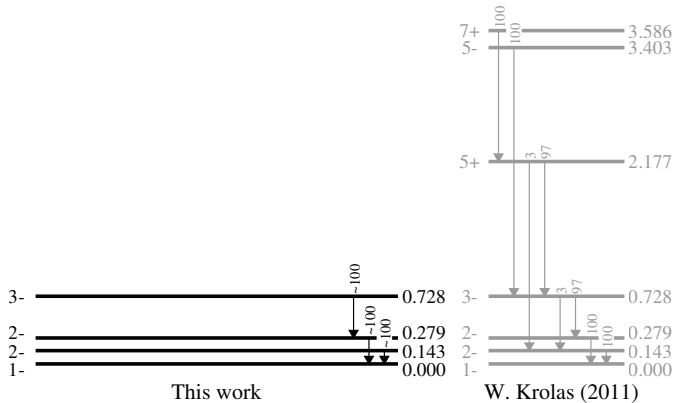
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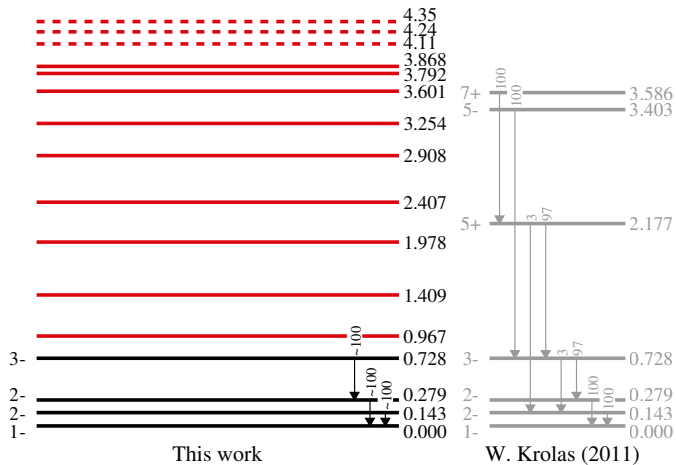
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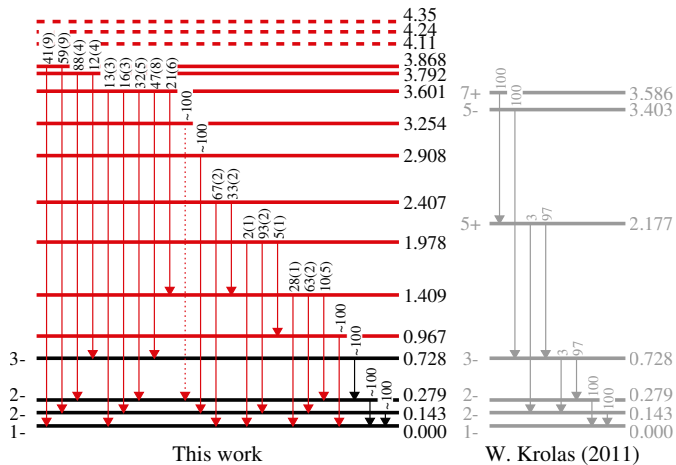


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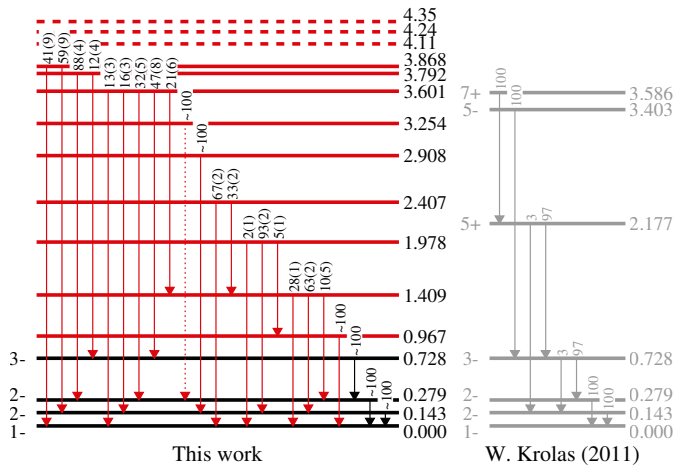
- Strength is in 2D analysis
- Determine E_x to keV precision
- Isolation of unresolved states
- Clear unbound strength!





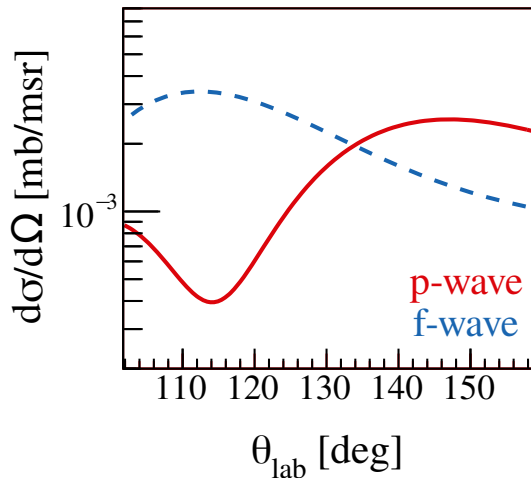


Spins and structure?



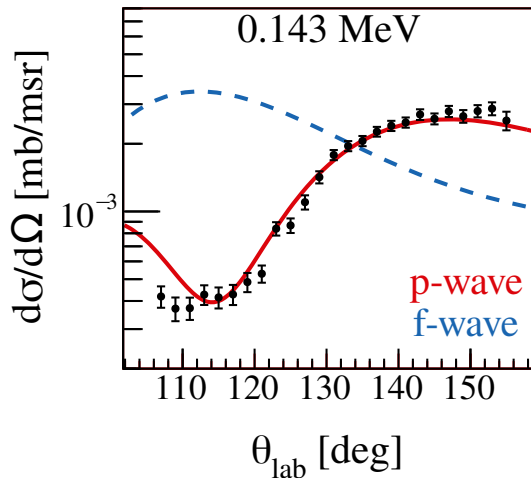
Angular Distributions

- Theoretical DCS from TWOFN R
- Johns.-Tandy & Kon.-Delar.



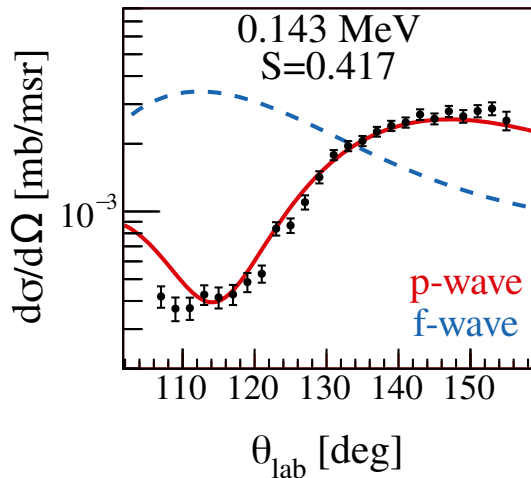
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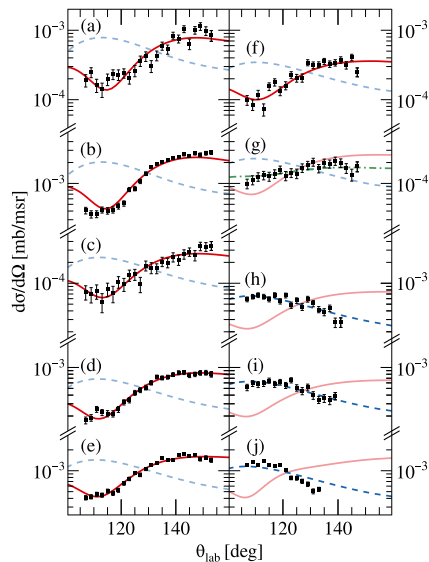
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- Unambiguous **p-wave** or **f-wave**
 - Angular resolution of GRIT
 - Efficiency from realistic simul.



Angular Distributions

- Theoretical DCS from TWOFN R
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- Unambiguous **p-wave** or **f-wave**
 - Angular resolution of GRIT
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- Scaling $\rightarrow$ spectroscopic factor!





^{48}K Exp. Results

- Nine novel states "complete"

Multip. 

3.868 (2⁻)

3.792 (3⁻)

3.601 2⁻

3.250 (3⁻)

2.908 2⁻

2.407 0⁻

1.978 1⁻

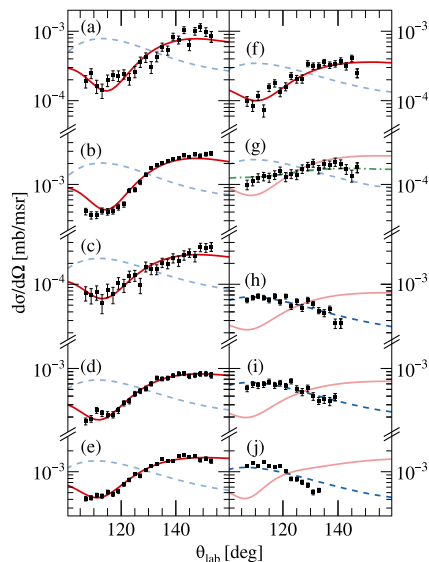
1.409 1⁻

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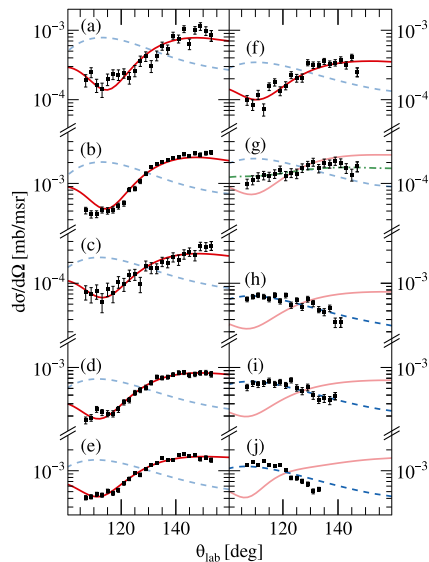
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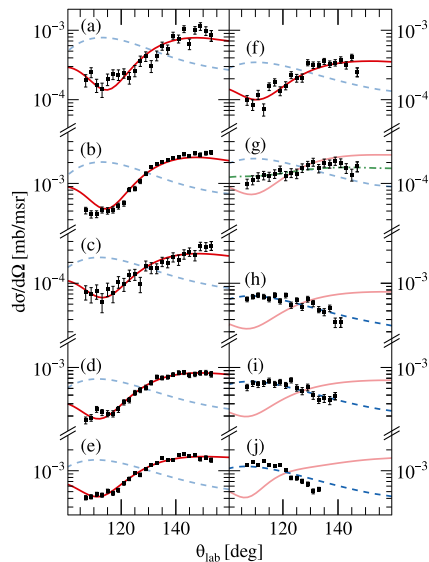
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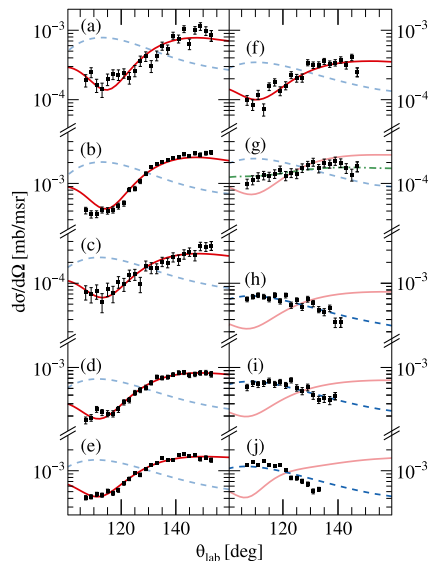
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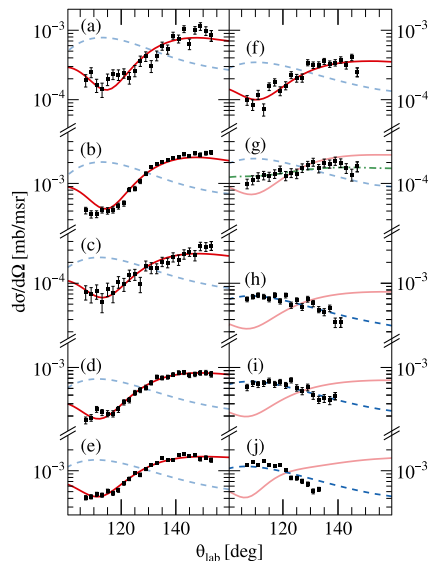
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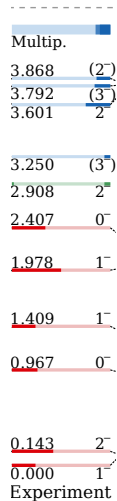
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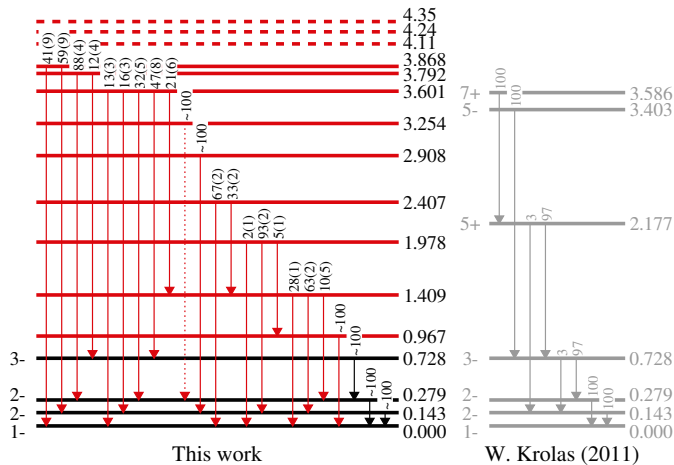


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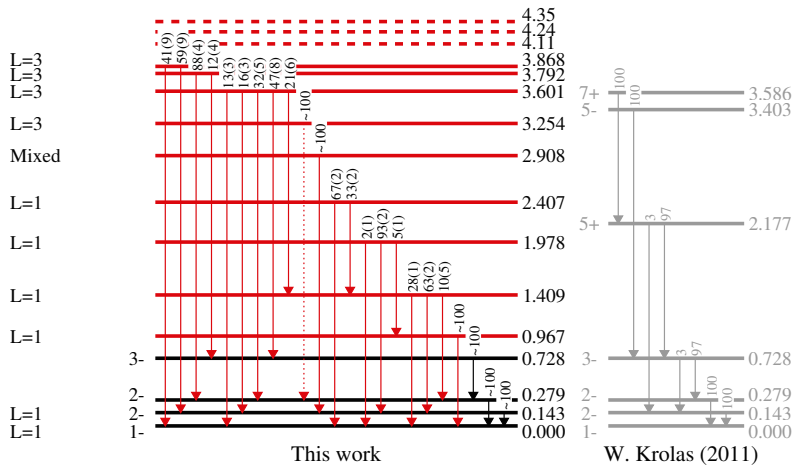
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- Adding this to the picture...

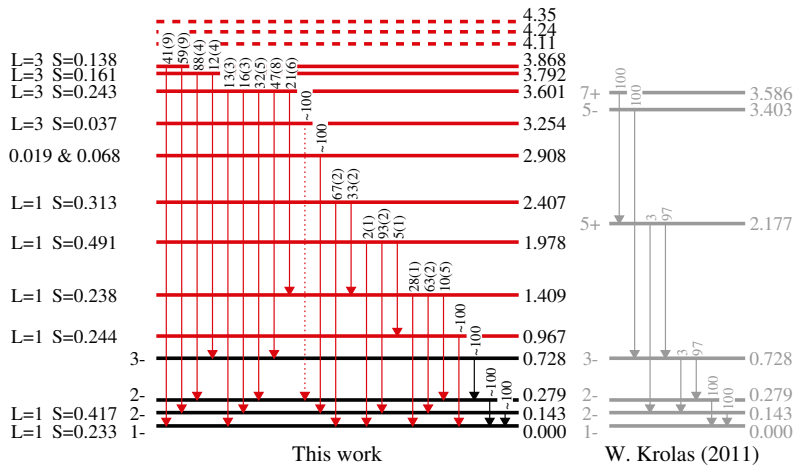


γ -ray transitions

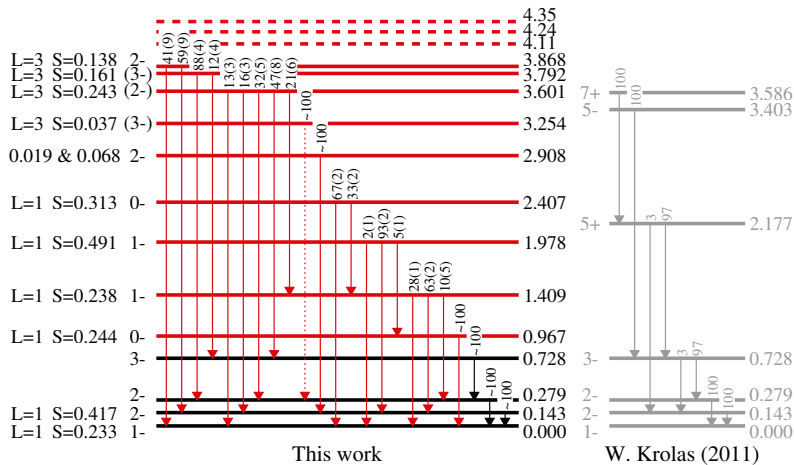


γ -ray transitions + ℓ -wave

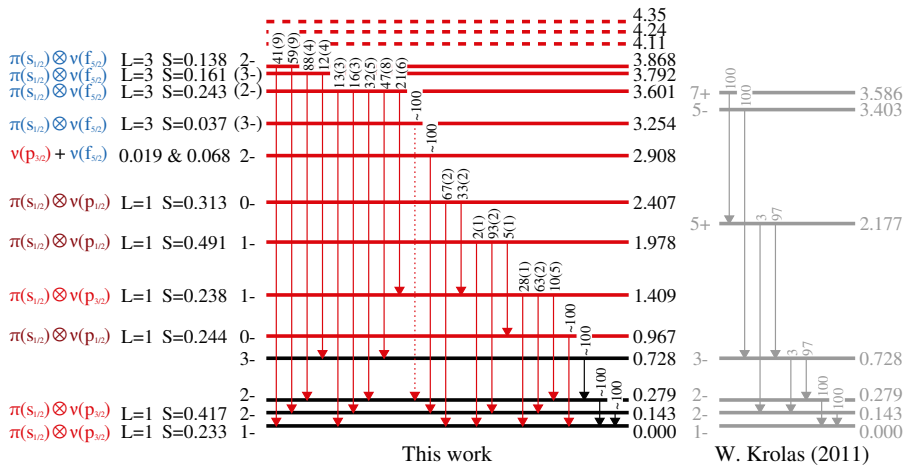


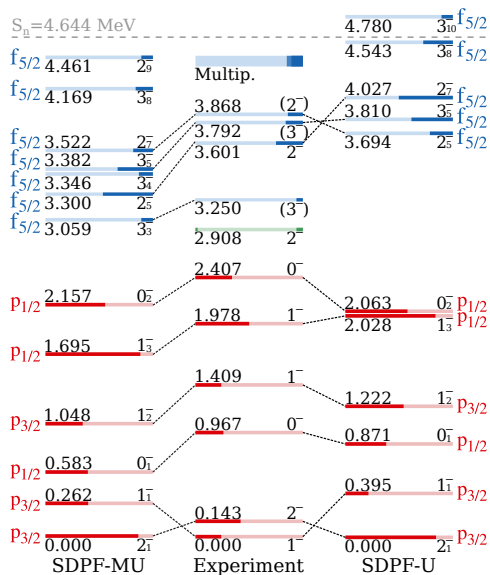
γ -ray transitions + ℓ -wave + spectroscopic factors

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

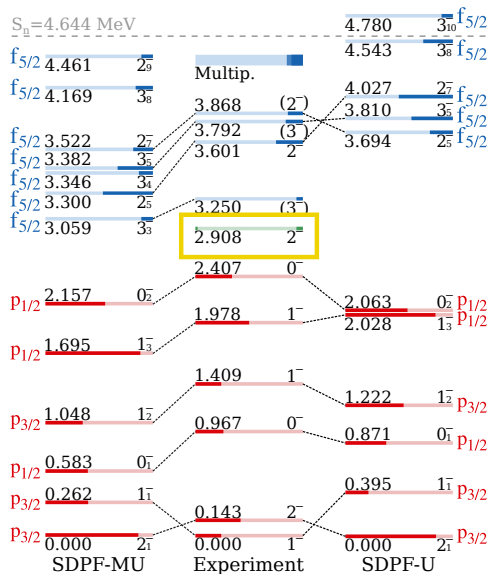


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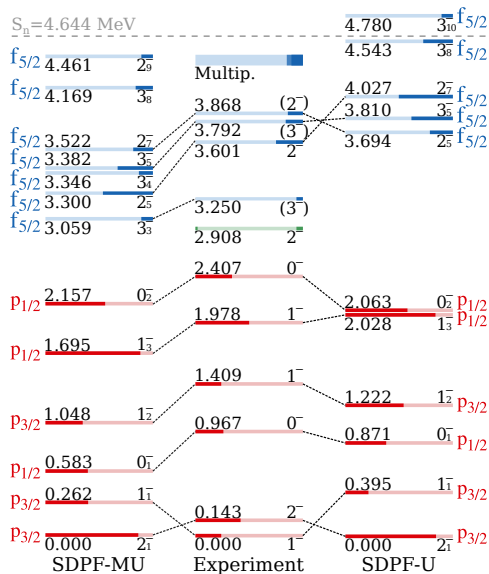


Observations



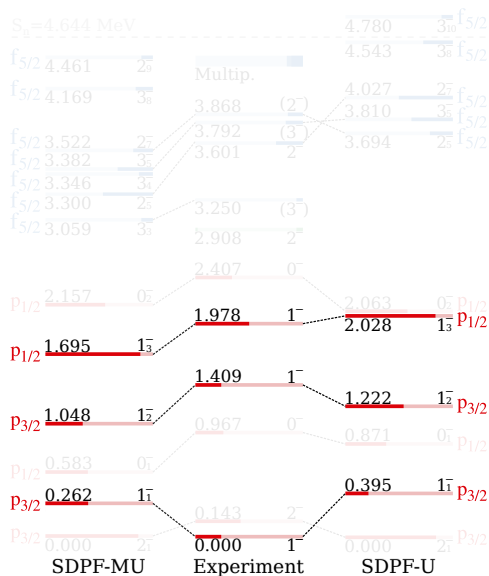
Observations

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- Challenge for shell model theorists



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- Spectroscopic factors are **small**
 - $^{47}\text{K}(d,t)$: no unexpected population
 - Suspect proton config. mixing

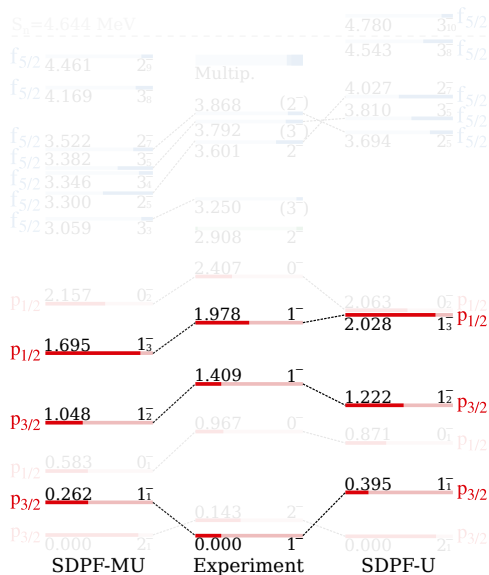


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- Failure to predict known 1^- g.s.
 - First observation of other 1^- states
 - Specific matrix elements:

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

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

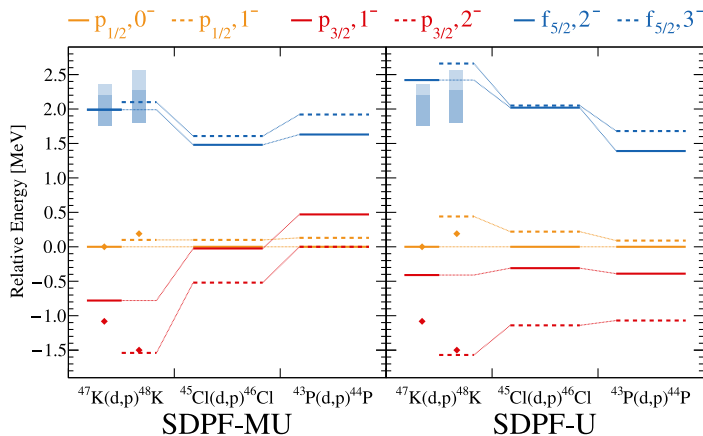


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 - $\langle p_{3/2}s_{1/2} | V_{int} | p_{3/2}s_{1/2} \rangle_{J=1, T=0}$
 - Implications down $N = 28$ chain...

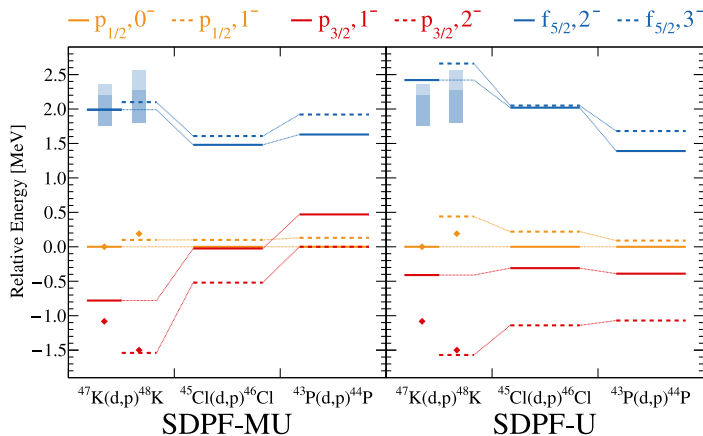
Extrapolation

- SF-weight. energy of ν, J^π



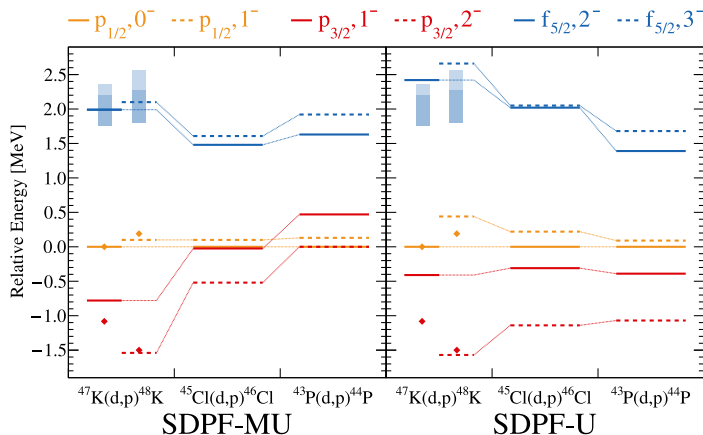
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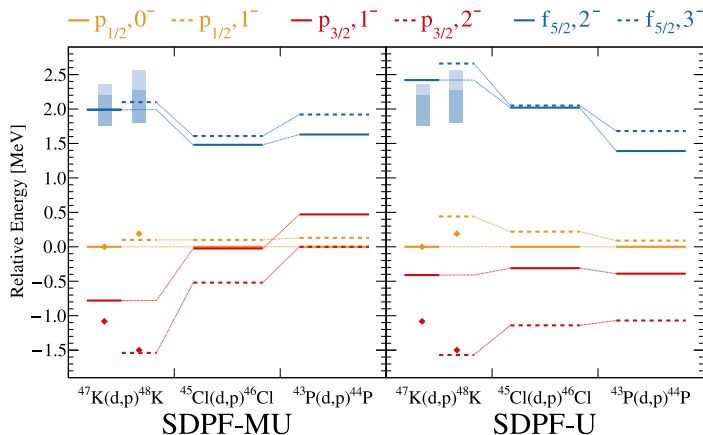
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- $\nu(p)$ degenerate in MU...
- ... separate in U

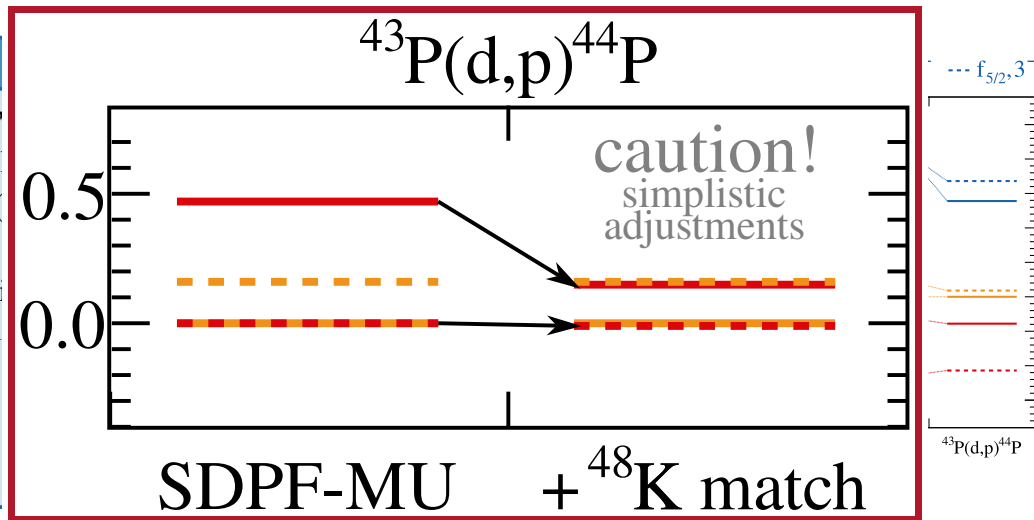


Extrapolation

- SF-weight. energy of ν , J^π
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 - ... separate in U
- Our interaction adjustments, even closer...

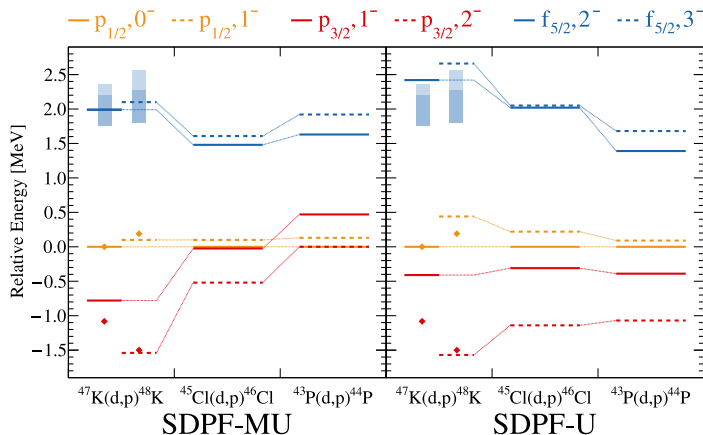


- SF-v
- Shell
- $\nu($
- ...
- Our
- even



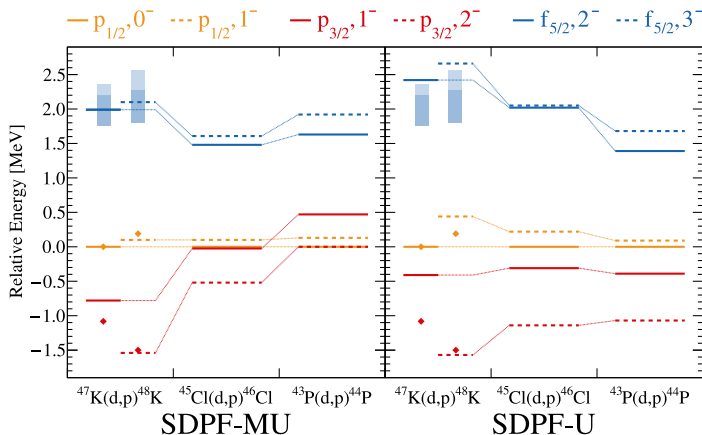
Extrapolation

- SF-weight. energy of ν , J^π
- Shell models diverge!
 - $\nu(p)$ degenerate in MU...
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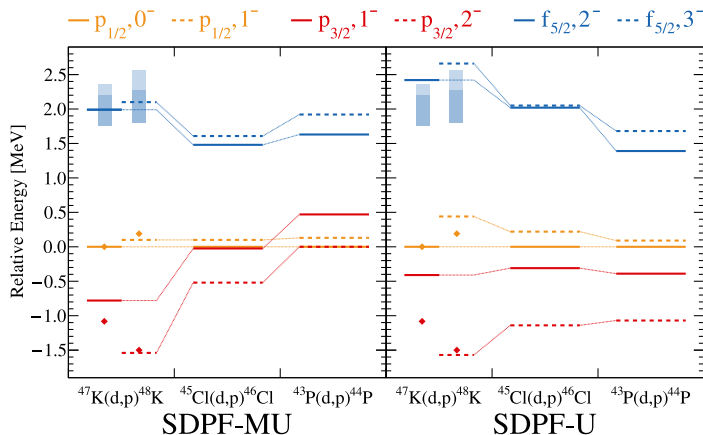
Extrapolation

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 - Increased collectivity?



Extrapolation

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



Summary

- **First experimental measurement** of exotic $\pi s_{1/2}^{-1} \otimes \nu f p$ interaction
- $^{47}\text{K}(\text{d,p})$ & $^{47}\text{K}(\text{d,t})$ 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 $^{48}\text{K} \rightarrow$ **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 , $N = 28 \rightarrow ^{45}\text{Cl}(\text{d,p})$?

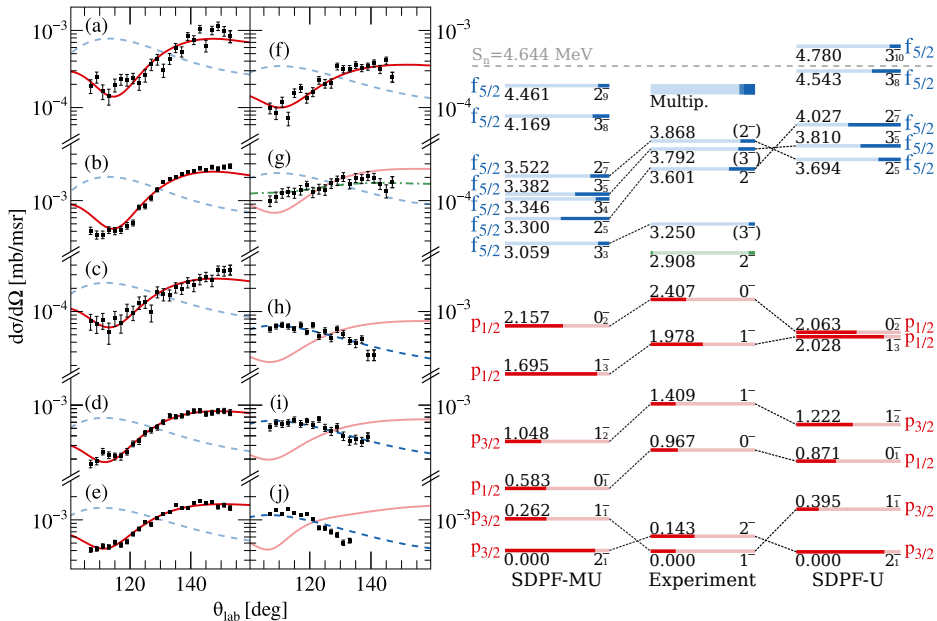
C. J. Paxman *et al.*, Phys. Rev. Lett. **134**, 162504 (2025)

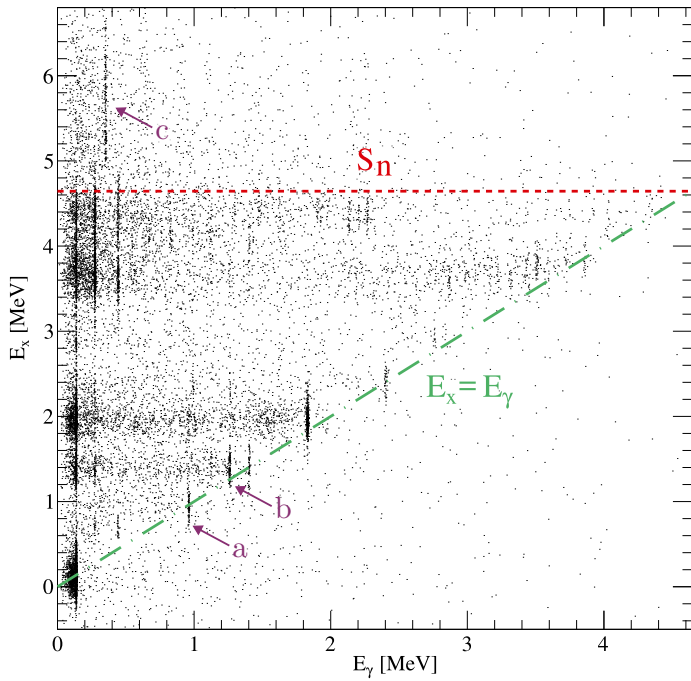
Thank you!

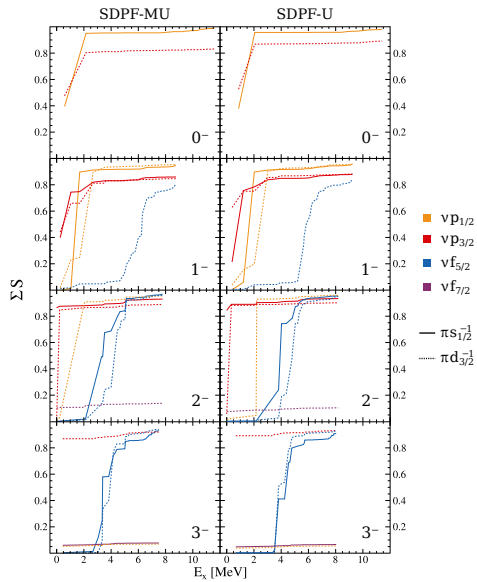
Probing Exotic Cross-Shell Interactions at $N=28$ with Single-Neutron Transfer on ^{47}K

C. J. Paxman^{1,*}, A. Matta², W. N. Catford¹, G. Lotay¹, M. Assié³, E. Clément⁴, A. Lemasson⁴, D. Ramos⁴, N. A. Orr², F. Galtarossa³, V. Girard-Alcindor⁴, J. Dudouet⁵, N. L. Achouri², D. Ackermann⁴, D. Barrientos⁶, D. Beaumel³, P. Bednarczyk⁷, G. Benzoni⁸, A. Bracco^{8,9}, L. Canete¹, B. Cederwall¹⁰, M. Ciemala⁷, P. Delahaye⁴, D. T. Doherty¹, C. Domingo-Pardo¹¹, B. Fernández-Domínguez¹², D. Fernández¹², F. Flavigny², C. Fougères⁴, G. de France⁴, S. Franchou³, A. Gadea¹¹, J. Gibelin², V. González¹³, A. Gottardo¹⁴, N. Goyal⁴, F. Hammache³, L. J. Harkness-Brennan¹⁵, D. S. Harrouz³, B. Jacquot⁴, D. S. Judson¹⁵, A. Jungclaus¹⁶, A. Kaşkaş¹⁷, W. Korten¹⁸, M. Labiche¹⁹, L. Lalanne^{3,4}, C. Lenain², S. Leoni^{8,9}, J. Ljungvall^{3,26}, J. Lois-Fuentes¹², T. Lokotko², A. Lopez-Martens³, A. Maj⁷, F. M. Marqués², I. Martel²⁰, R. Menegazzo²¹, D. Mengoni^{21,22}, B. Million⁸, J. Nyberg²³, R. M. Pérez-Vidal^{11,14}, L. Plagnol², Zs. Podolyák¹, A. Pullia^{8,9}, B. Quintana²⁴, D. Regueira-Castro¹², P. Reiter²⁵, M. Rejmund⁴, K. Rezynek^{26,21}, E. Sanchis¹³, M. Şenyigit¹⁷, N. de Séréville³, M. Siciliano^{14,18,27}, D. Sohler²⁸, O. Stezowski⁵, I.-C. Thomas⁴, A. Ulenov⁴, I. I. Valiente-Dobón^{11,14}, D. Verneev³ and M. Zielińska¹⁸

BACKUP SLIDES

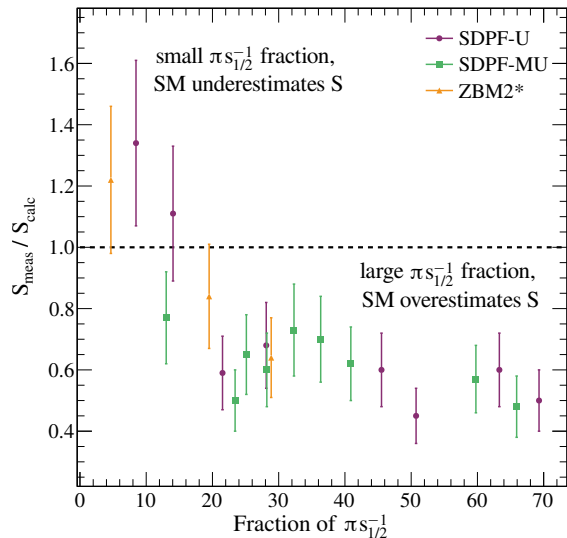






Shell model ‘accuracy’

- 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)

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Analytical

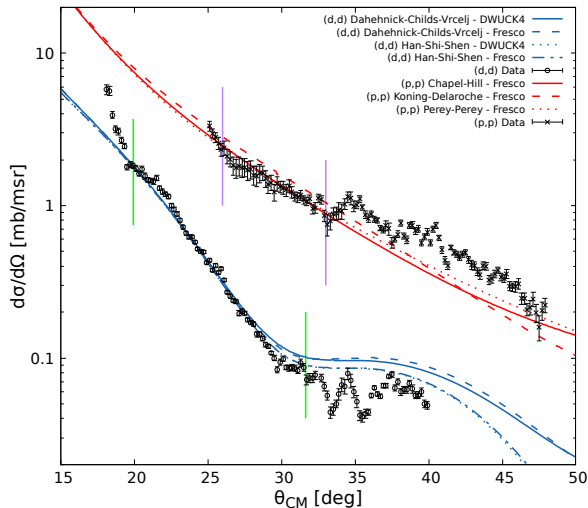
- Same normalisation factor for (d,p), (d,t) and (d,d)
- Includes beam intensity and target thickness.
- N_{beam} monitored with CATS.

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

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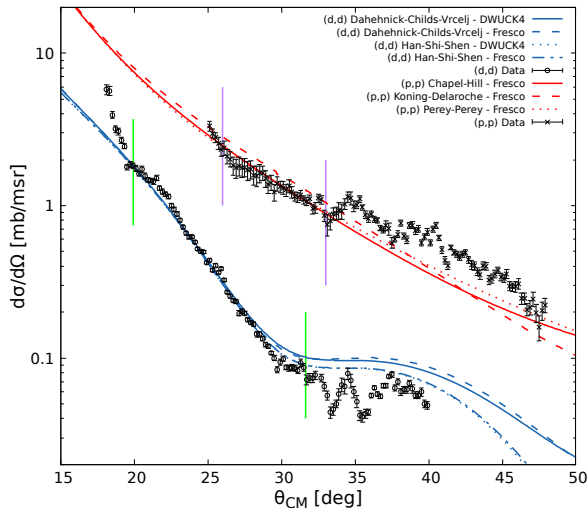
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- Therefore can find B , extract T :



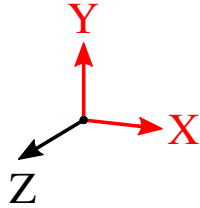
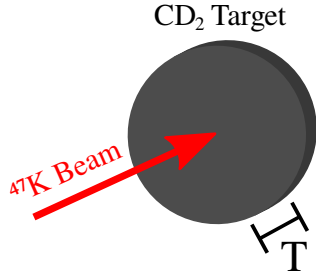
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- Includes **beam intensity** and **target thickness**.
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 - $0.31(2) \text{ mg/cm}^2 \text{ CD}_2$
 - $0.02(1) \text{ mg/cm}^2 \text{ CH}_2$



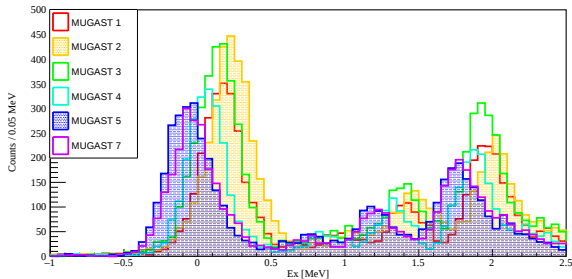
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- Use range as limits on numerical method...



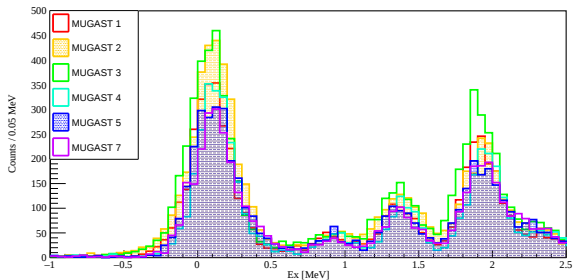
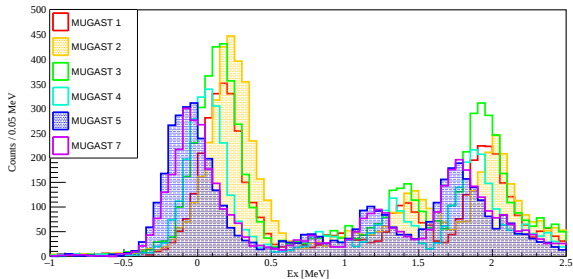
Numerical

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



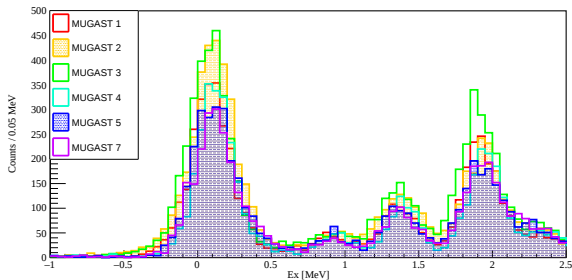
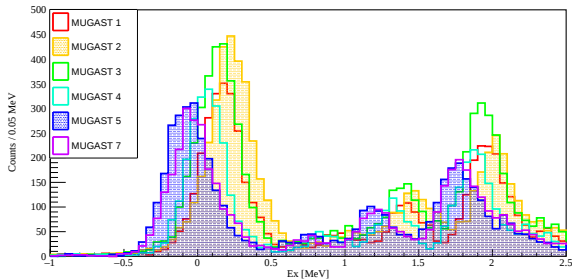
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Numerical

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- Minimisation, with restricted T from analytical method.

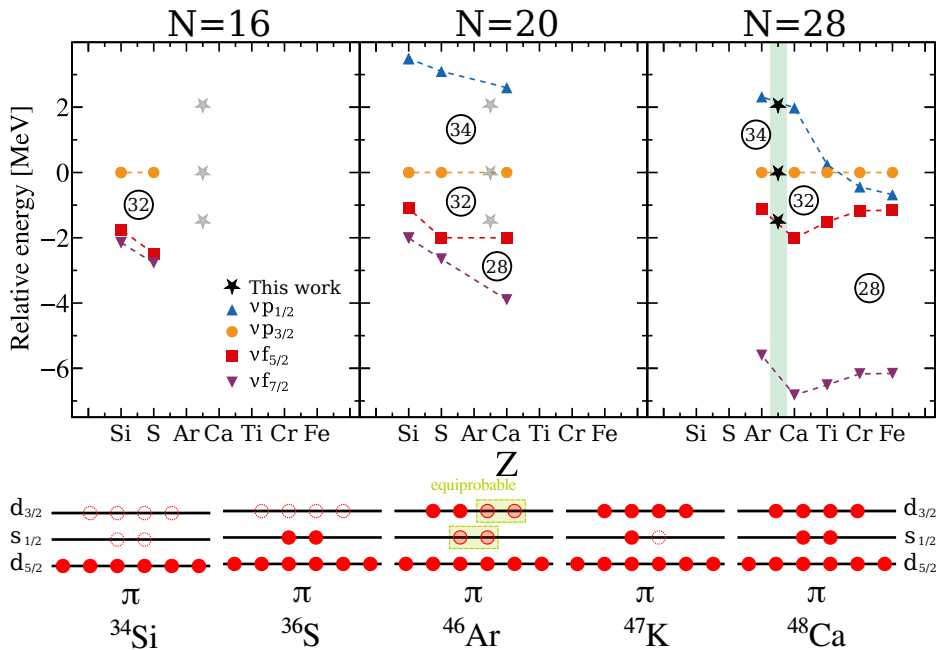


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- Affects the accuracy of energy and peak width of excitation peaks.
- Minimisation, with restricted T from analytical method.

$X = -4.15$ mm $Y = 0.47$ mm

$Z = +0.22$ mm $T = 3.25\mu\text{m}$



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:

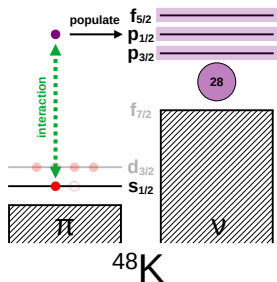
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

and the shell model states and the experimental measurements are¹:

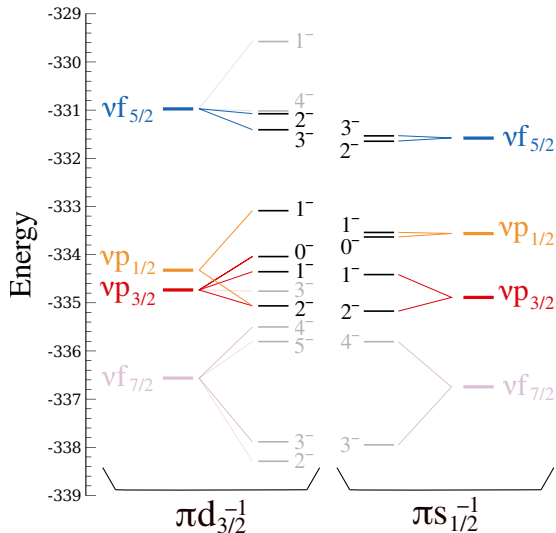
$$\begin{pmatrix} 0.44 & 0.40 & 0.00 & 0.02 \\ 0.22 & 0.35 & 0.01 & 0.21 \\ 0.00 & 0.00 & 0.88 & 0.02 \\ 0.15 & 0.07 & 0.01 & 0.65 \end{pmatrix} \wedge \begin{pmatrix} 0.24 & \hat{c}_1 \\ 0.24 & \hat{c}_2 \\ 0.50 & \hat{c}_3 \end{pmatrix}$$

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