Cross-shell interactions at the N = 28 shell closure through ^{47}K(d,pγ) and ^{47}K(d,tγ) with MUGAST+AGATA+VAMOS

Charlie J. Paxman (University of Surrey)
+ e793s collaboration

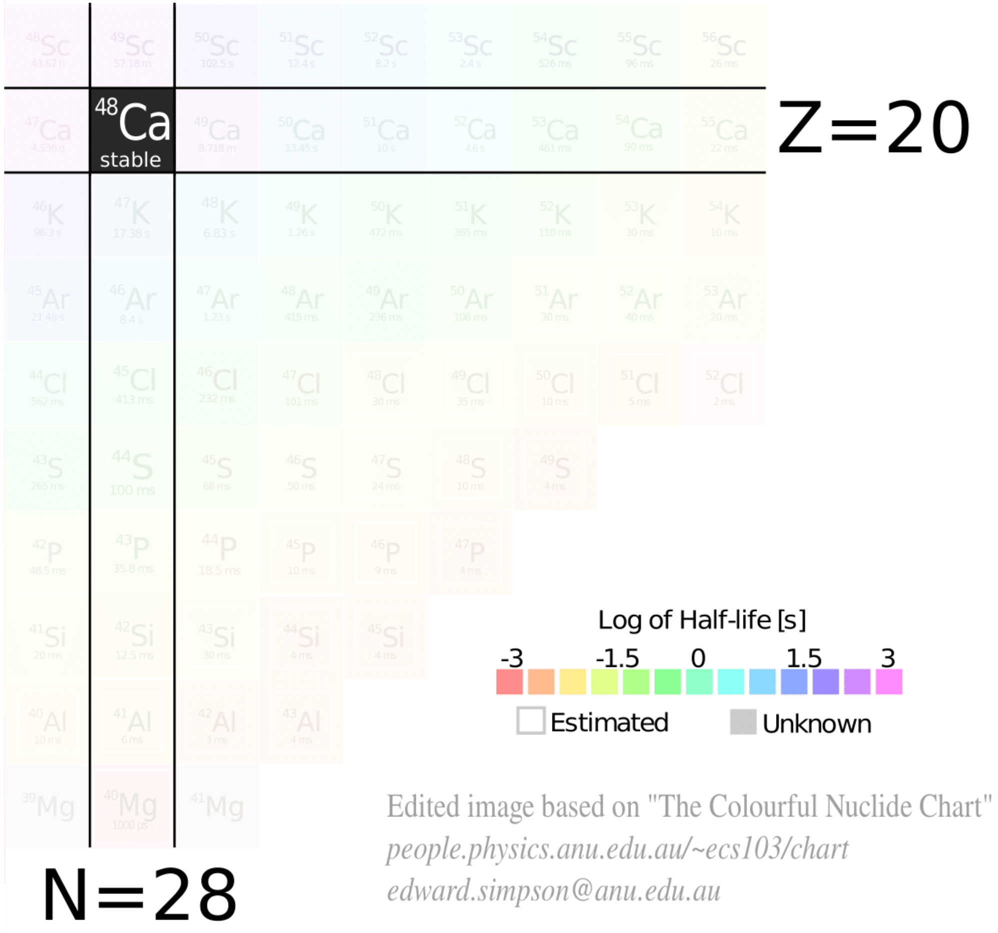
laboratoire commun CEA/DRF CNRS/IN2P3

UNIVERSITY OF SURREY

AGATA ADVANCED GAMMA TRACKING ARRAY

Shell Evolution

Far from stability, magic numbers change due to relative shifting of orbital energies [1].



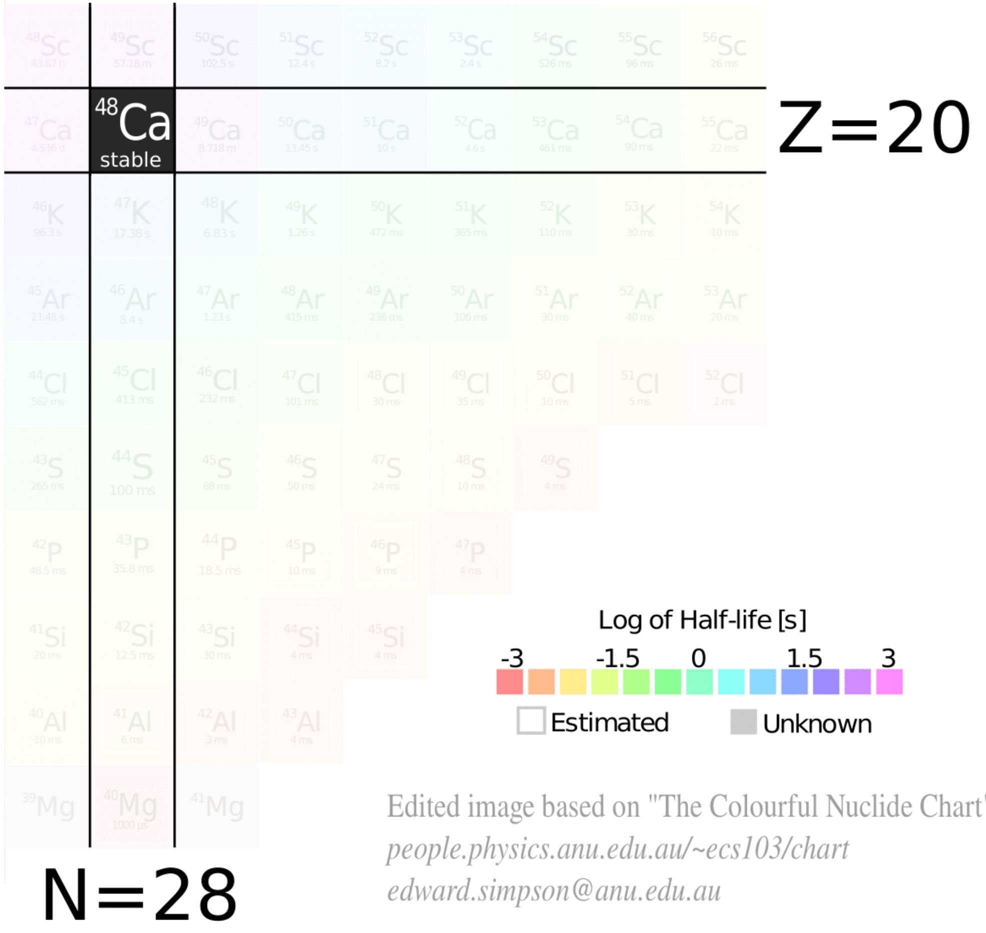
[1] T. Otsuka *et al.* Rev. Mod. Phys. **92**, 015002 (2020)

Shell Evolution

Far from stability, magic numbers change due to relative shifting of orbital energies.

Predicted that N = 28 gap weakens, N = 32, 34 gaps emerge [2].

[2] T. Otsuka *et al.* Phys. Rev. Lett. **87**, 082502 (2001)



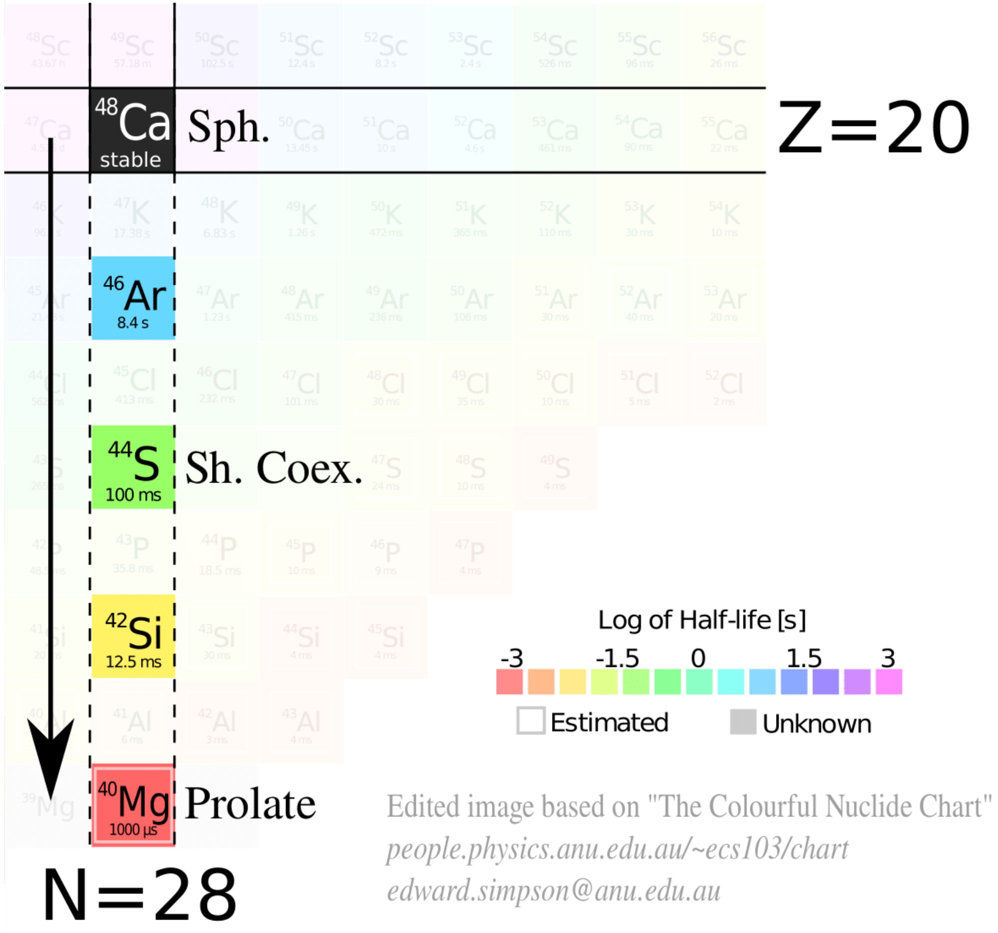
Edited image based on "The Colourful Nuclide Chart"
people.physics.anu.edu.au/~ecs103/chart
edward.simpson@anu.edu.au

Shell Evolution

Far from stability, magic numbers change due to relative shifting of orbital energies.

Predicted that N = 28 gap weakens, N = 32, 34 gaps emerge.

- Deformation at N = 28, Z<20 [3].



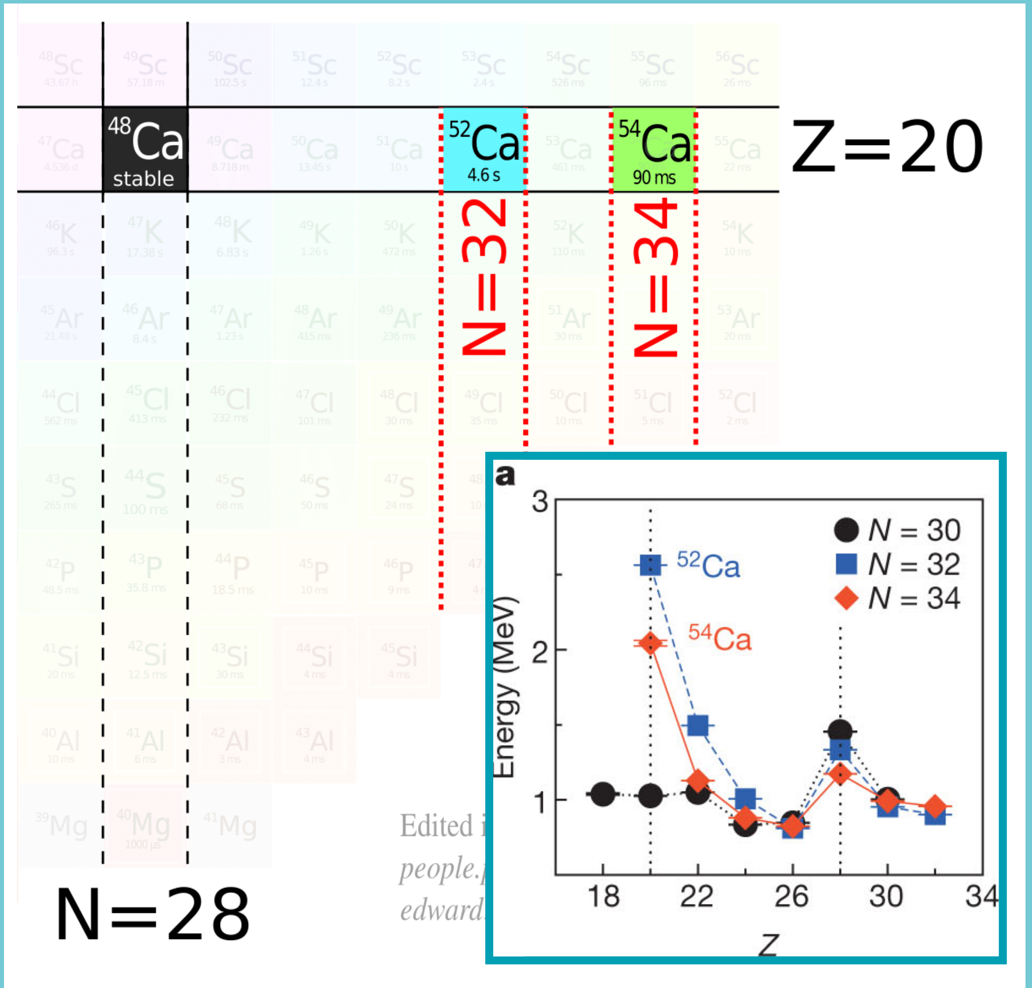
[3] H.L. Crawford *et al.* Phys. Rev. Lett **122**, 052501 (2019)

Shell Evolution

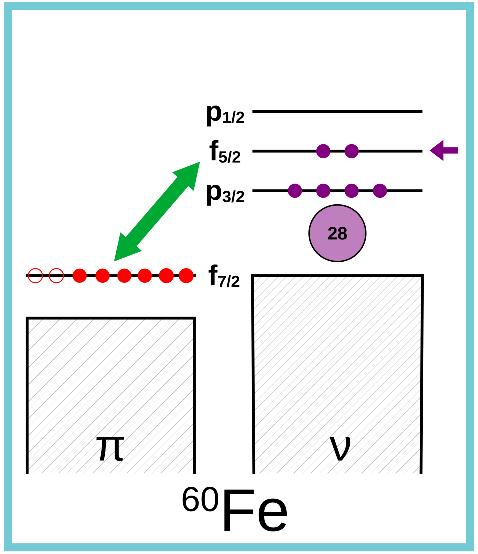
Far from stability, magic numbers change due to relative shifting of orbital energies.

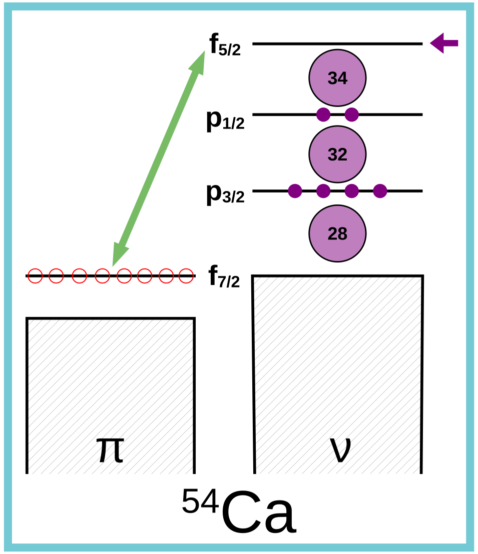
Predicted that N = 28 gap weakens, N = 32, 34 gaps emerge.

- Deformation at N = 28, Z<20.
- Doubly-magic ^{52,54}Ca from E(2_1^+) [4].



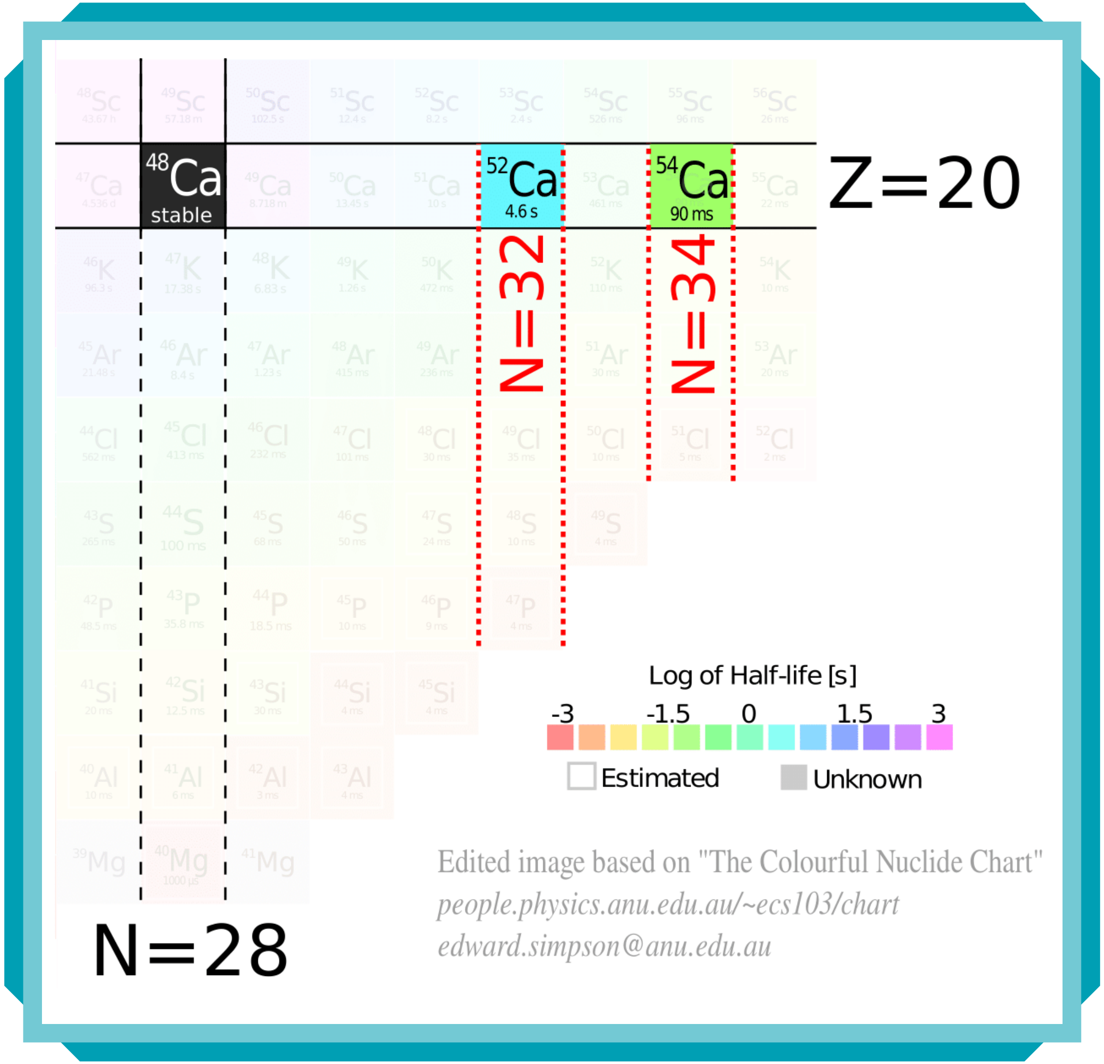
[4] D. Steppenbeck *et al.* Nature **502**, 207 (2013)

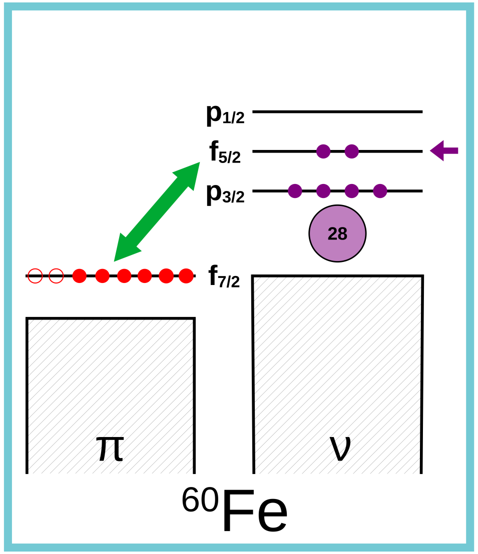


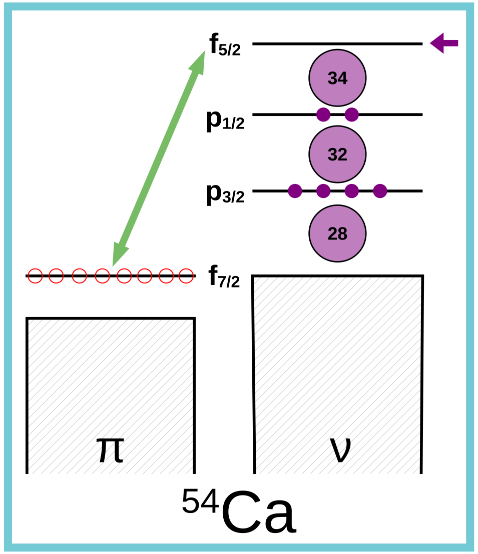


Removing protons

$\nu(f_{5/2})$ moves outside of $\nu(p)$ shell







Removing protons

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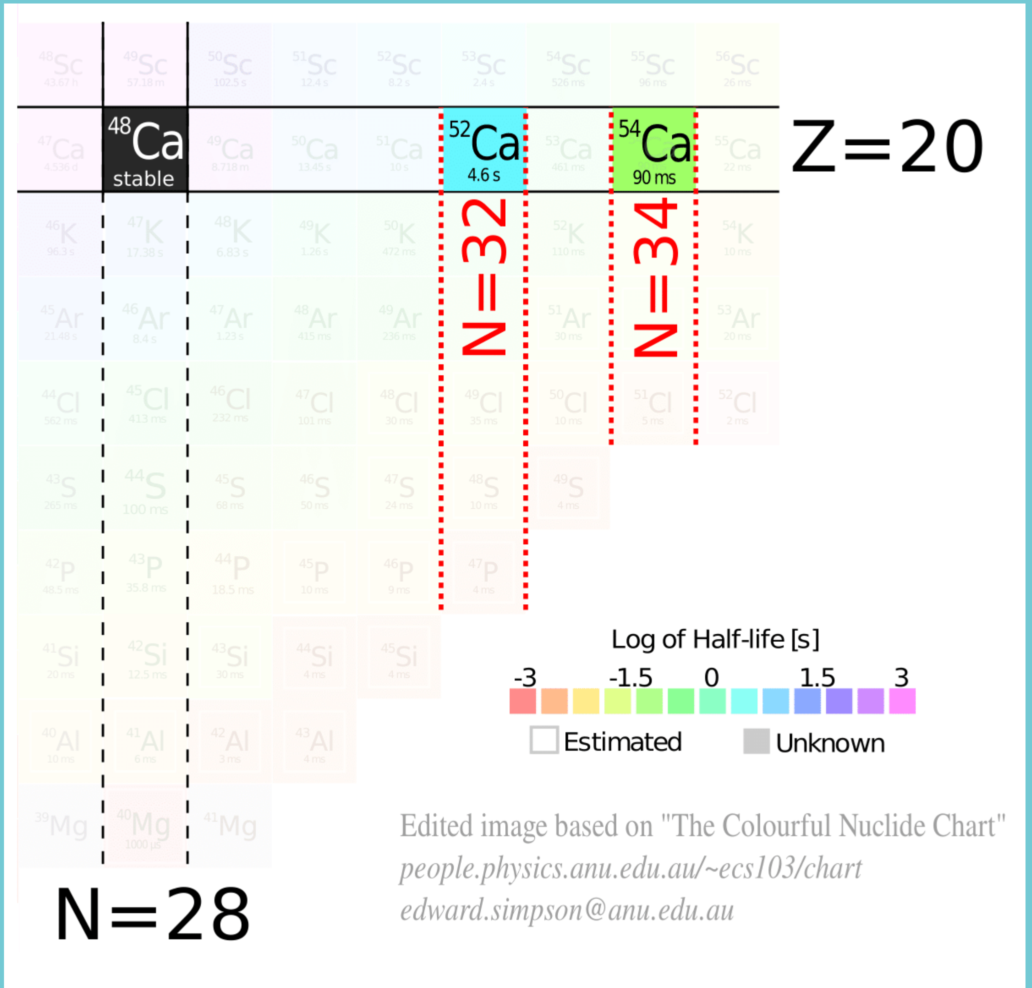
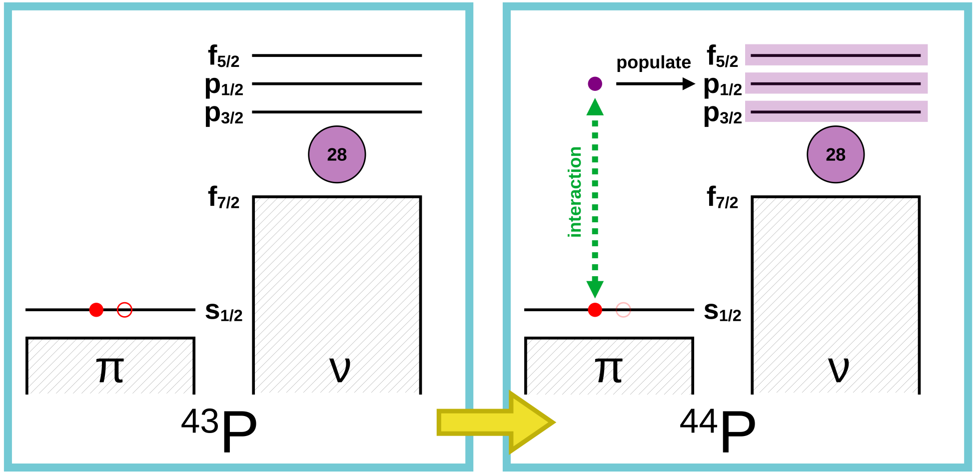
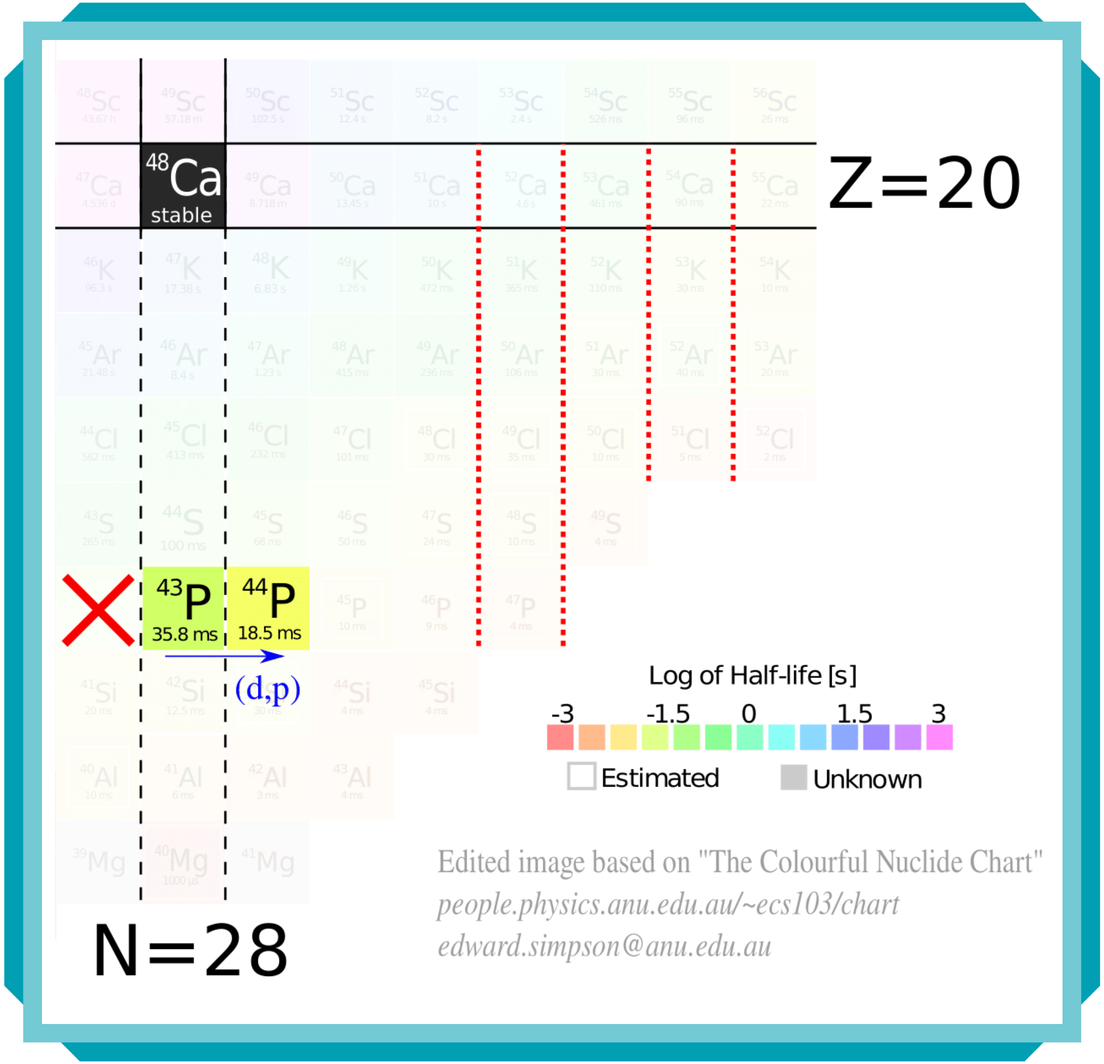
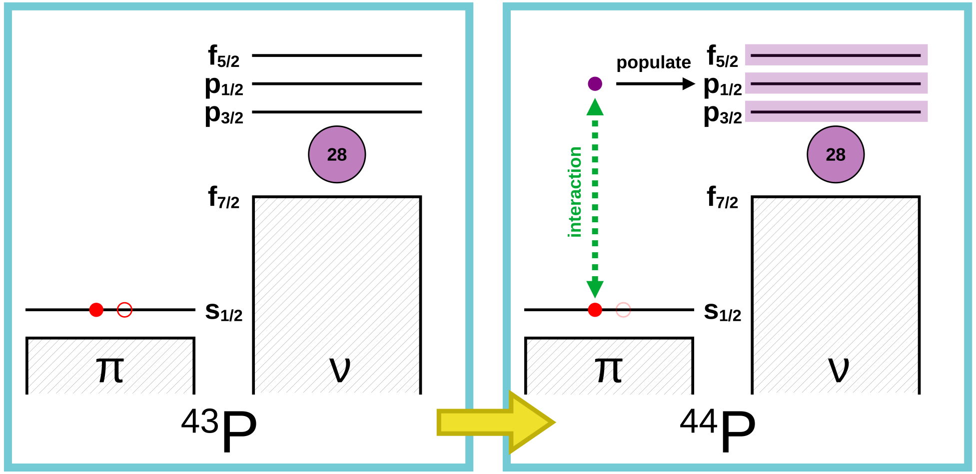
What if we continue to remove protons?





Selective (d,p) reaction





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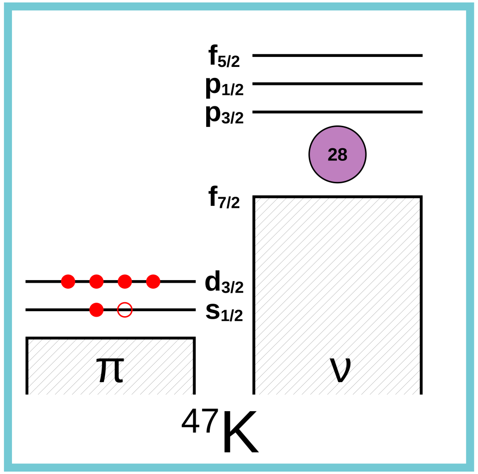

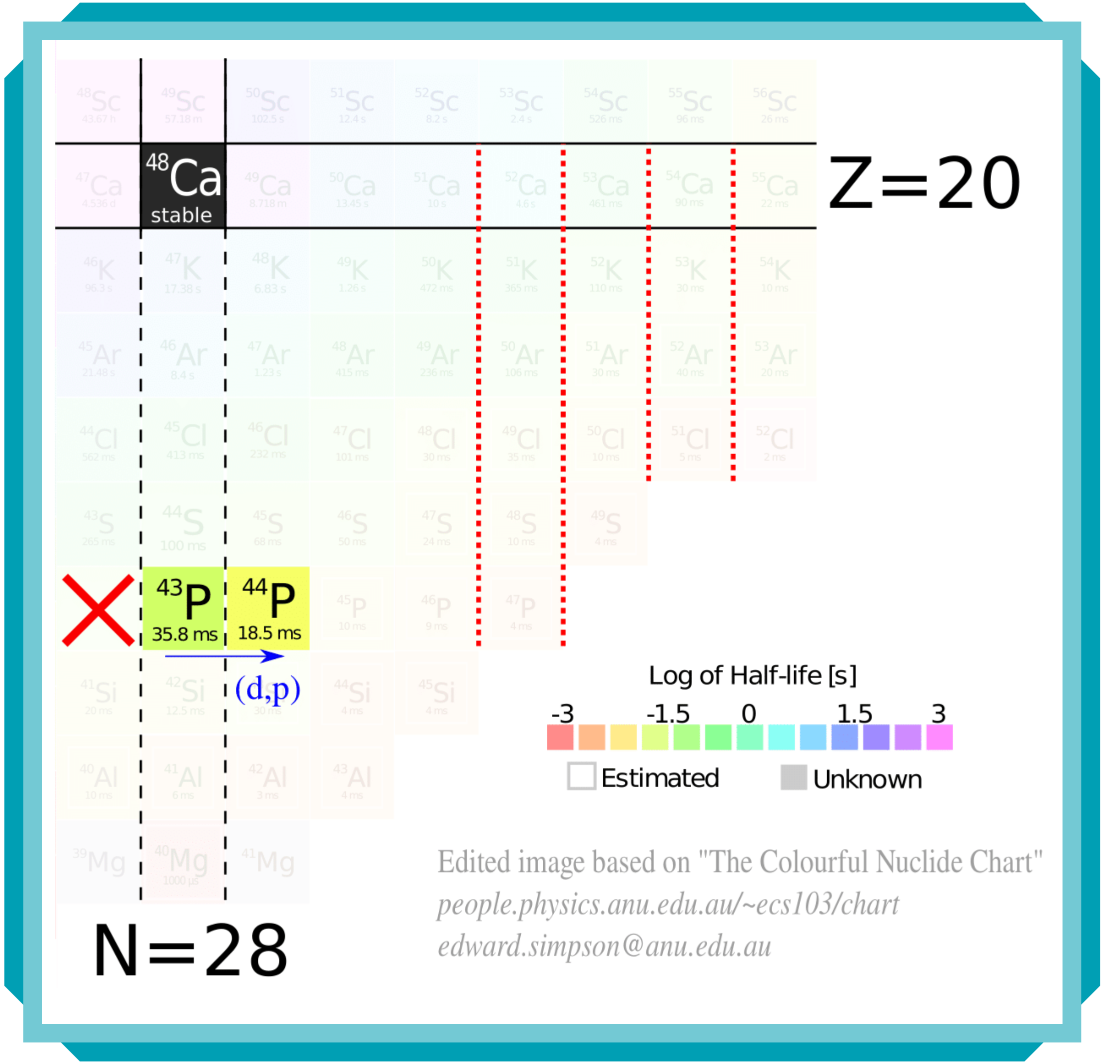

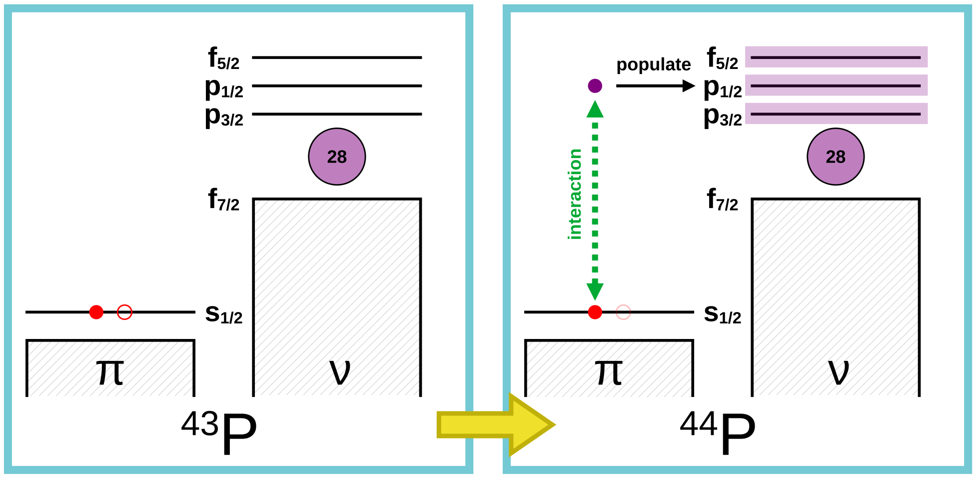

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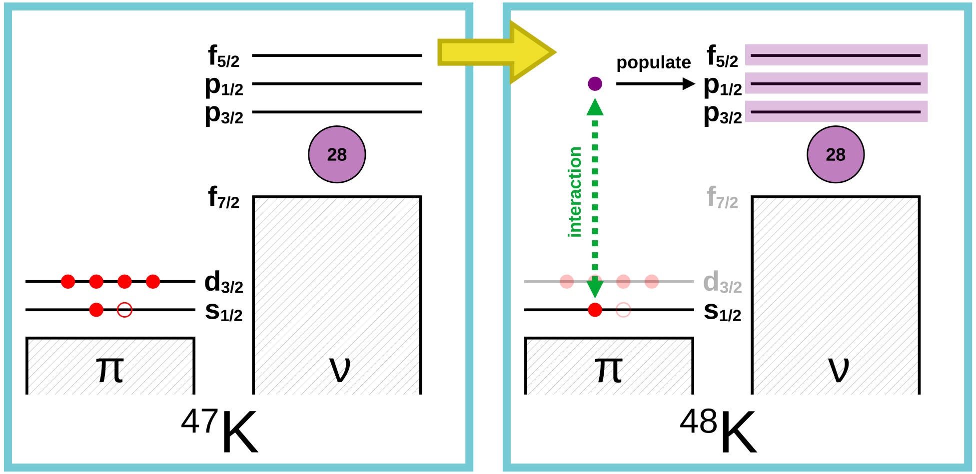
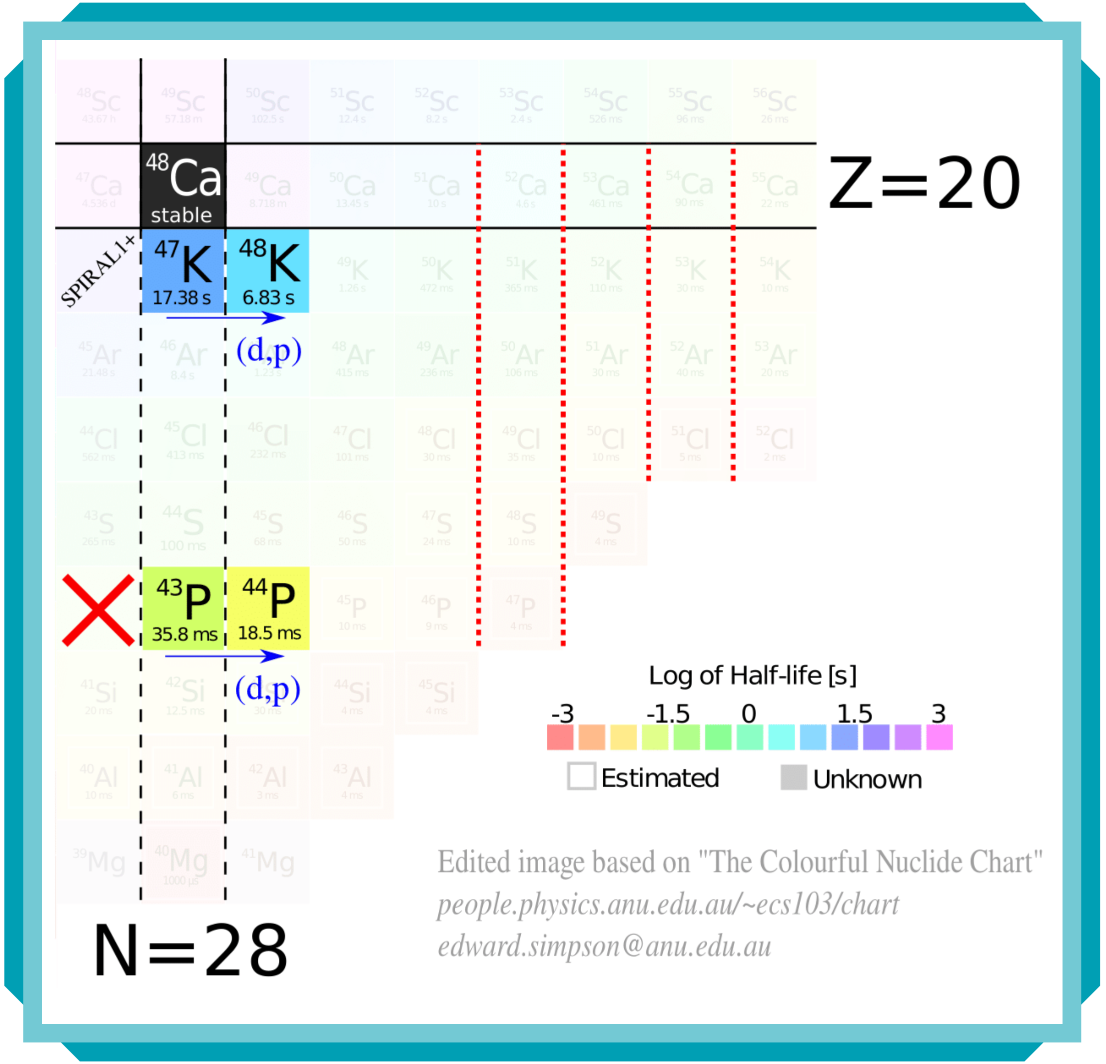
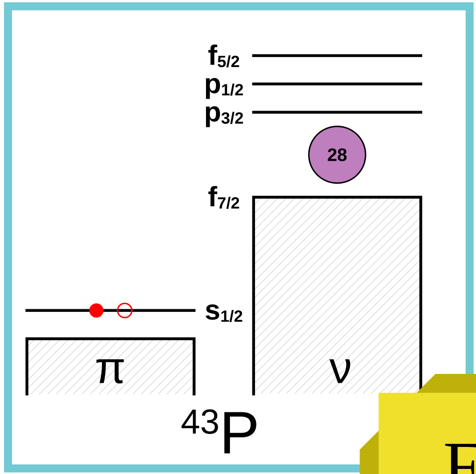
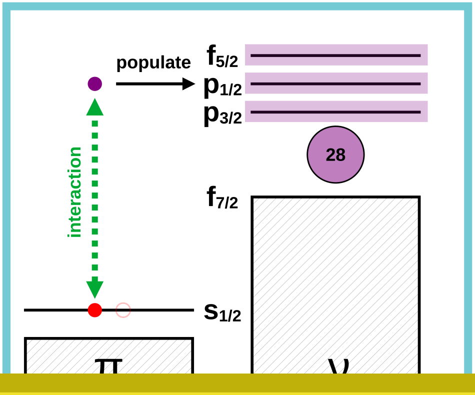
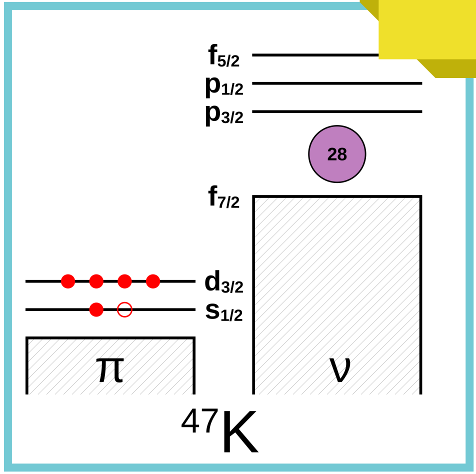


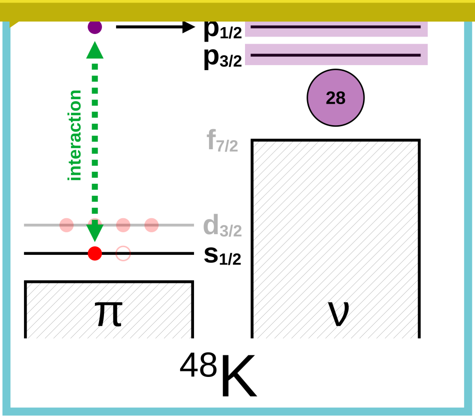


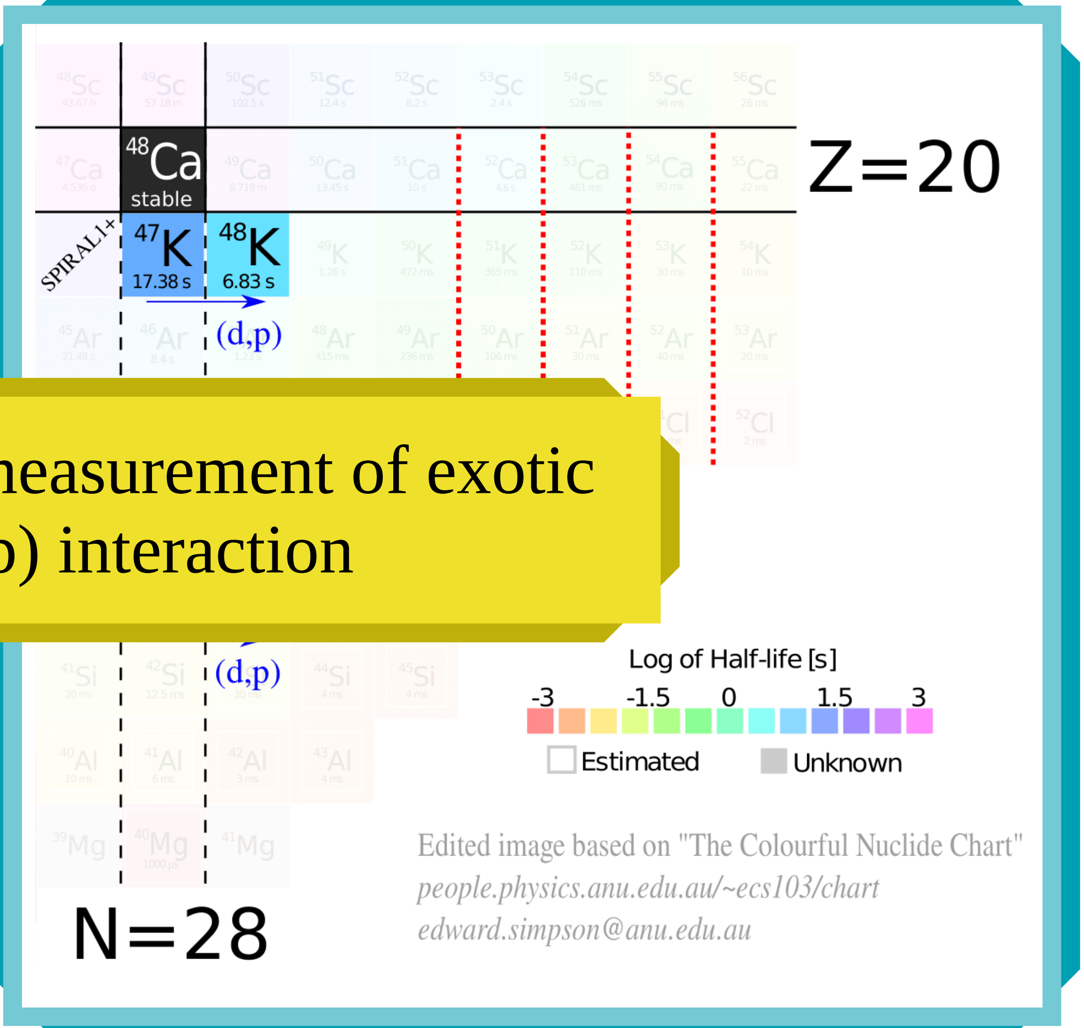




Sele





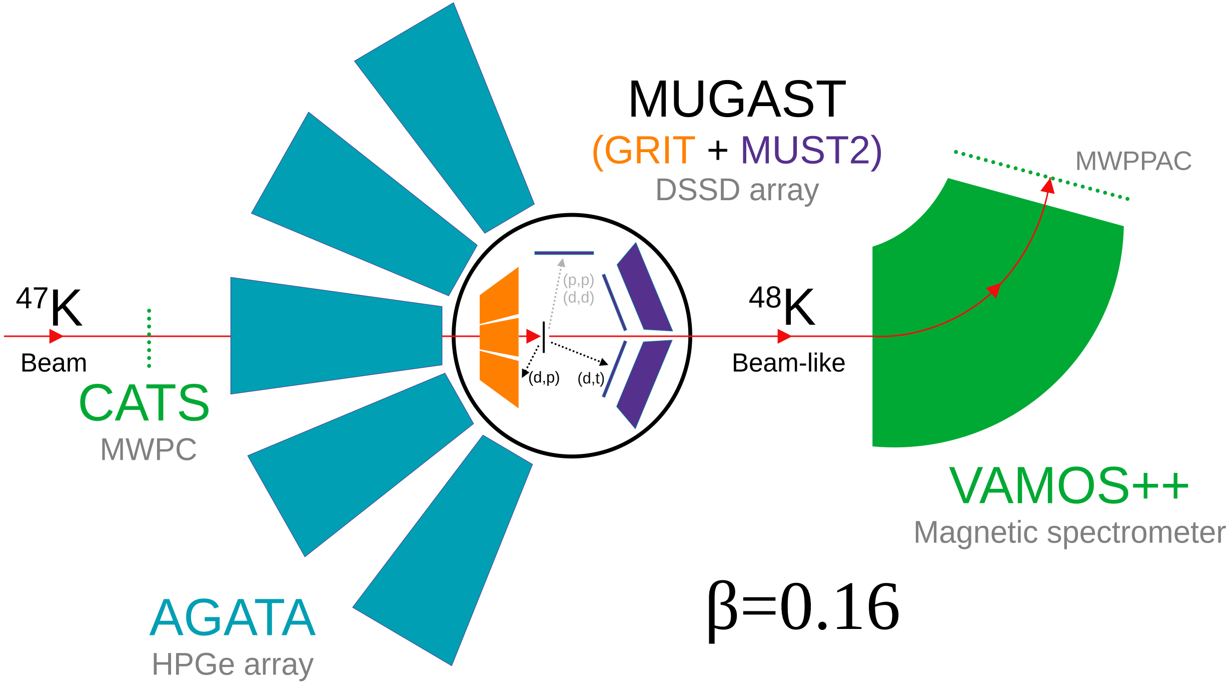


First experimental measurement of exotic $\pi(s_{1/2}) \otimes \nu(fp)$ interaction

Methodology

SPIRAL1+
- ^{47}K RIB @ 7.7MeV/u.
- 5×10^5 pps, 10^{-4} mass res. → pure beam

TARGET
- 0.31(2) mg/cm^2 CD_2



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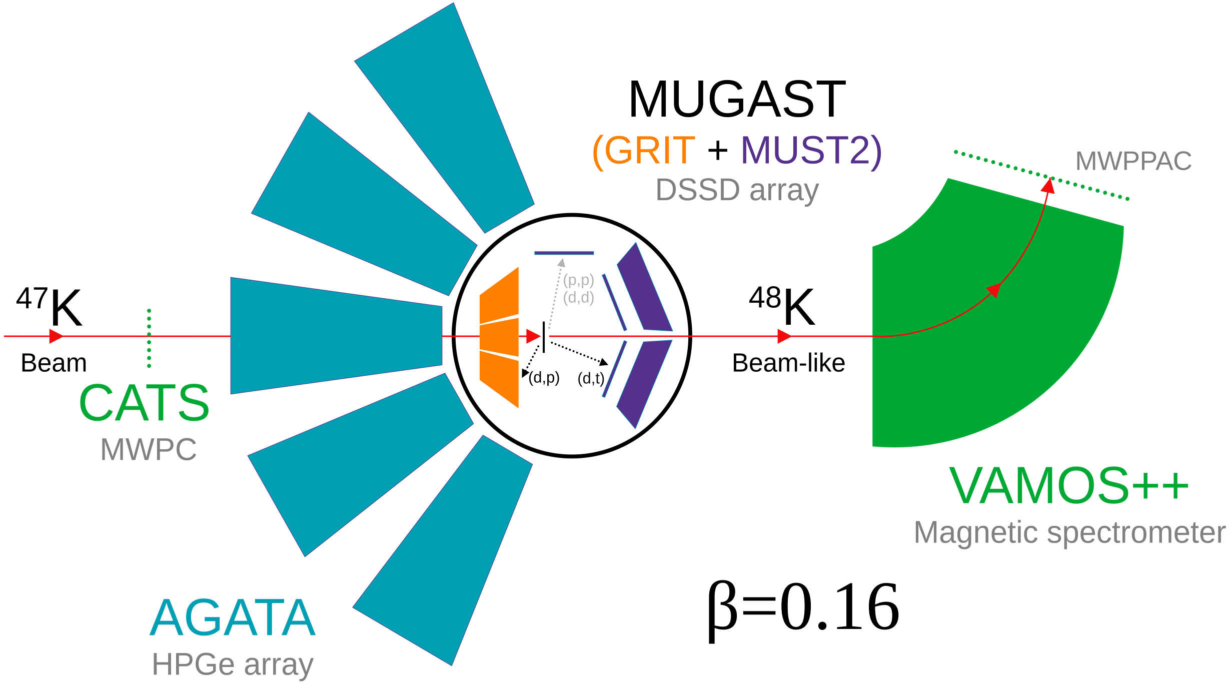
VAMOS++

- Zero degree; fast counting
- **Recoil timing** & reject C reactions



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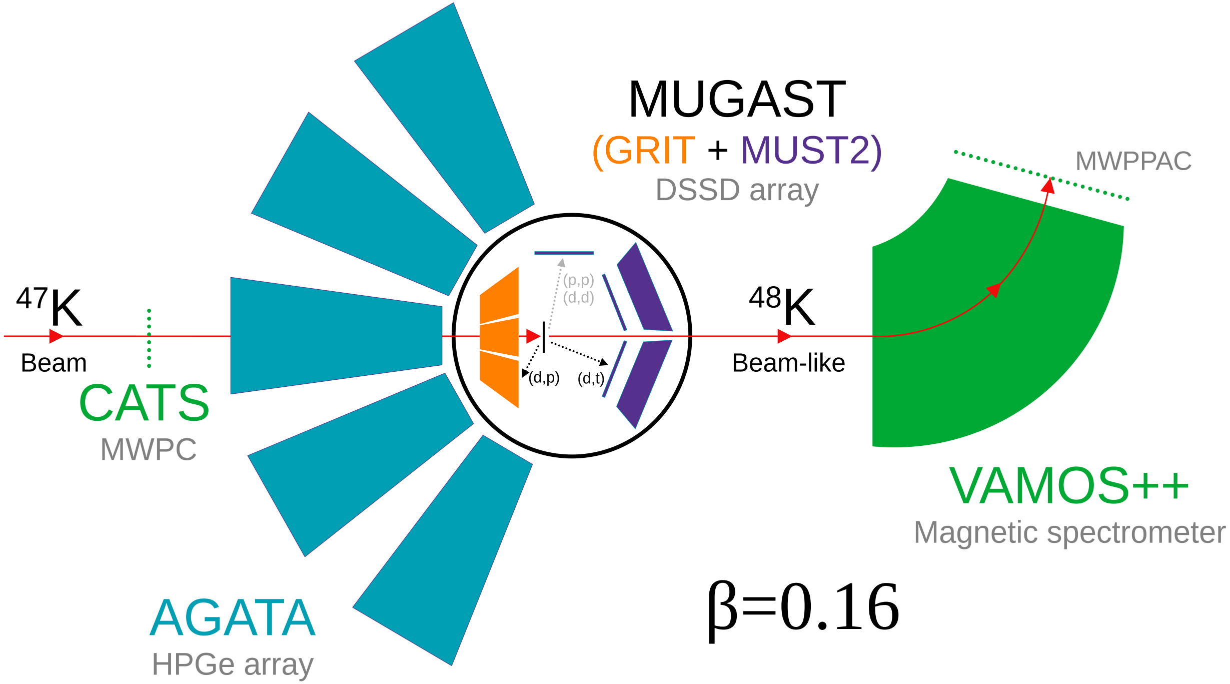
- **Light ejectile** detection
- FWHM ≈ 300 keV in ^{48}K excitation.



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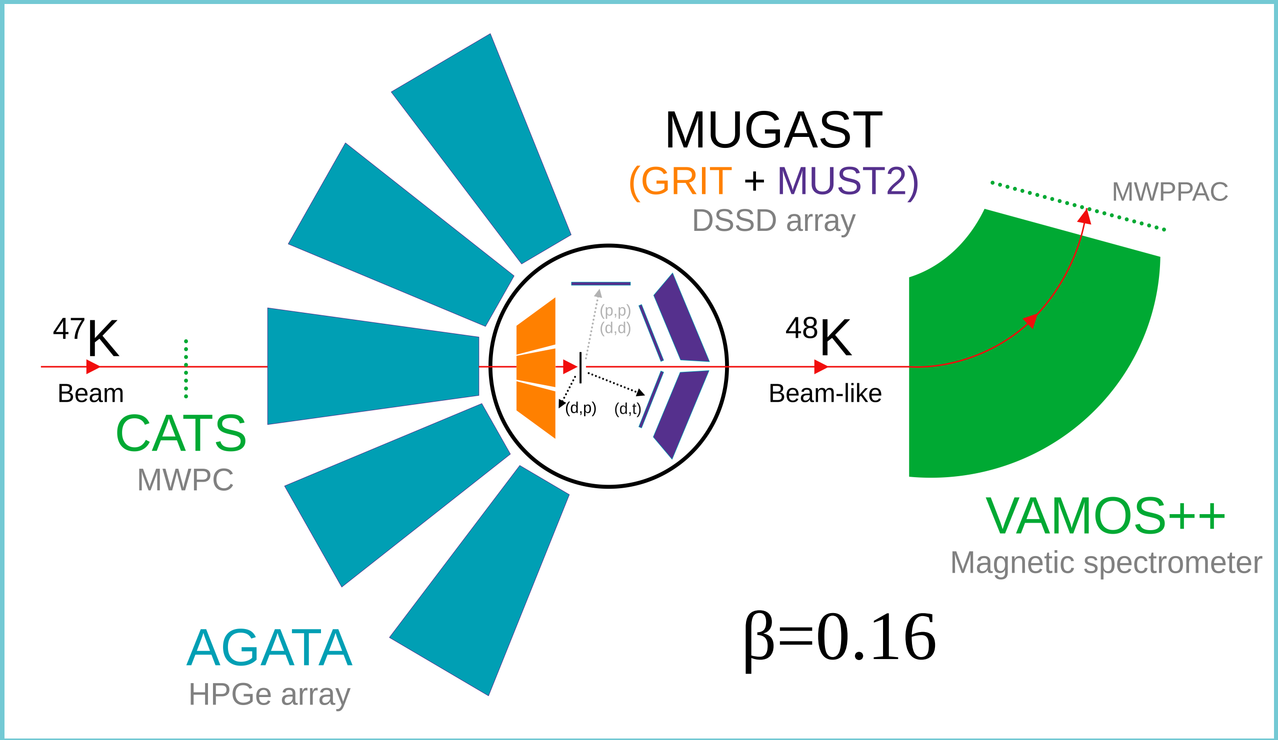
AGATA

- **Prompt γ-ray** emissions
- 16 ATC's @ 18 cm
- Pulse shape analysis, add-back & DC
- FWHM ≈ 7 keV @ 1.8 MeV; β = 0.16



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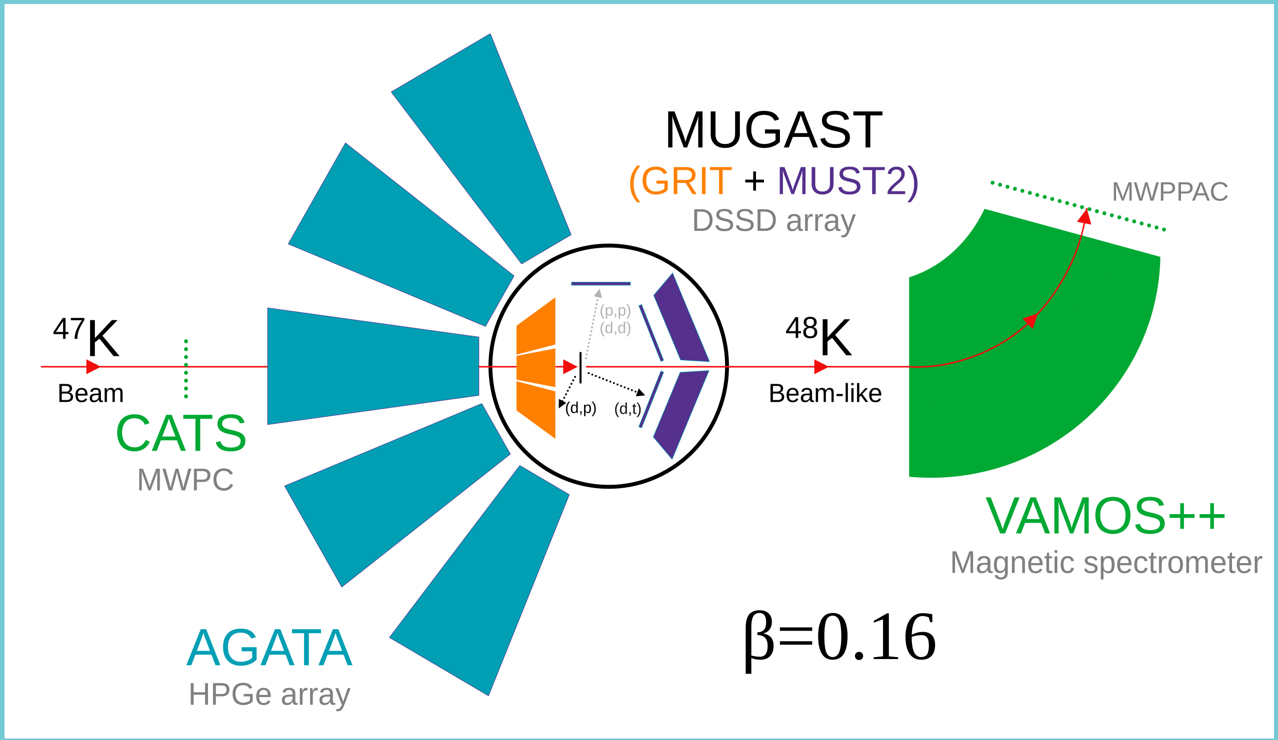
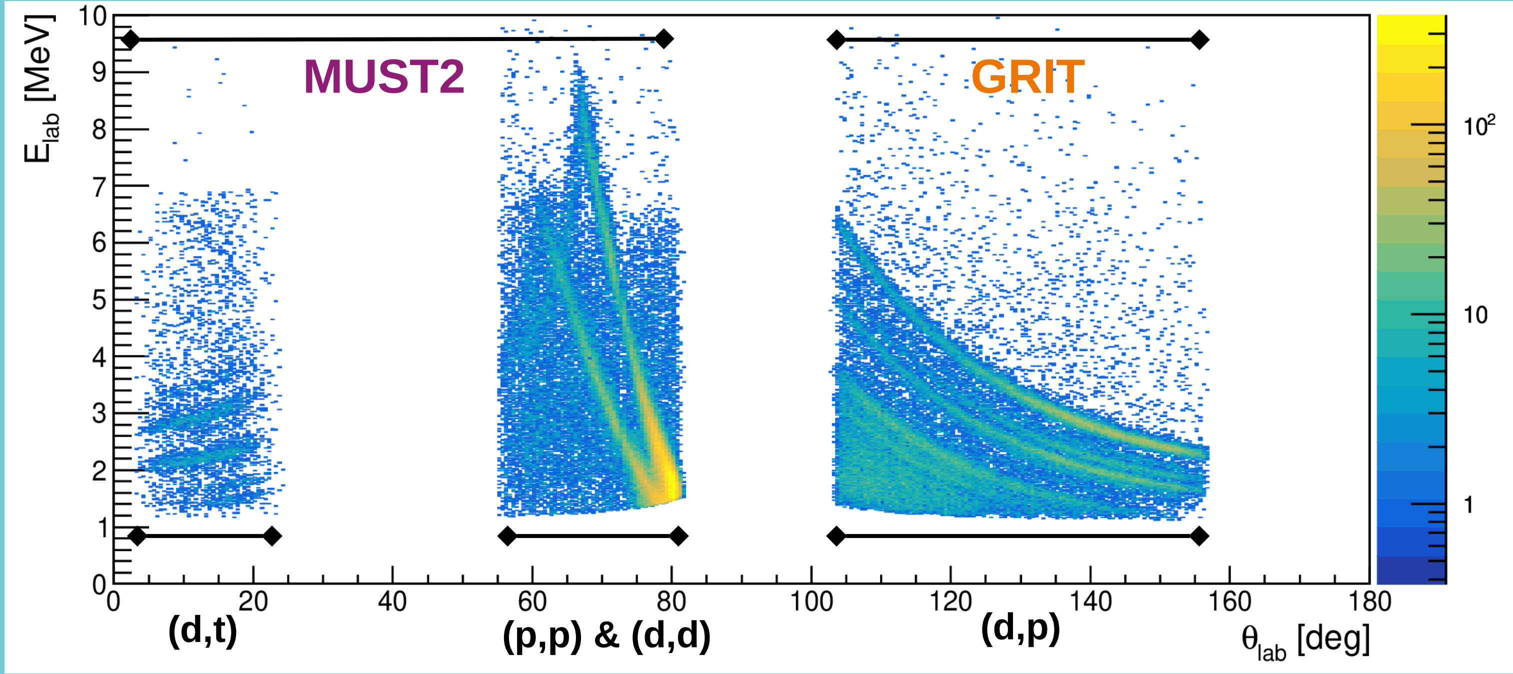


Triple-coincidence is critical

MUGAST & VAMOS++



Unambiguous kinematic selection of reaction channel
(d,d) elastic scattering provides internally consistent normalisation.
(d,tγ) transfer allows for neutron hole investigation.

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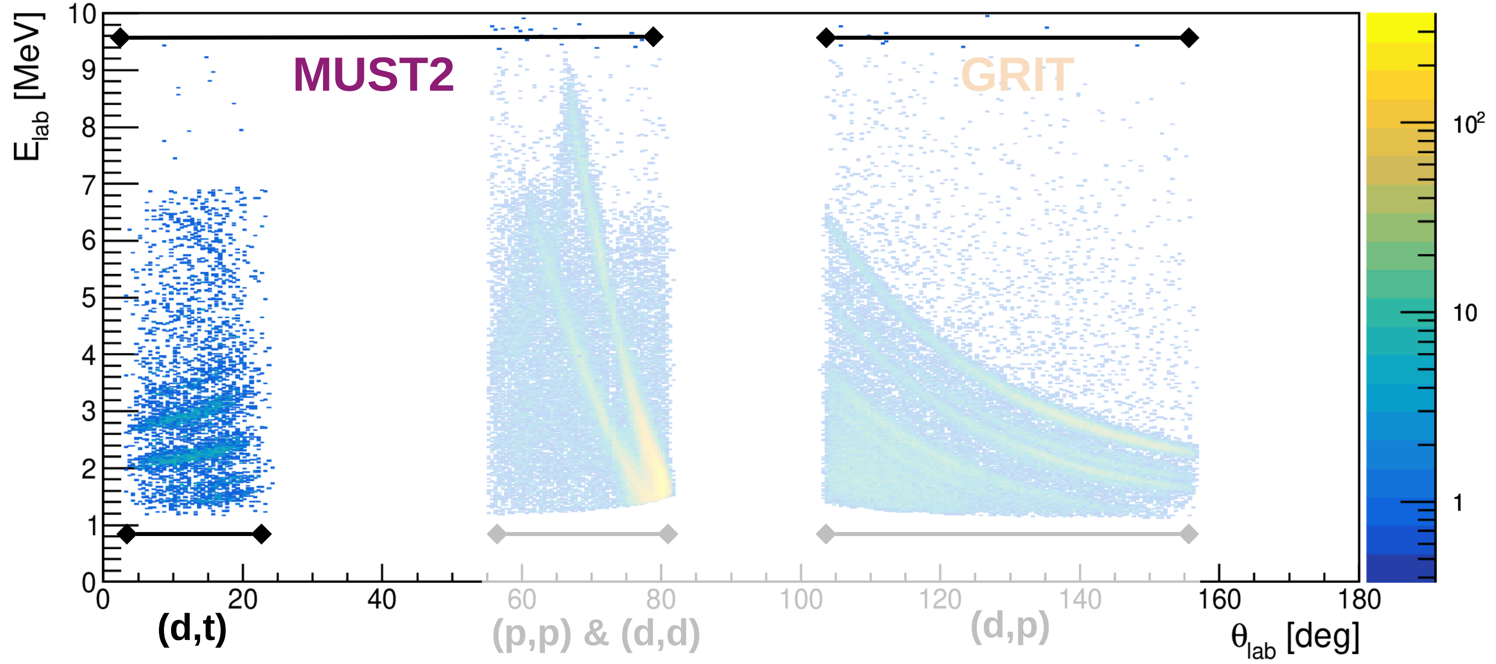

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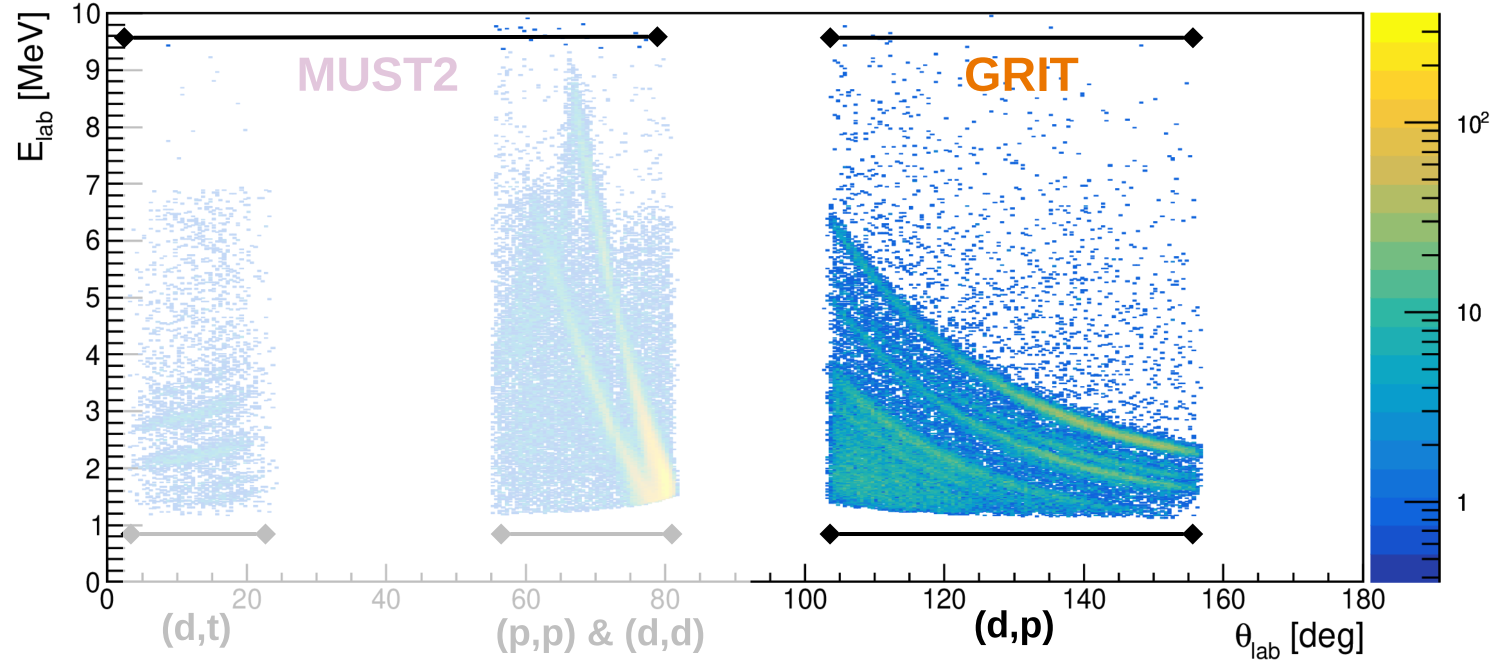

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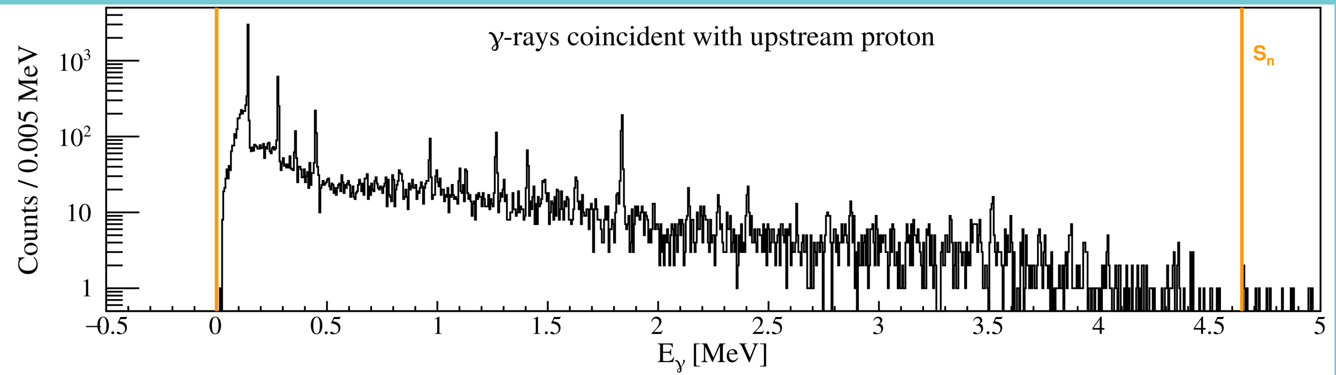
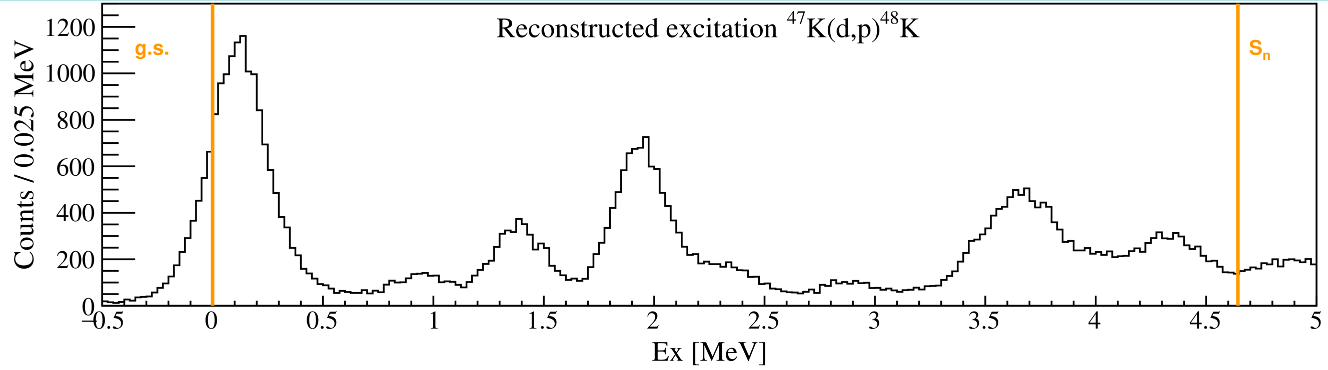
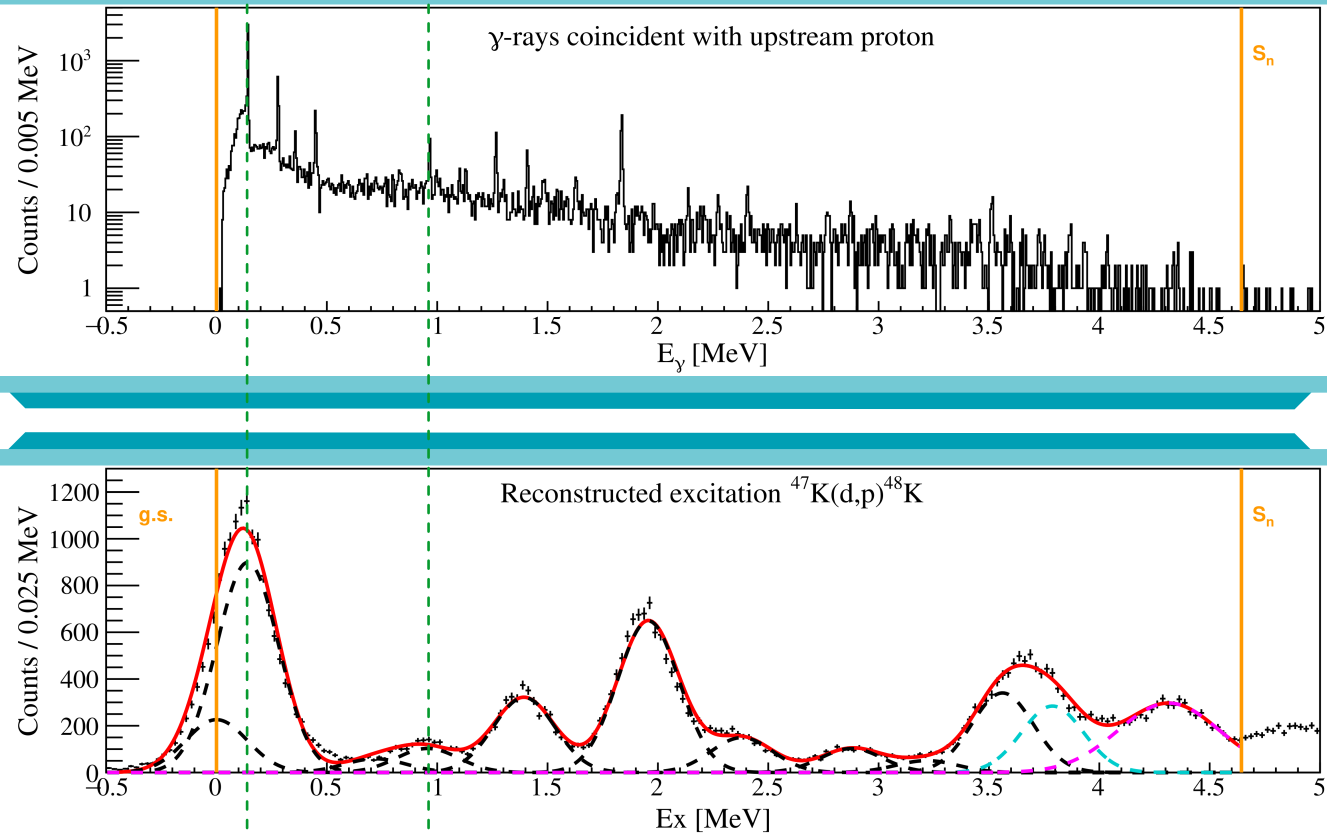




p-γ Coinc.

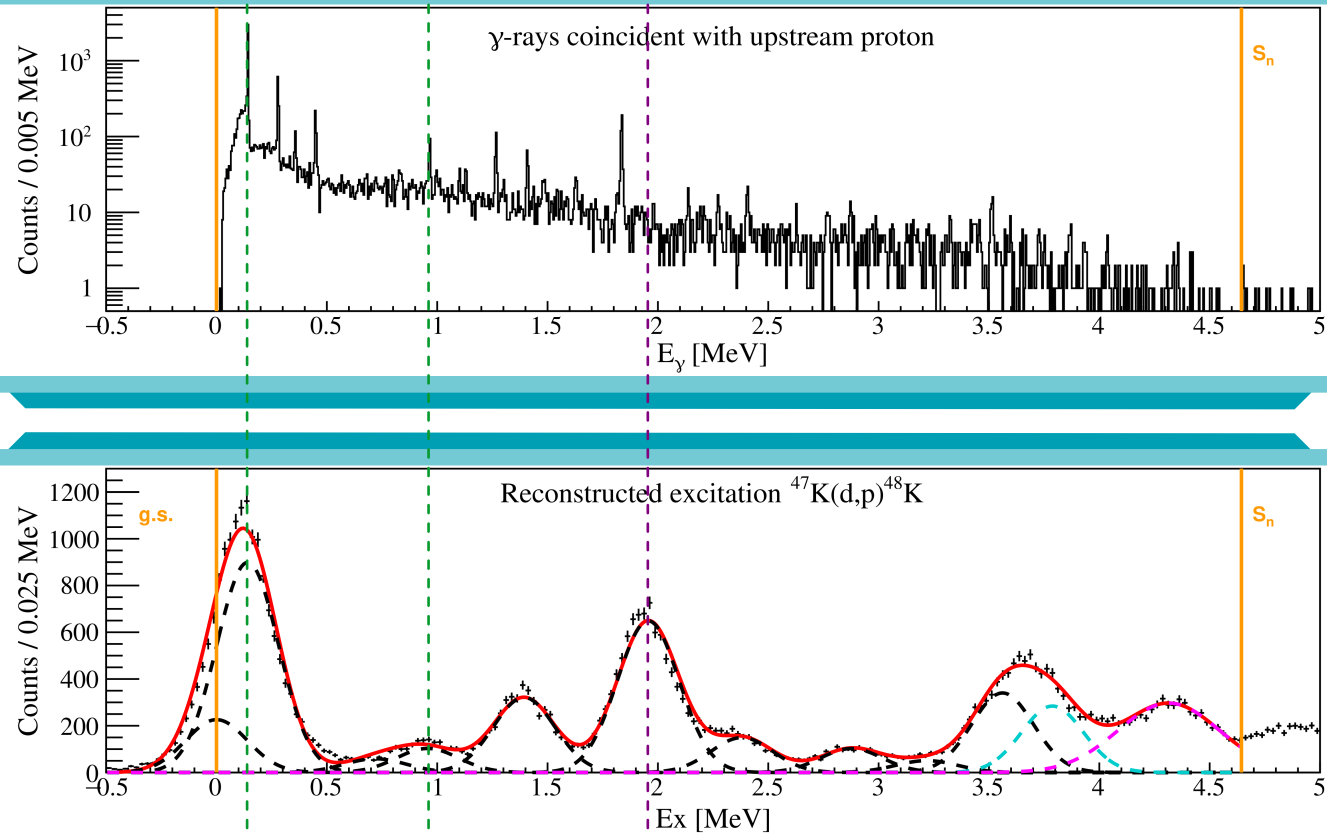
MUGAST & AGATA & VAMOS++



p-γ Coinc.

Precise determination of state energies.

MUGAST & AGATA & VAMOS++

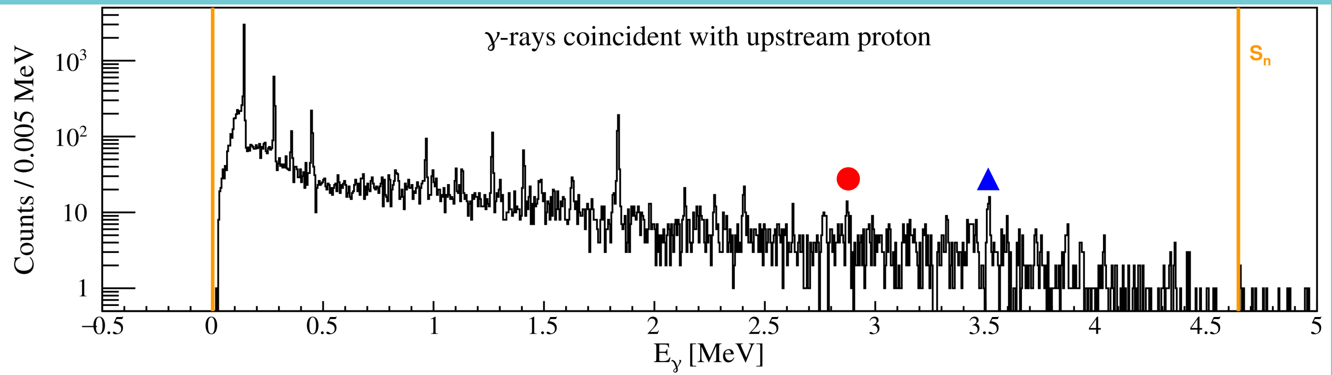


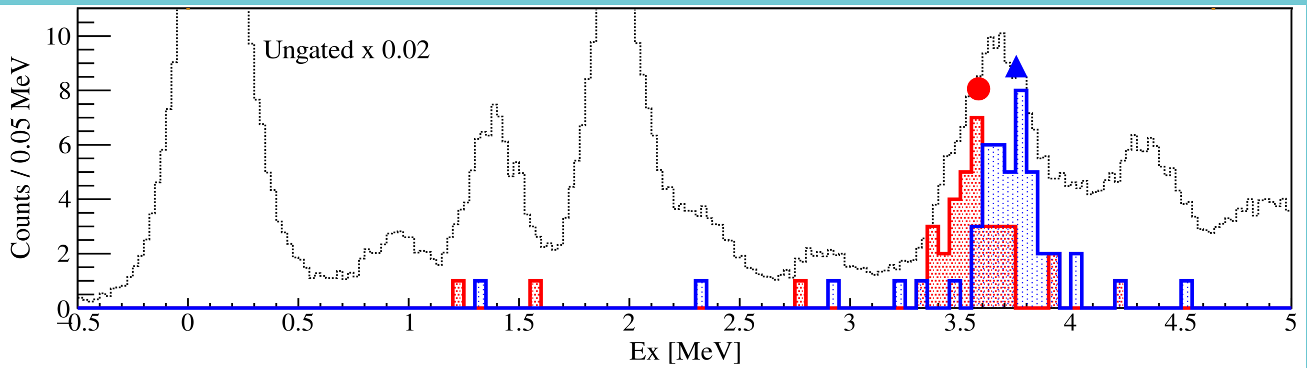
p-γ Coinc.

Precise determination of state energies.

Construction of level scheme.

MUGAST & AGATA & VAMOS++



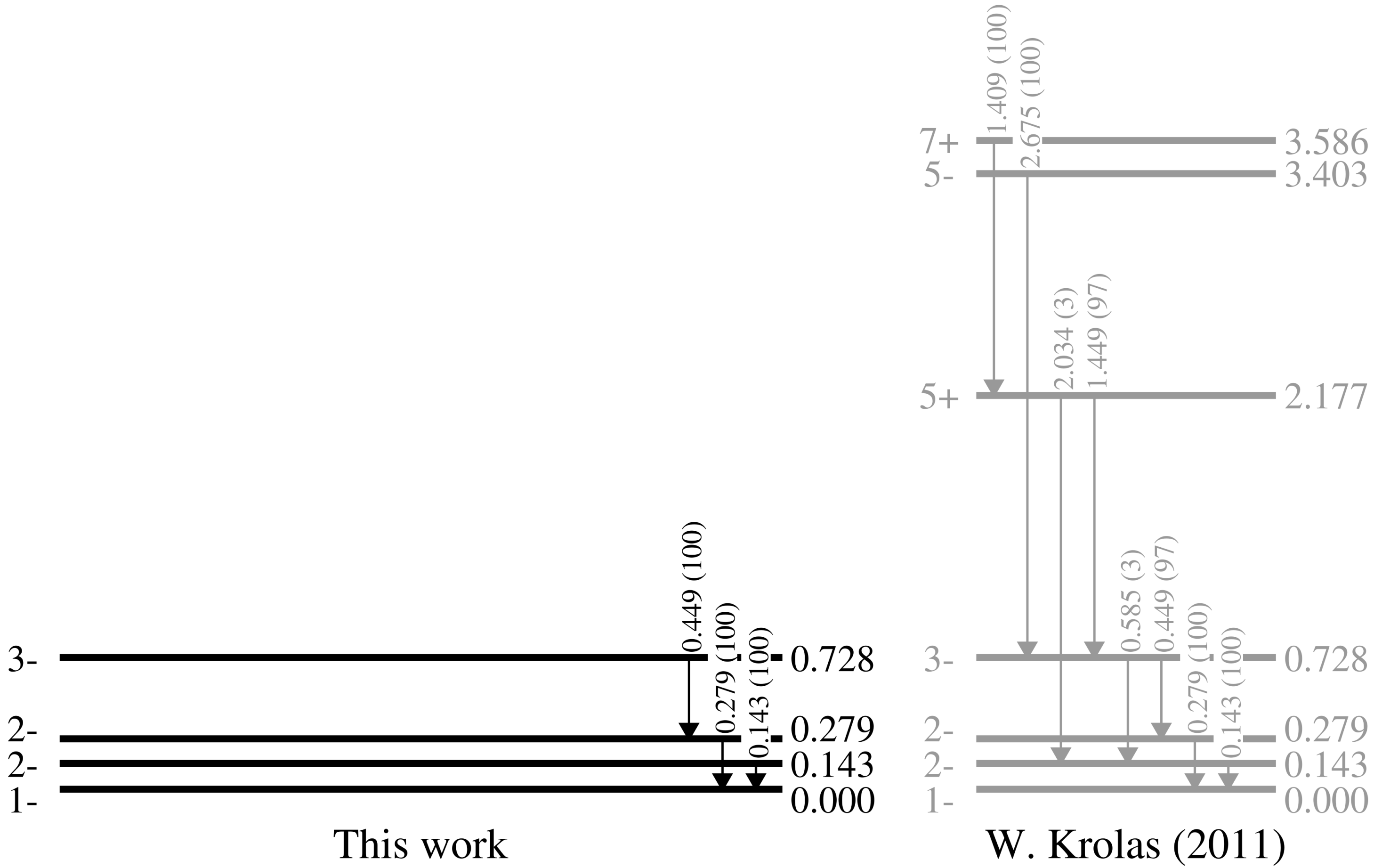


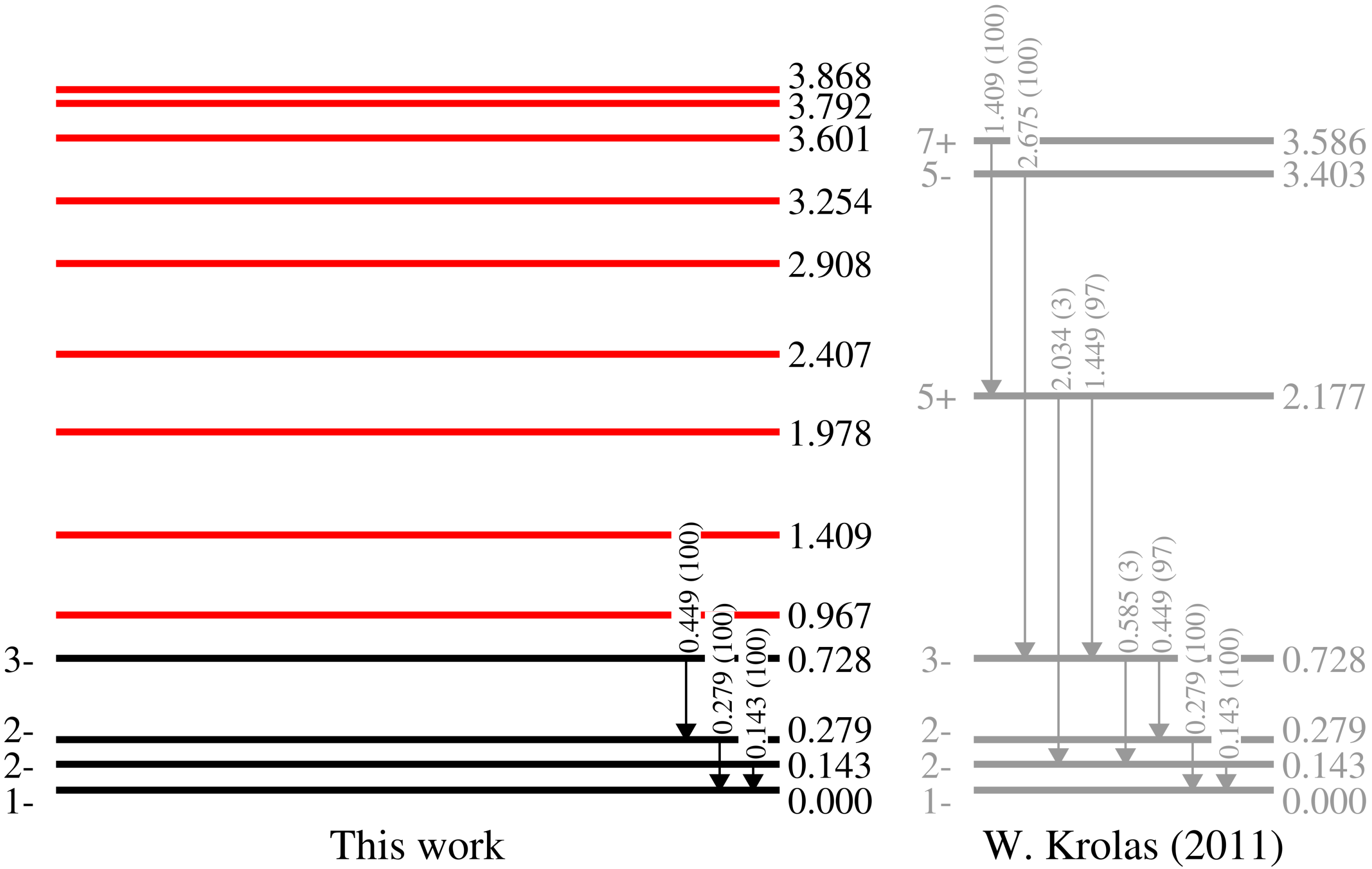
p-γ Coinc.

Precise determination of state energies.

Construction of level scheme.

Clear isolation of specific states.


3-
2-
2-
1-
0.449 (100)
0.279 (100)
0.143 (100)
0.728
0.279
0.143
0.000
This work
7+
5-
5+
3-
2-
2-
1-
1.409 (100)
2.675 (100)
2.034 (3)
1.449 (97)
0.585 (3)
0.449 (97)
0.279 (100)
0.143 (100)
3.586
3.403
2.177
0.728
0.279
0.143
0.000
W. Krolas (2011)


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
0.449 (100)
0.279 (100)
0.143 (100)
This work
7+ 3.586
5- 3.403
5+ 2.177
3- 0.728
2- 0.279
2- 0.143
1- 0.000
1.409 (100)
2.675 (100)
2.034 (3)
1.449 (97)
0.585 (3)
0.449 (97)
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0.143 (100)
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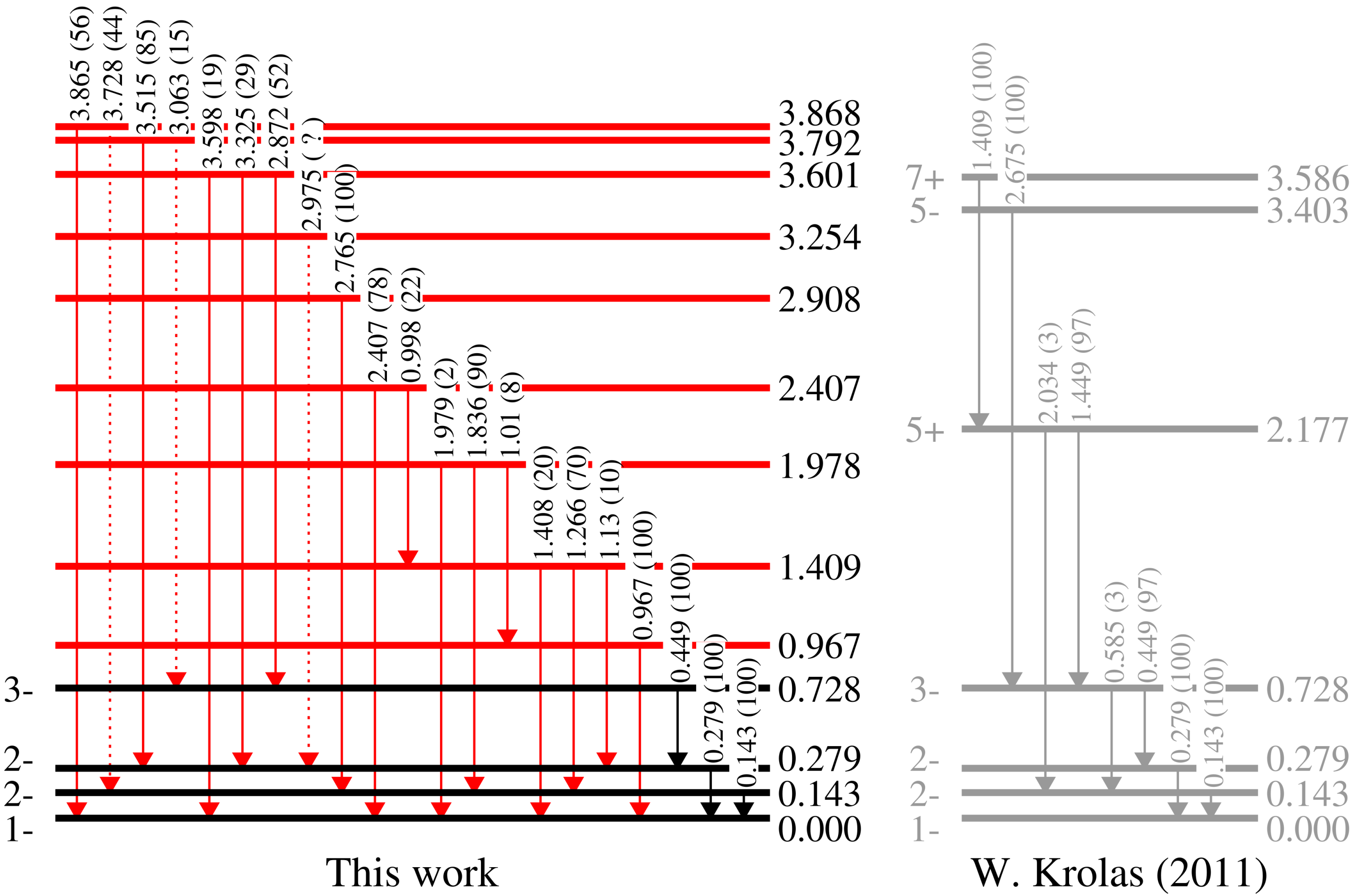
3.865 (56)
3.728 (44)
3.515 (85)
3.063 (15)
3.598 (19)
3.325 (29)
2.872 (52)
2.975 (?)
2.765 (100)
2.407 (78)
0.998 (22)
1.979 (2)
1.836 (90)
1.01 (8)
1.408 (20)
1.266 (70)
1.13 (10)
0.967 (100)
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3.868
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This work
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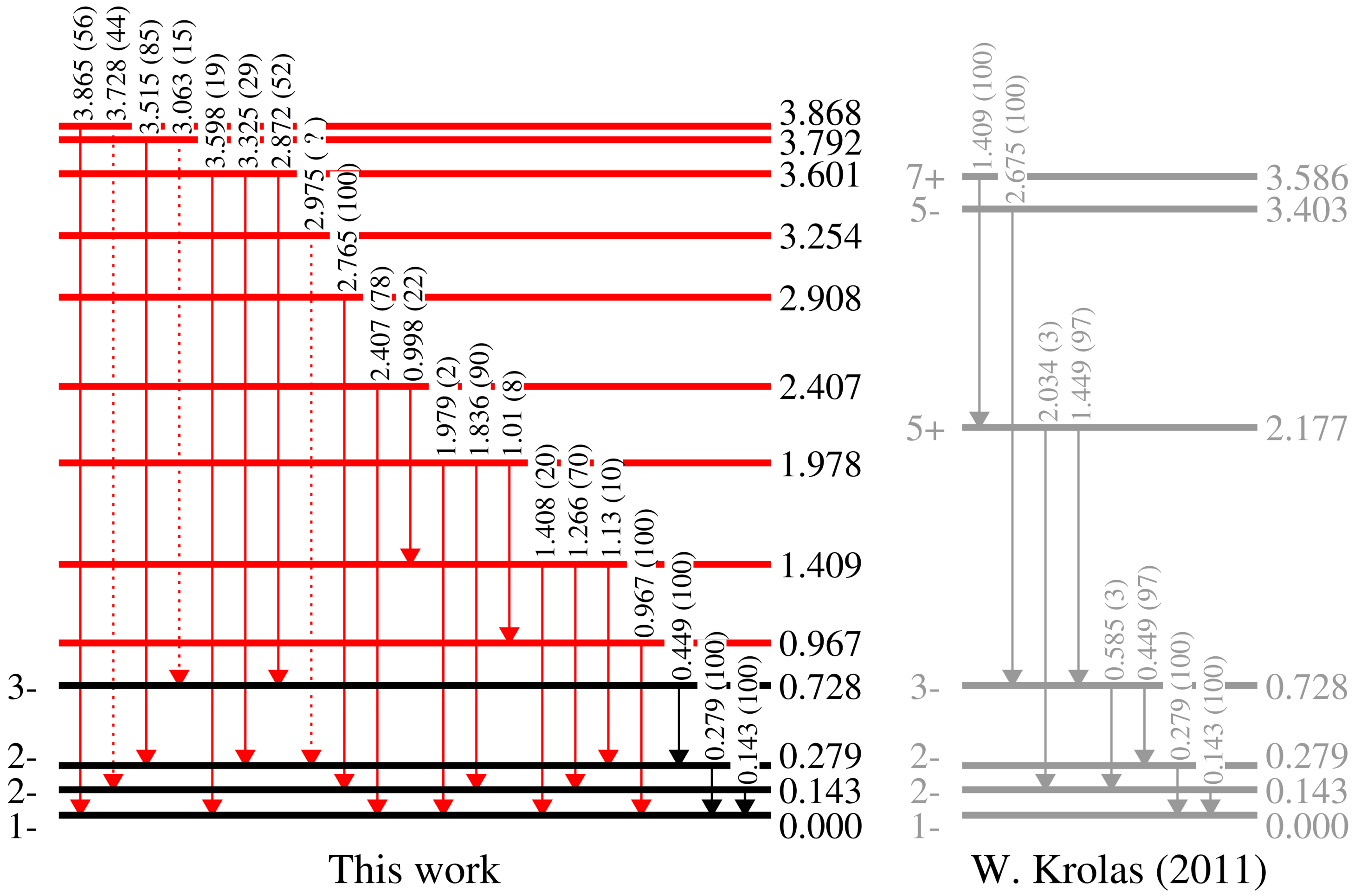
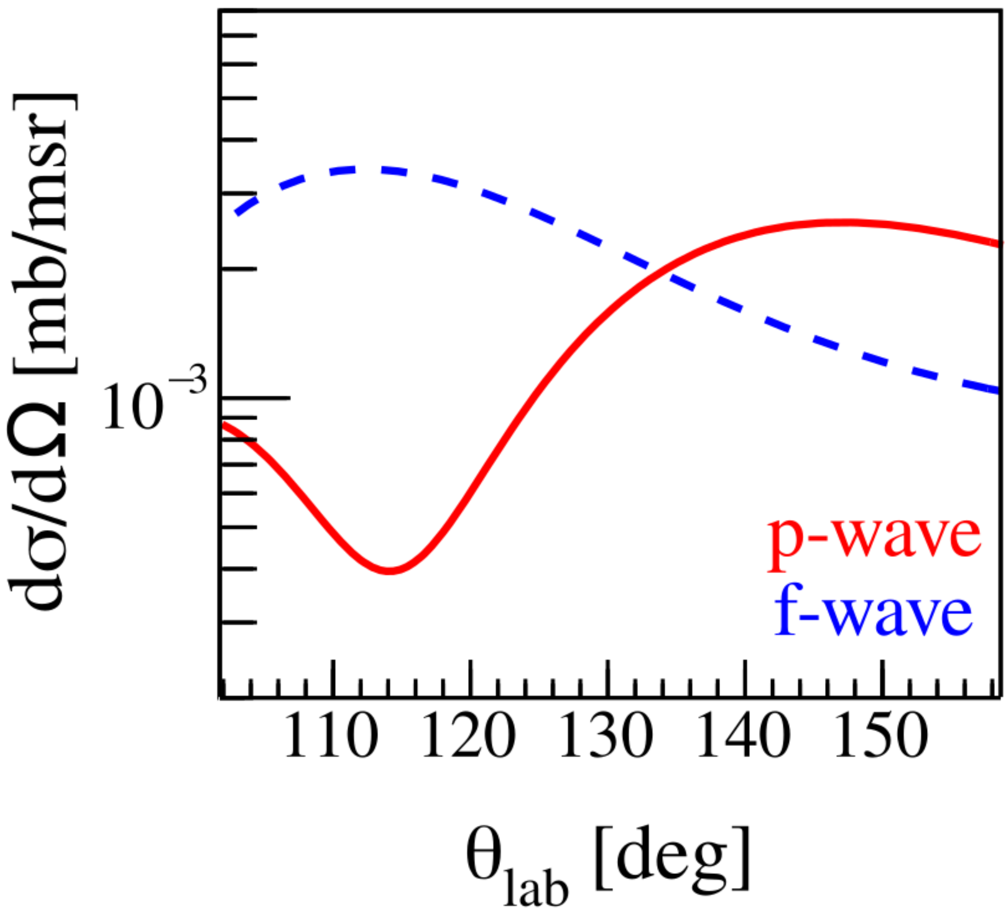
W. Krolas (2011)

Spins & spectroscopic factors?



Angular Distributions

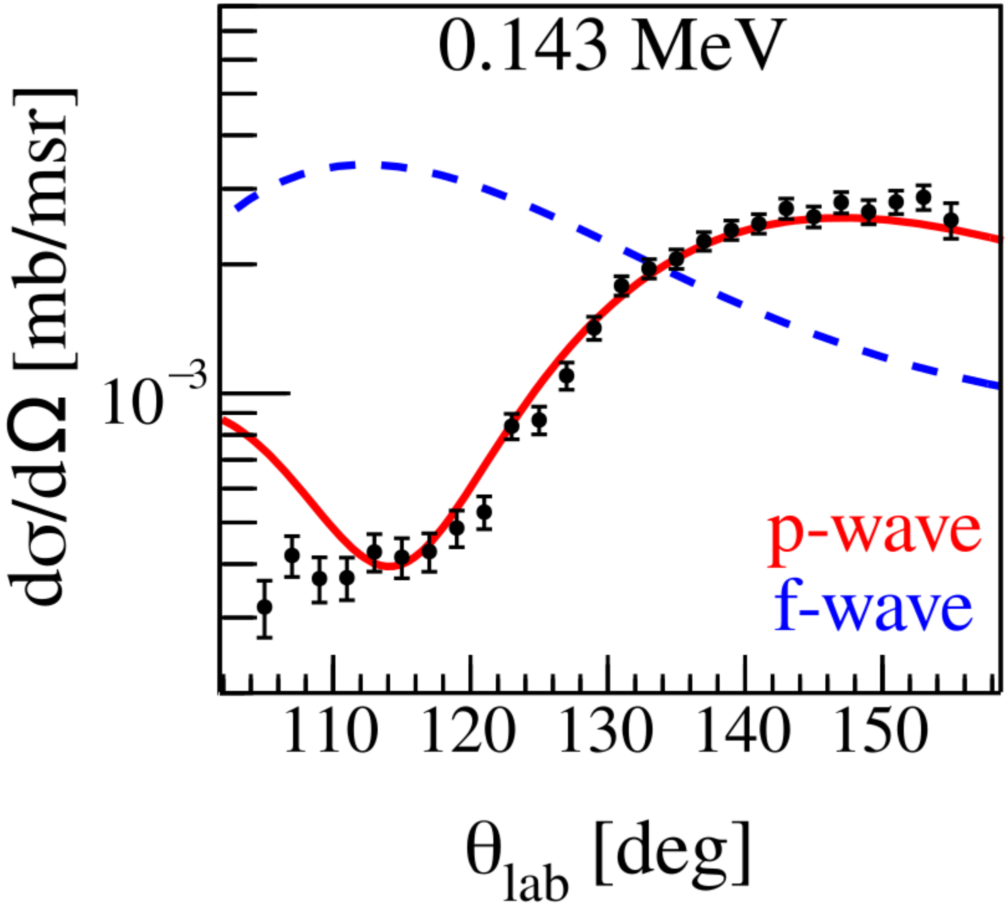
- Discriminate between p-wave (L=1) and f-wave (L=3) transfer by differential cross section



Angular Distributions

- Discriminate between p-wave (L=1) and f-wave (L=3) transfer by differential cross section

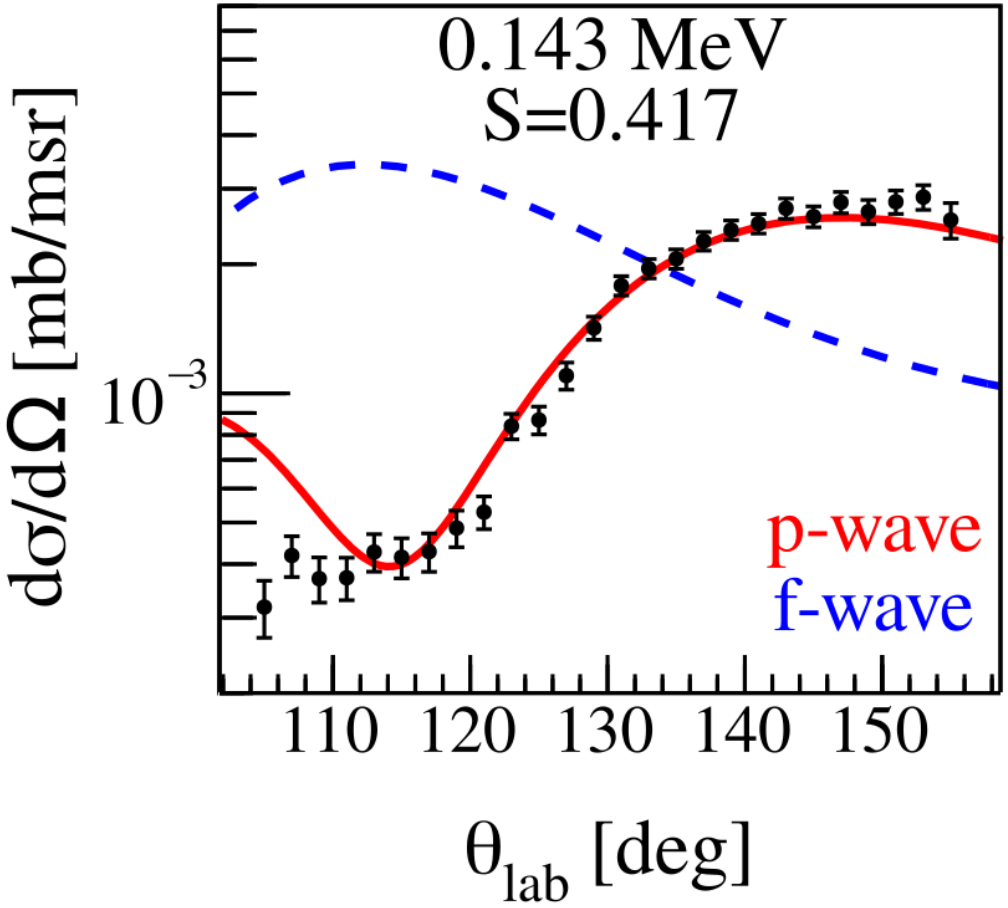
- Comparison to data provides unambiguous L-transfer assignment



Angular Distributions

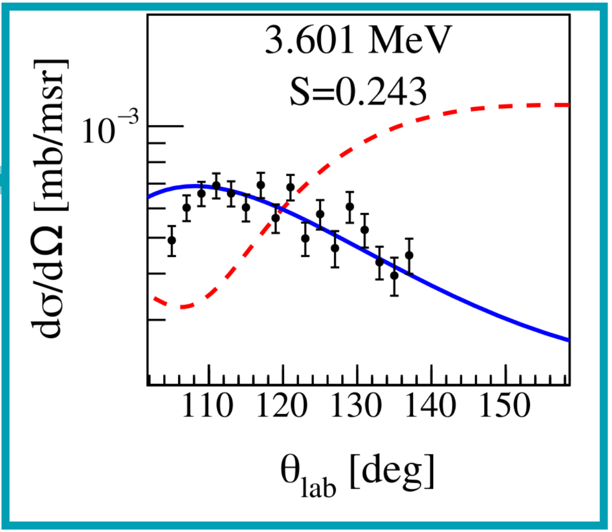
- Discriminate between p-wave (L=1) and f-wave (L=3) transfer by differential cross section
- Comparison to data provides unambiguous L-transfer assignment
- Scaling factor between exp. and theory represents strength of population

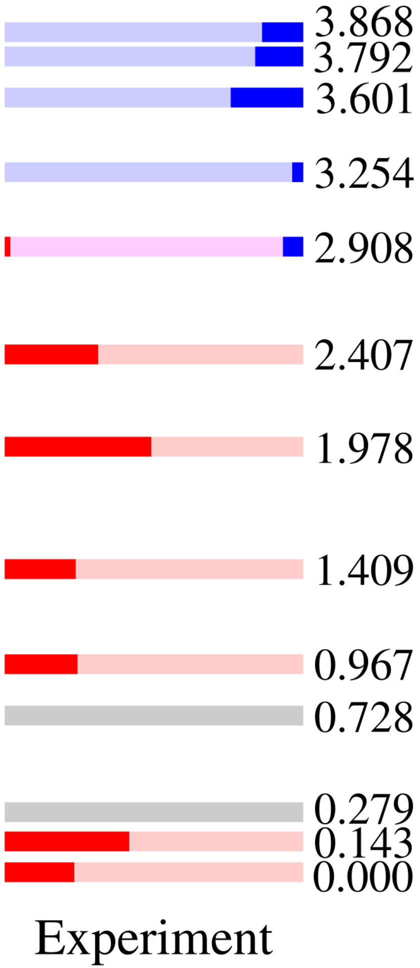
→ Spectroscopic factor

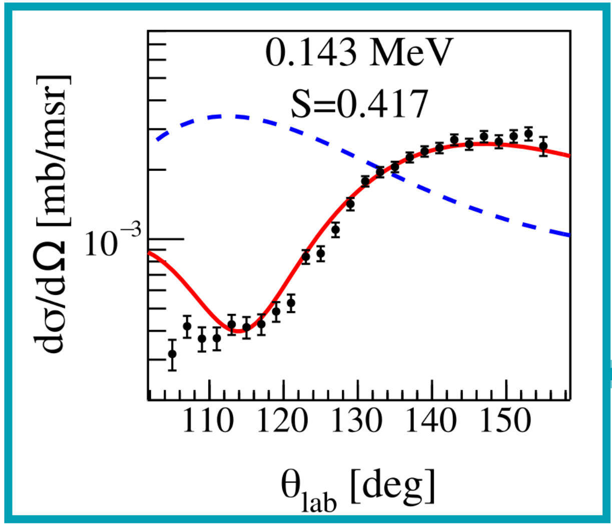


Distinct regions of **p-wave** states and **f-wave** states.

p-wave: $p_{1/2}$, $p_{3/2}$
f-wave: $f_{5/2}$



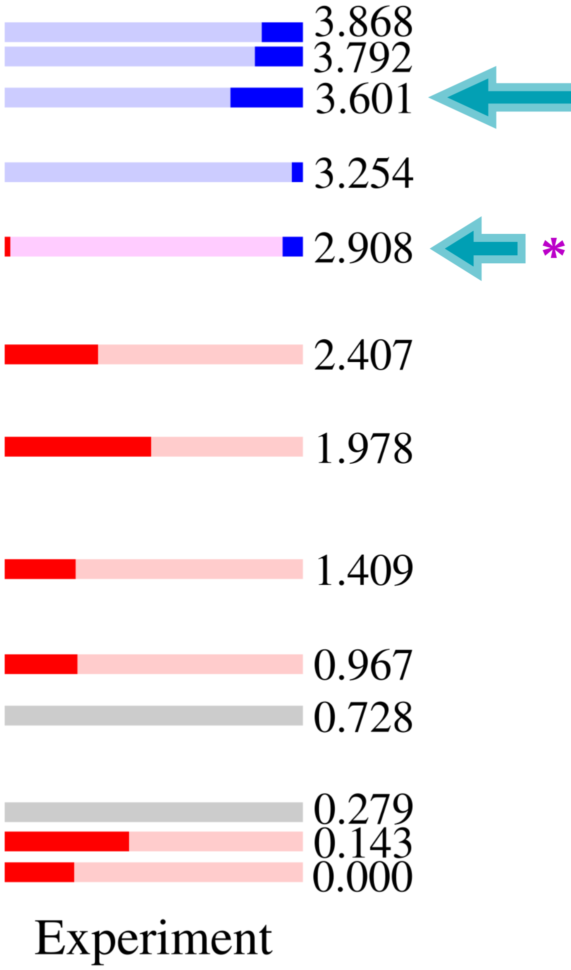


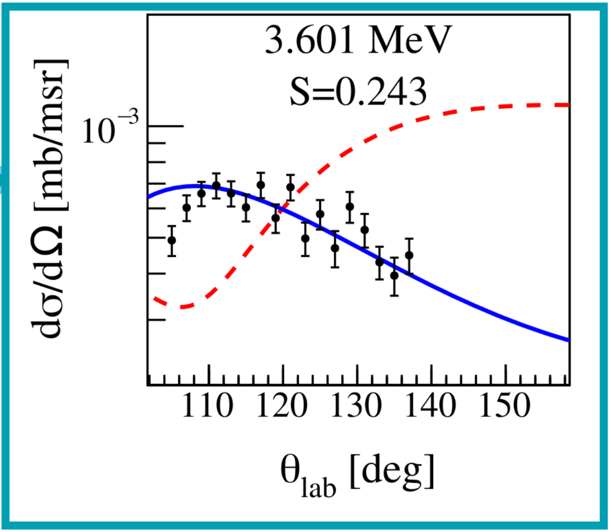


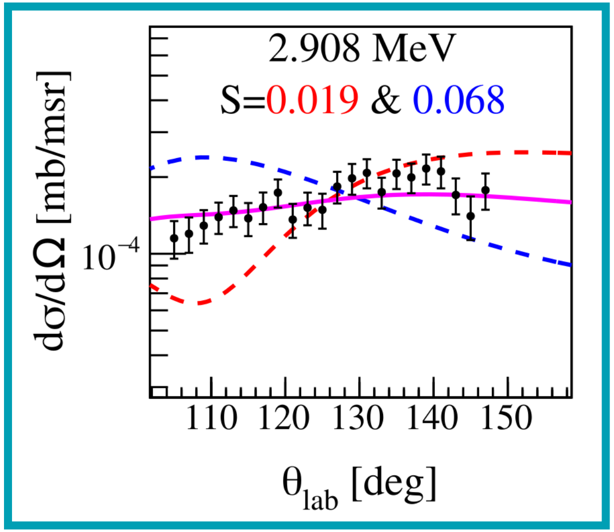
Distinct regions of **p-wave** states and **f-wave** states.

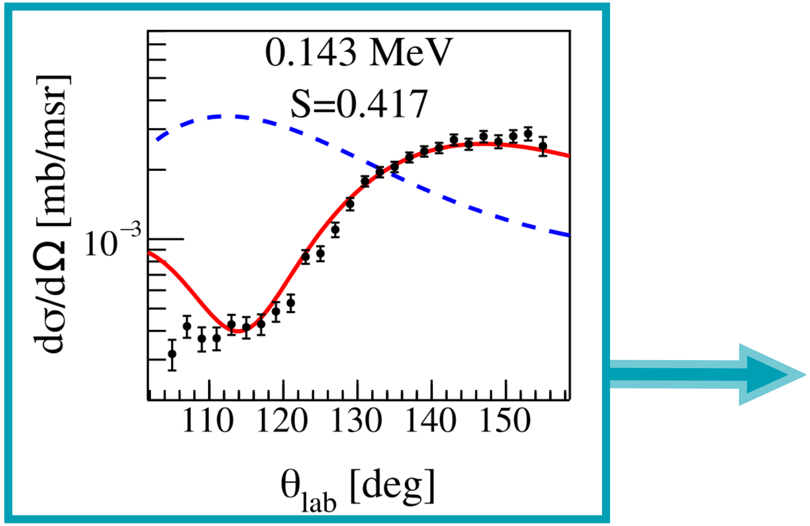
p-wave: $p_{1/2}$, $p_{3/2}$
f-wave: $f_{5/2}$

Preliminary results suggest **mixed state** between the two regions.

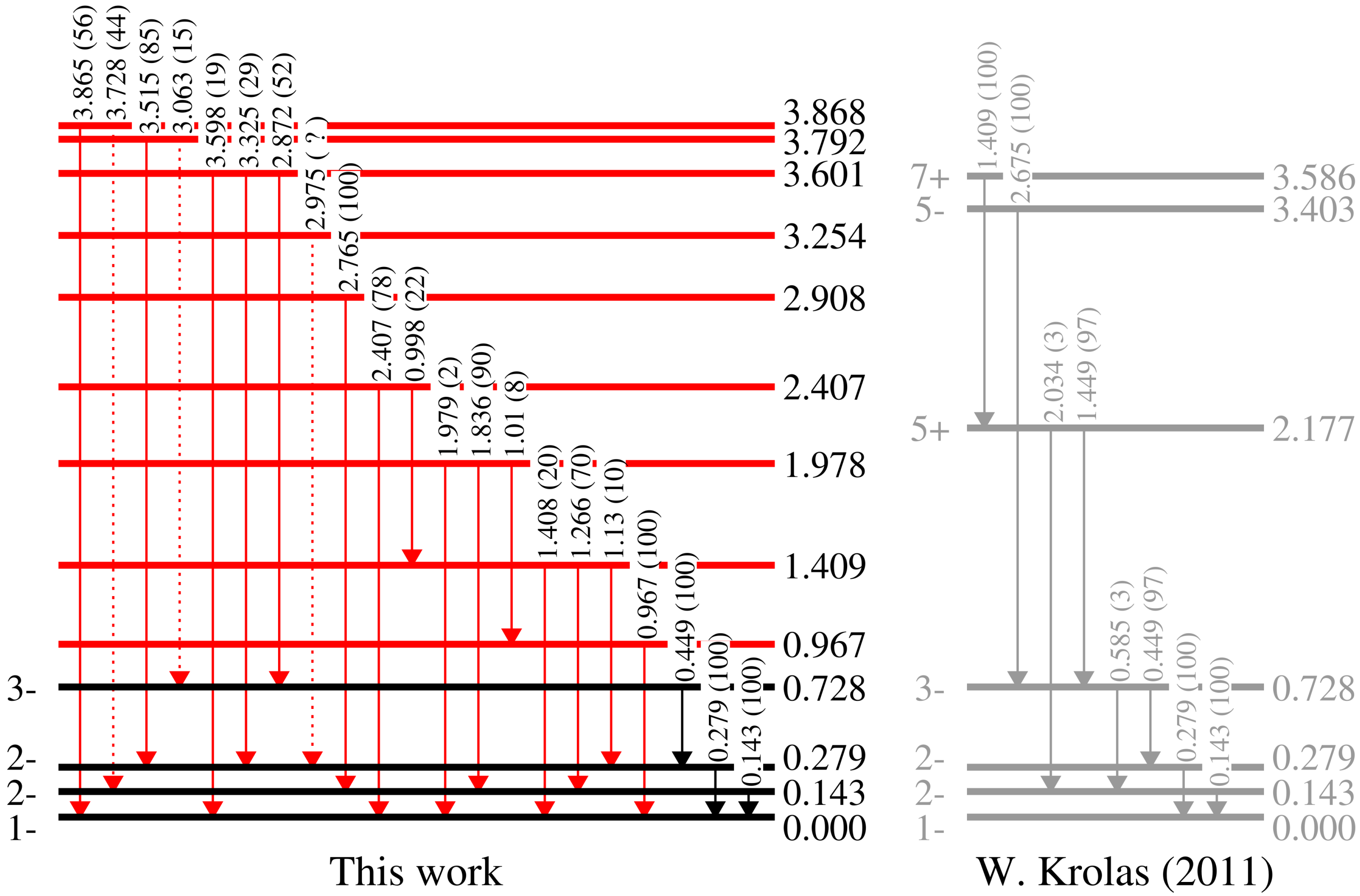




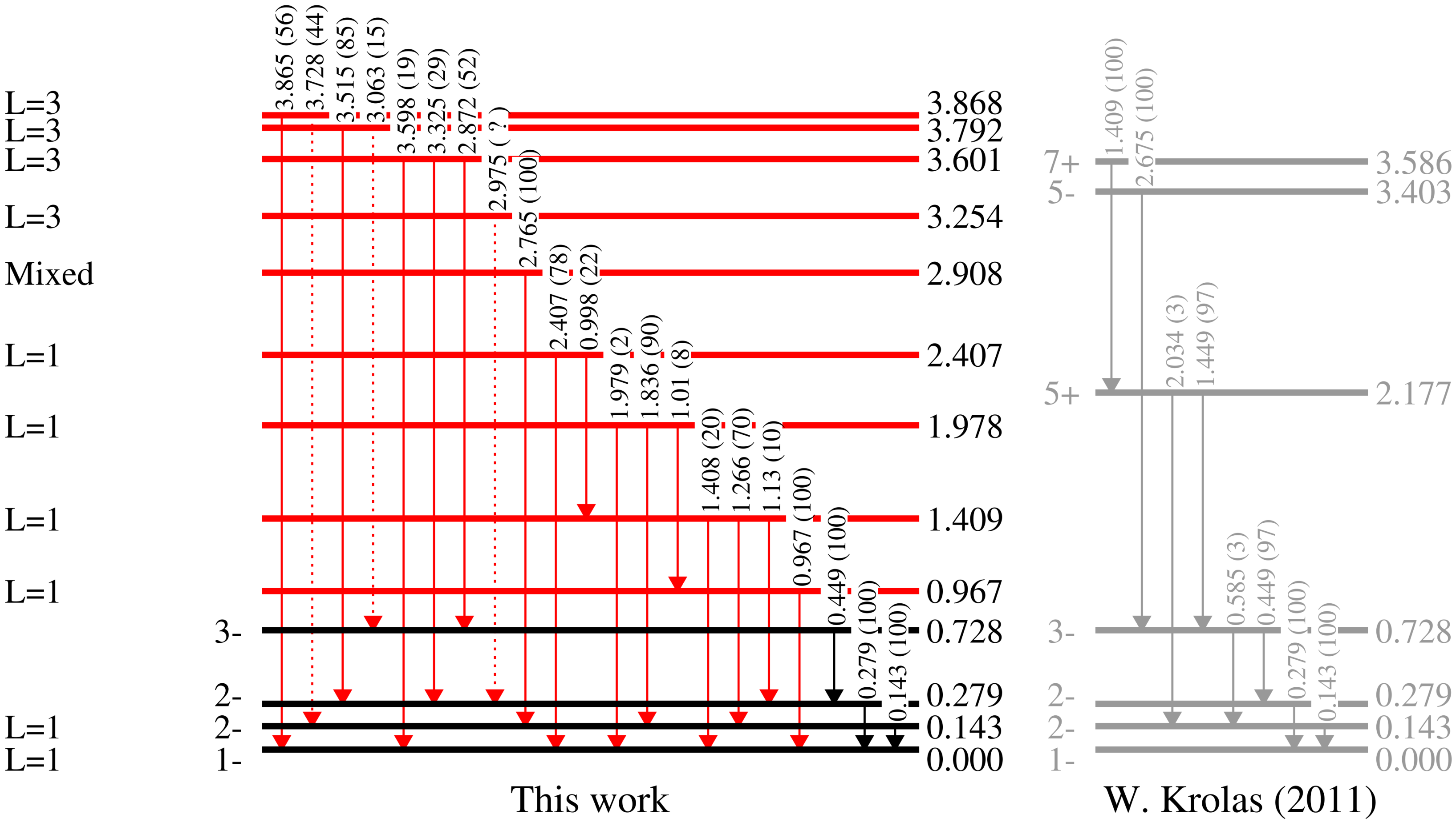




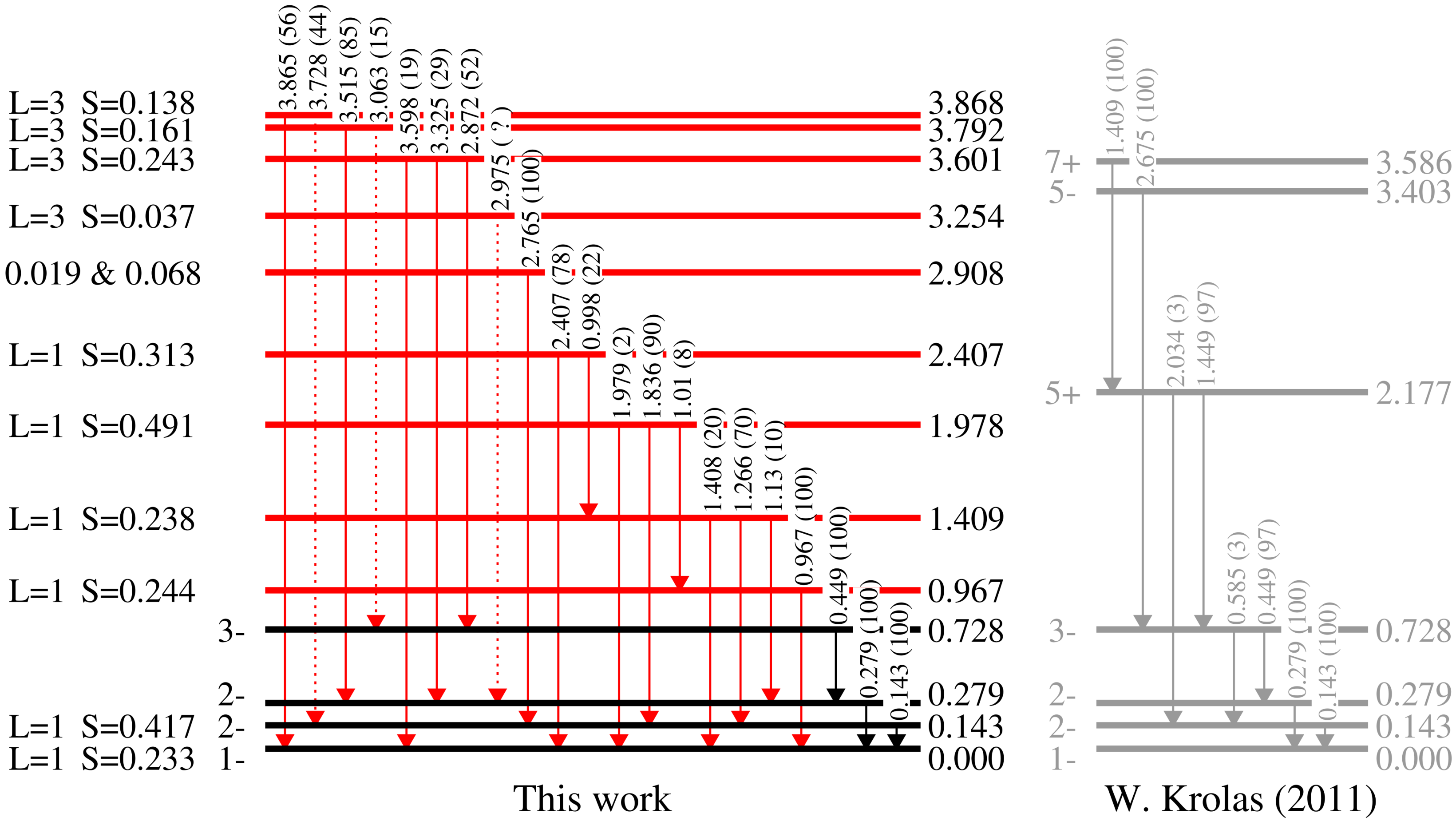
γ-ray transitions + ...



γ-ray transitions + L-transfers + ...



γ-ray transitions + L-transfers + spectroscopic factors (vs. theory) = ...



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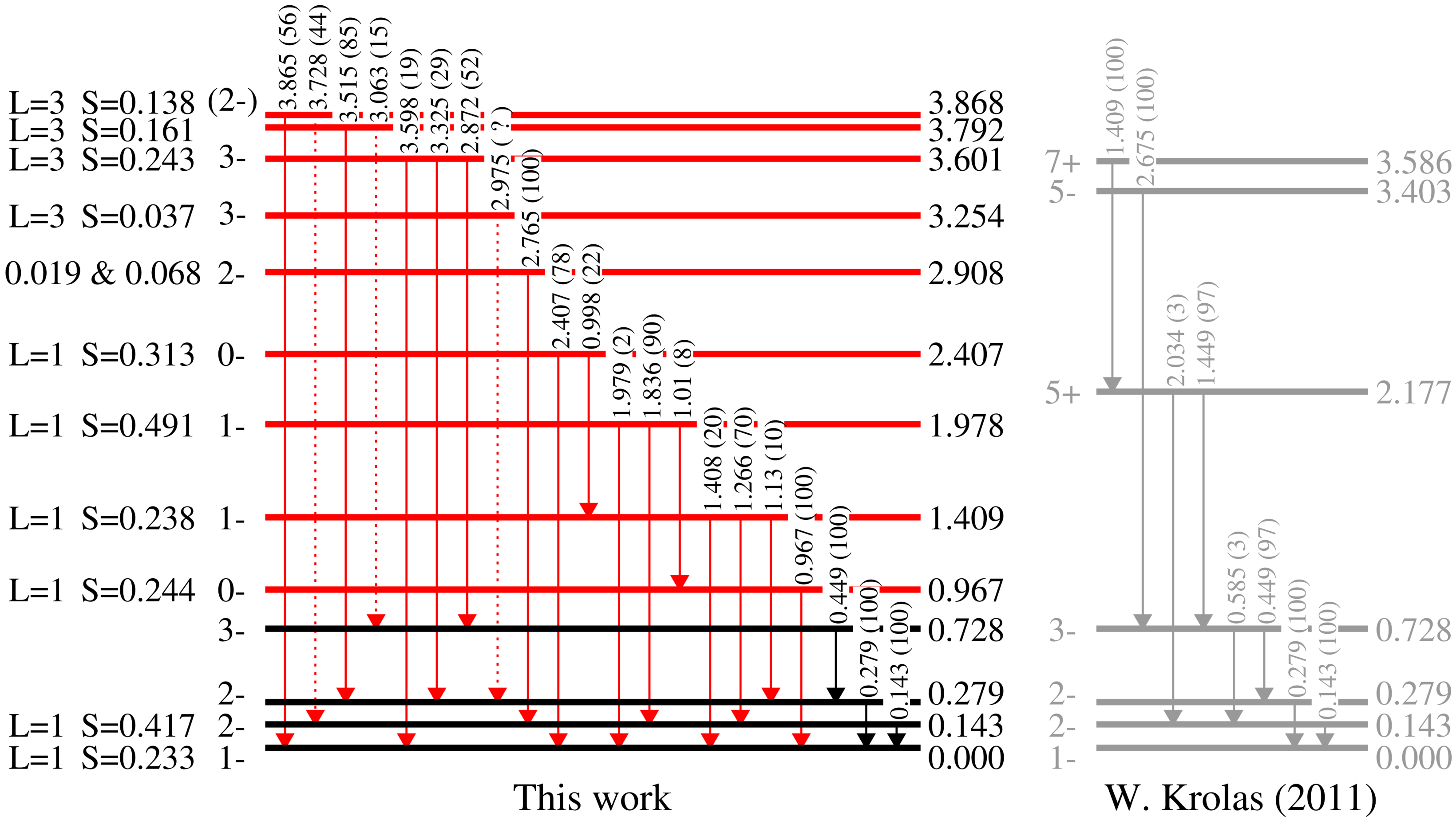
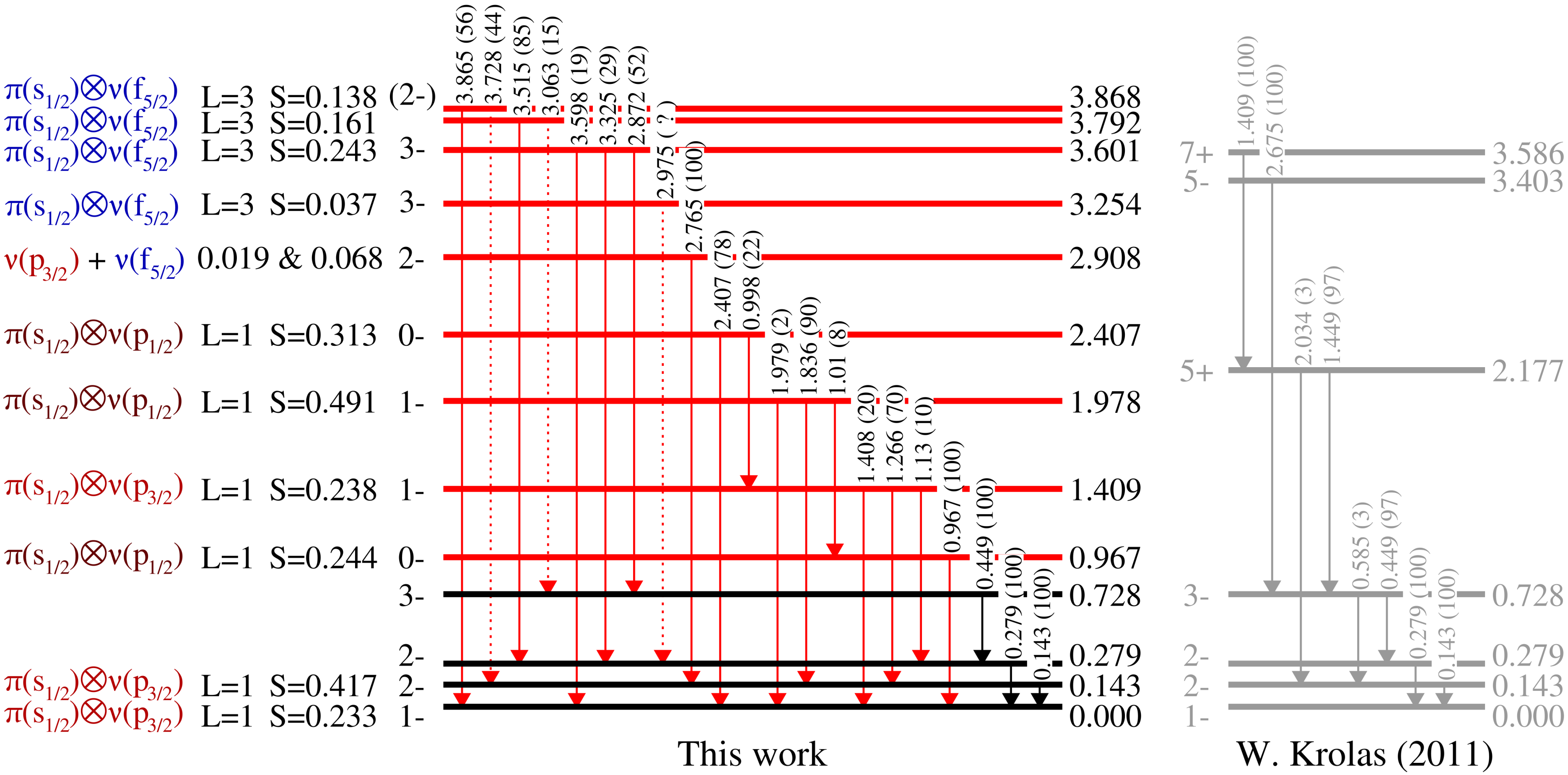
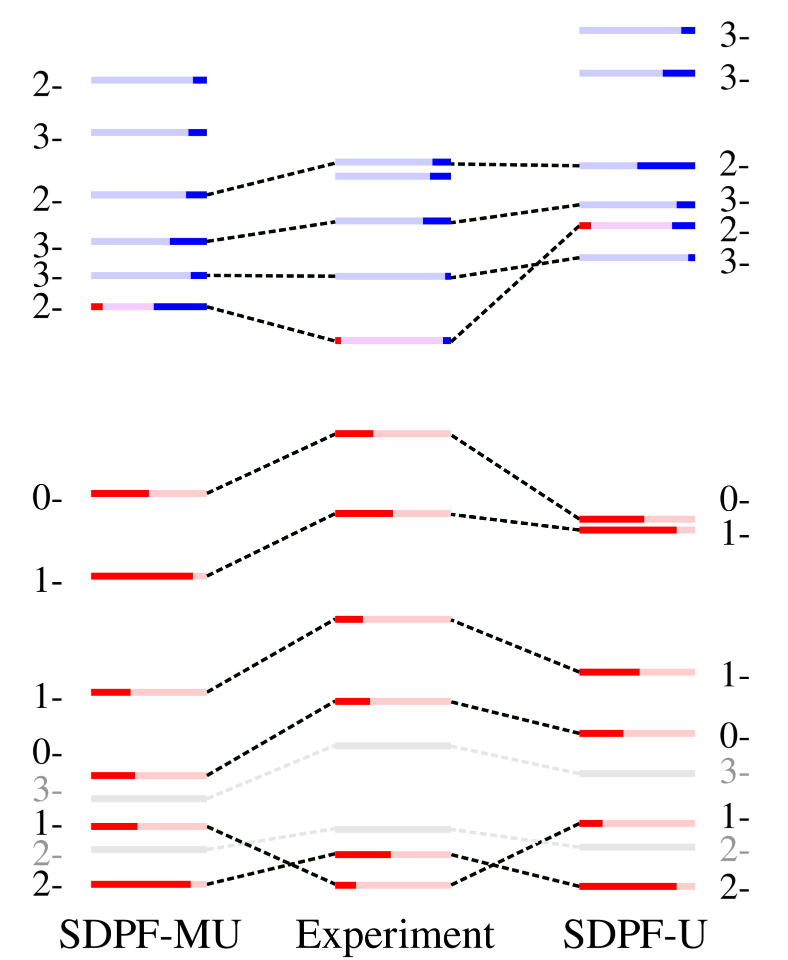
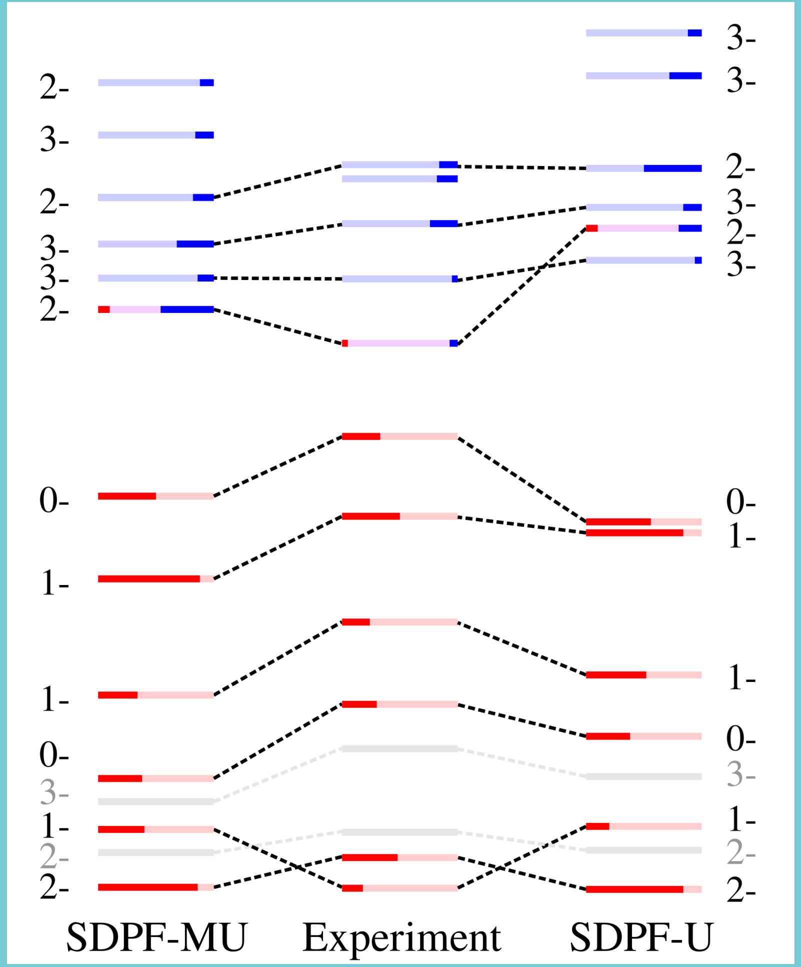


γ-ray transitions + L-transfers + spectroscopic factors (vs. theory) = state spin (J^π) + structure



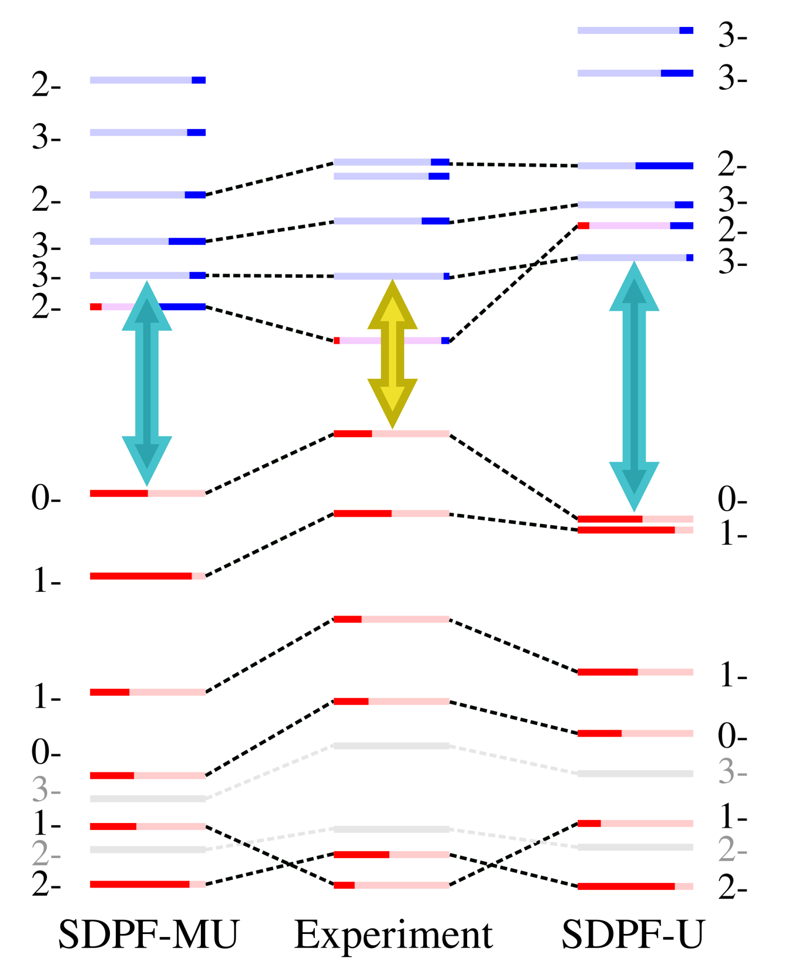


Observations from (d,p)



Observations from (d,p)

Shell model fails to predict 1- ground state.



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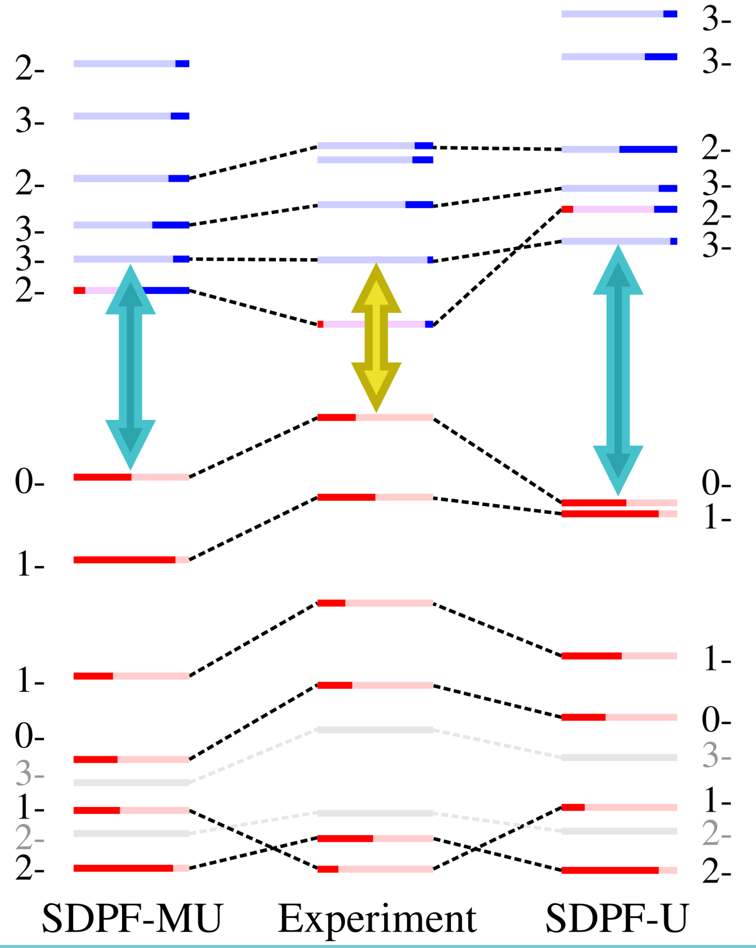

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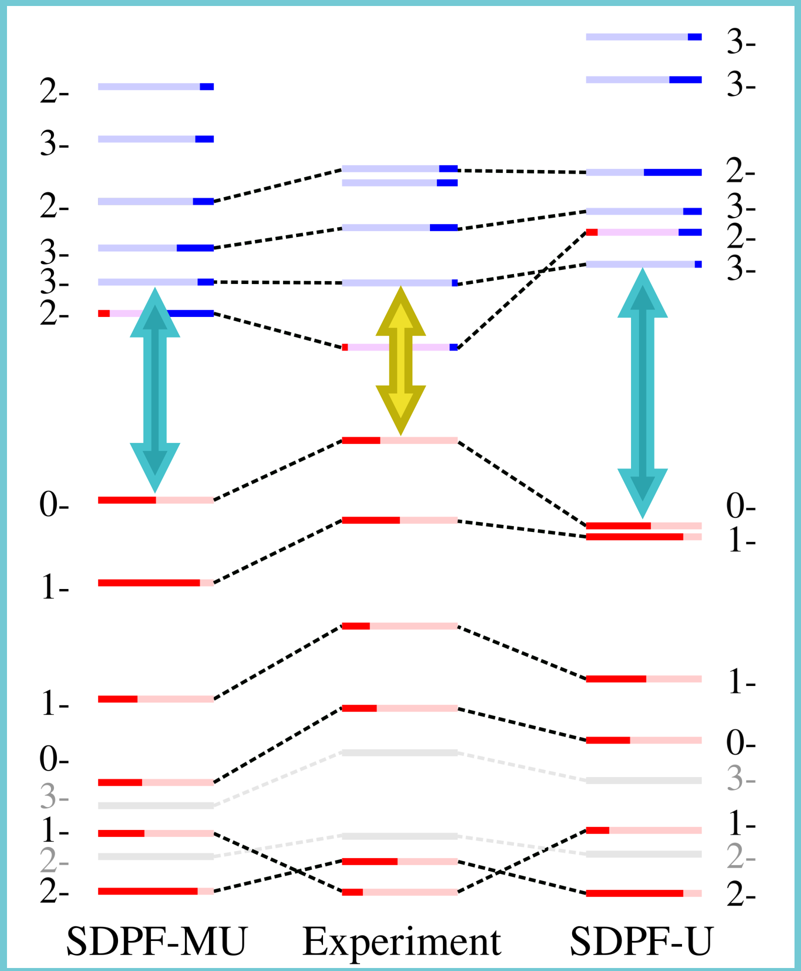

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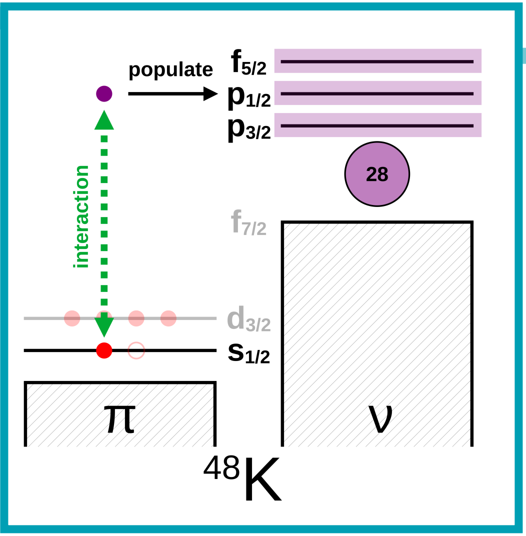
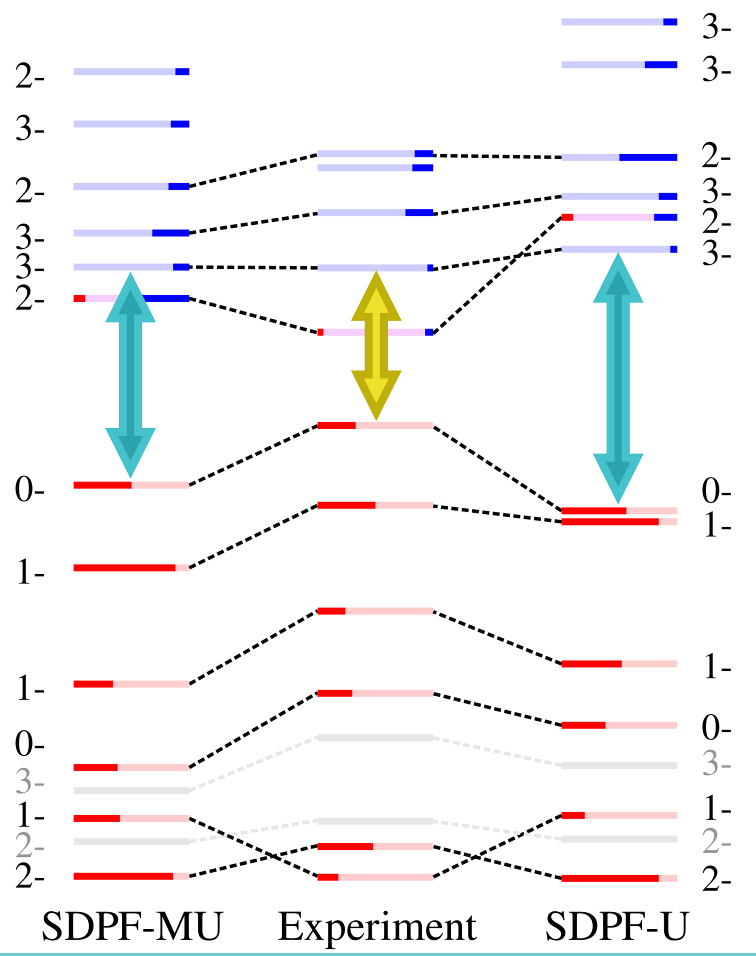
- Implications for N=34?





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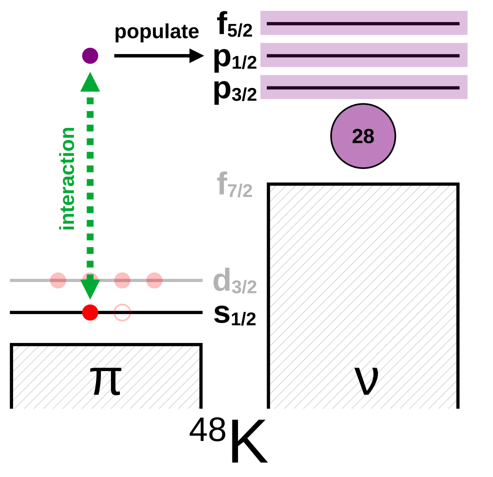

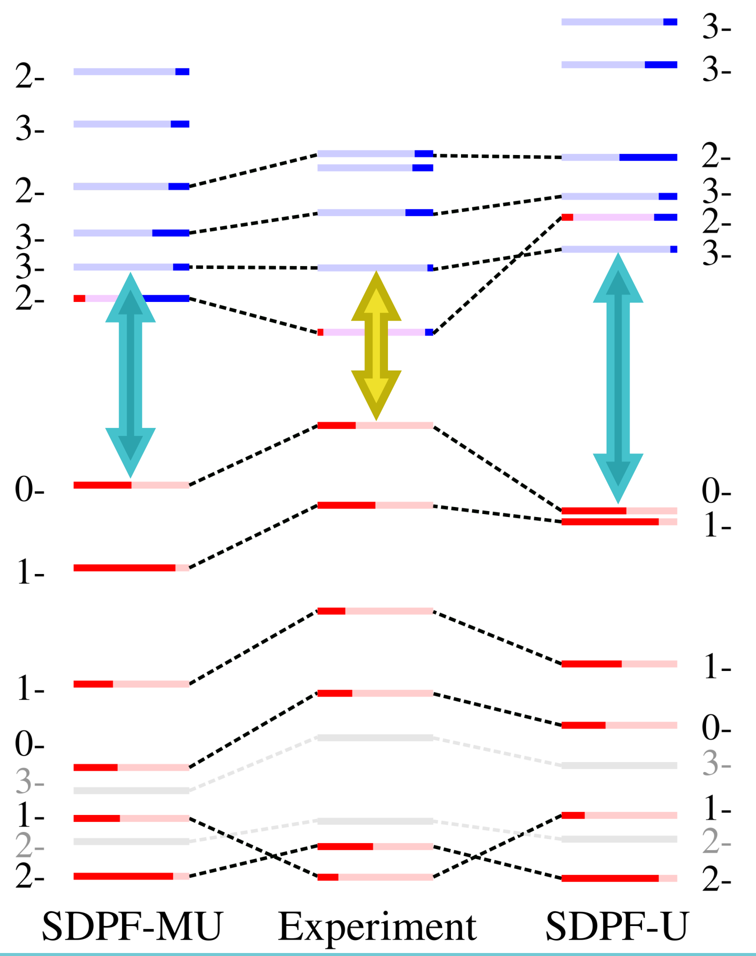

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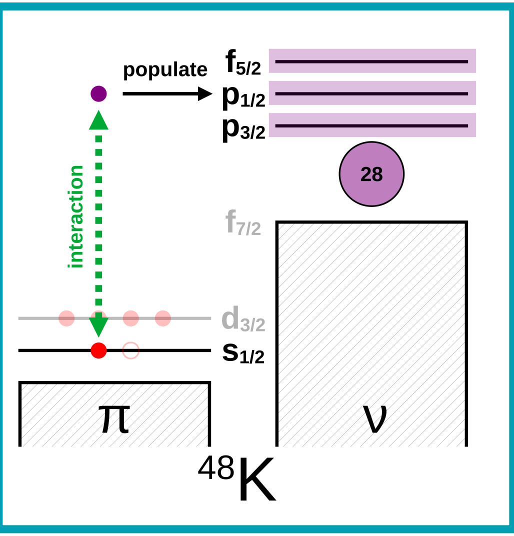

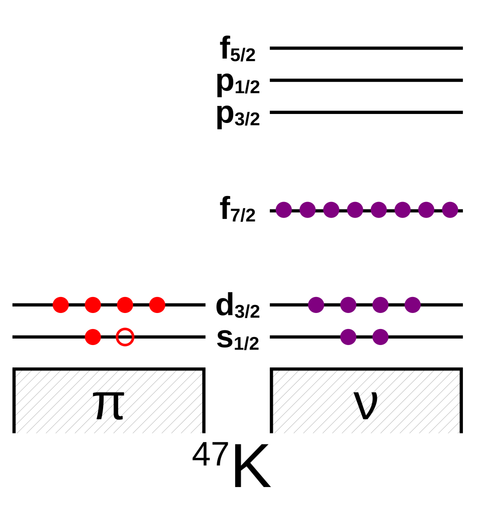

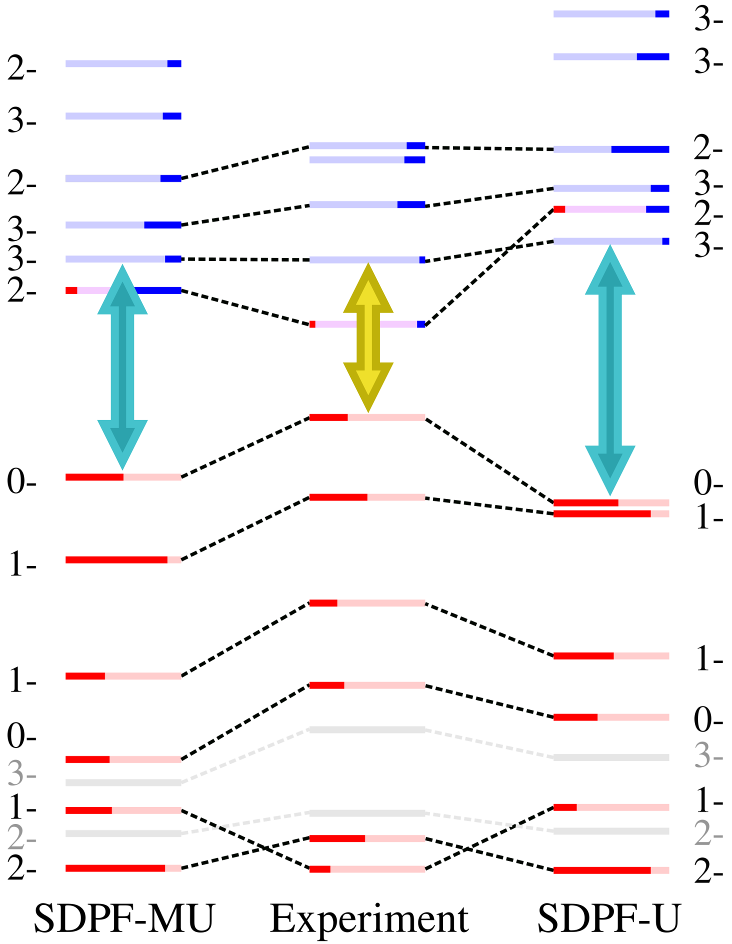

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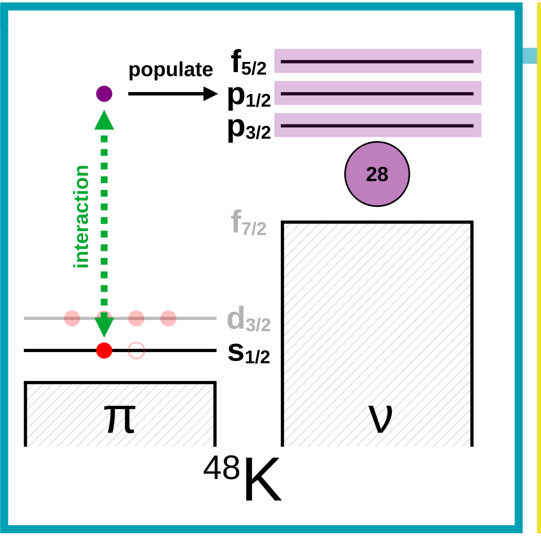
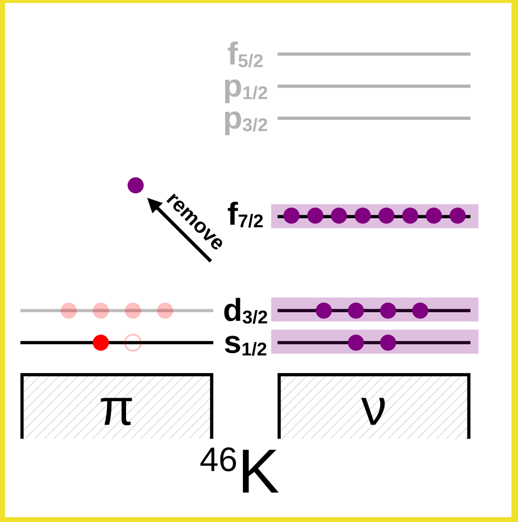
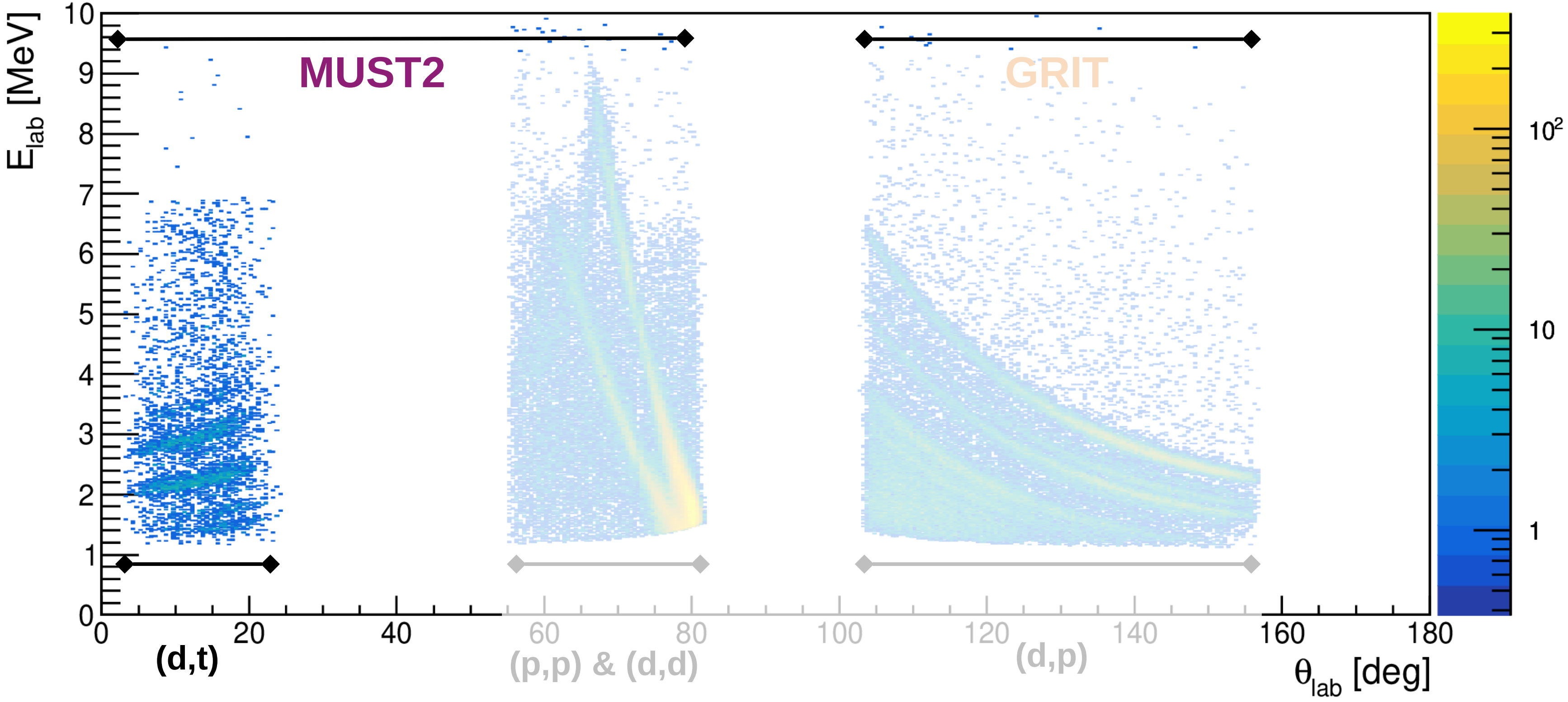
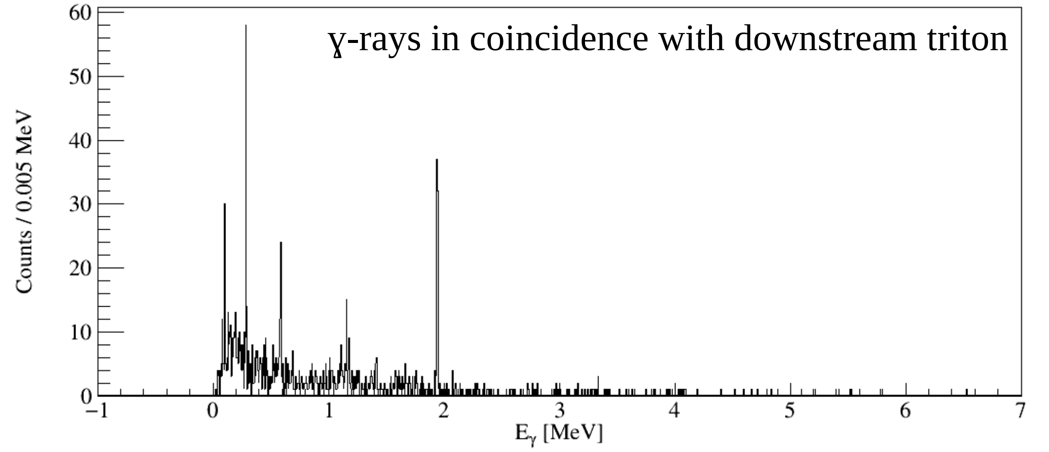
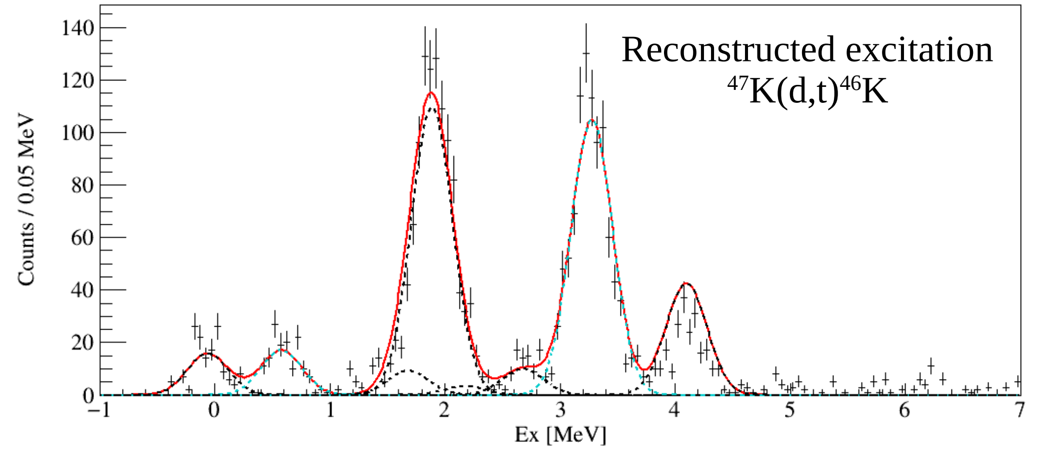




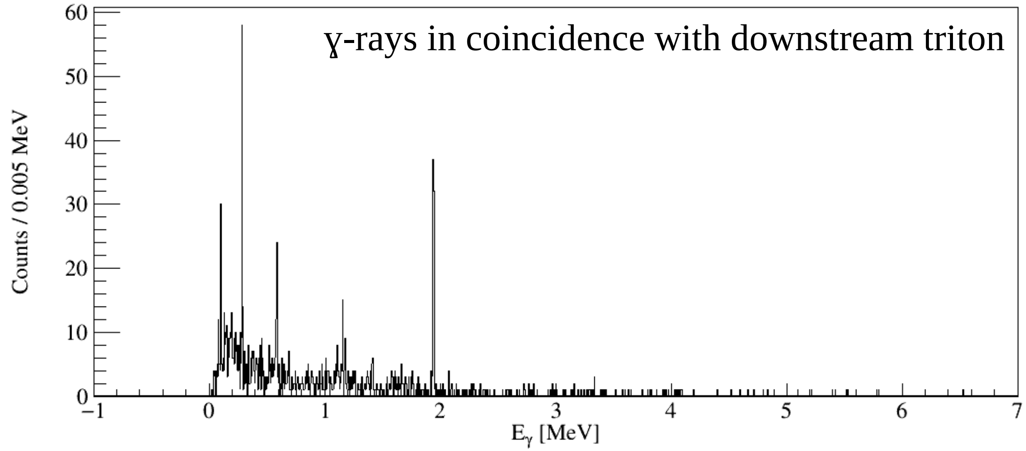


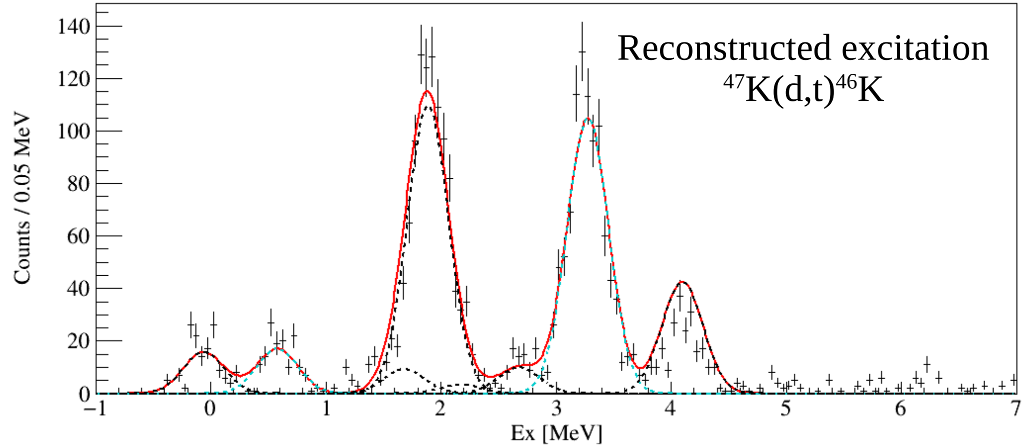
Collected simultaneous data for **adding** and **removing** a neutron.

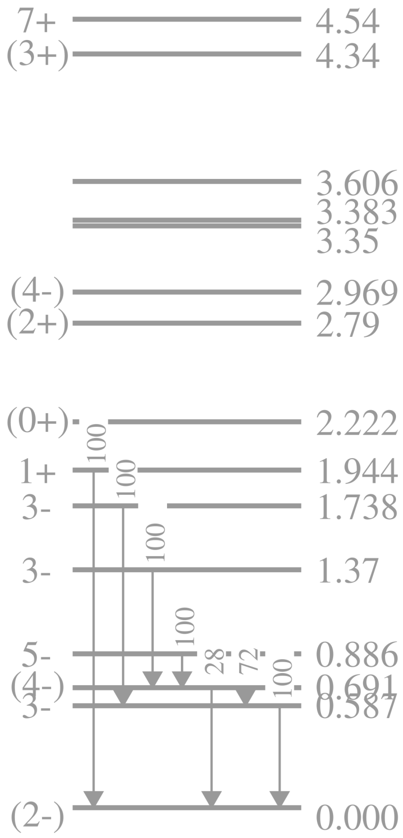

γ-rays in coincidence with downstream triton
Counts / 0.005 MeV
Eγ [MeV]
60
50
40
30
20
10
0
−1
0
1
2
3
4
5
6
7


Reconstructed excitation
47K(d,t)46K
Counts / 0.05 MeV
Ex [MeV]
140
120
100
80
60
40
20
0
−1
0
1
2
3
4
5
6
7

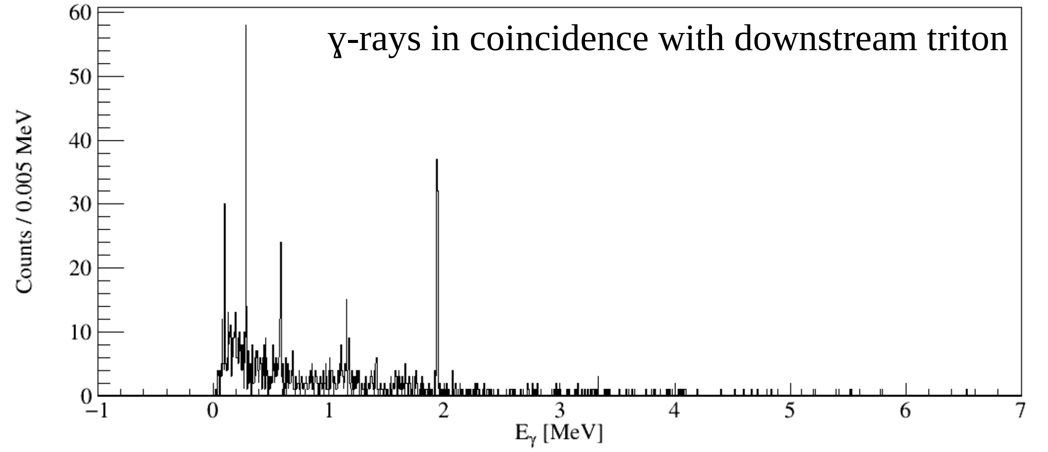
More well-known nucleus than ^{48}K.

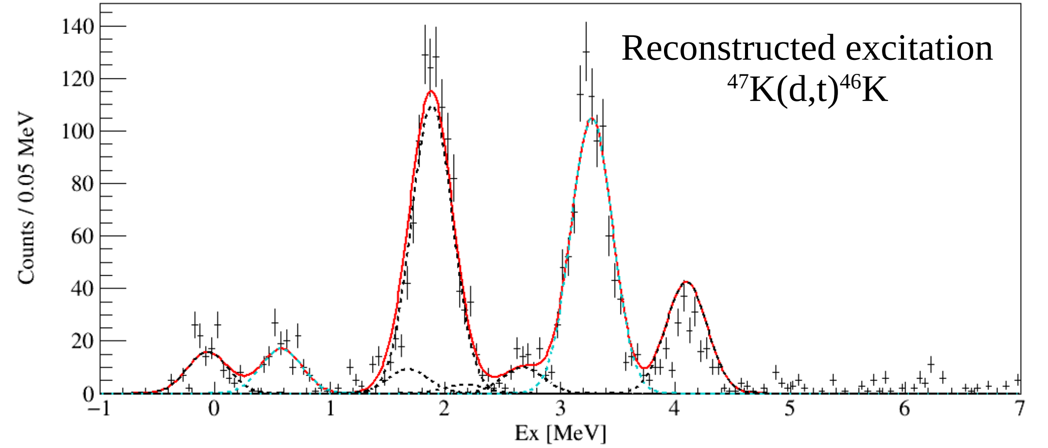




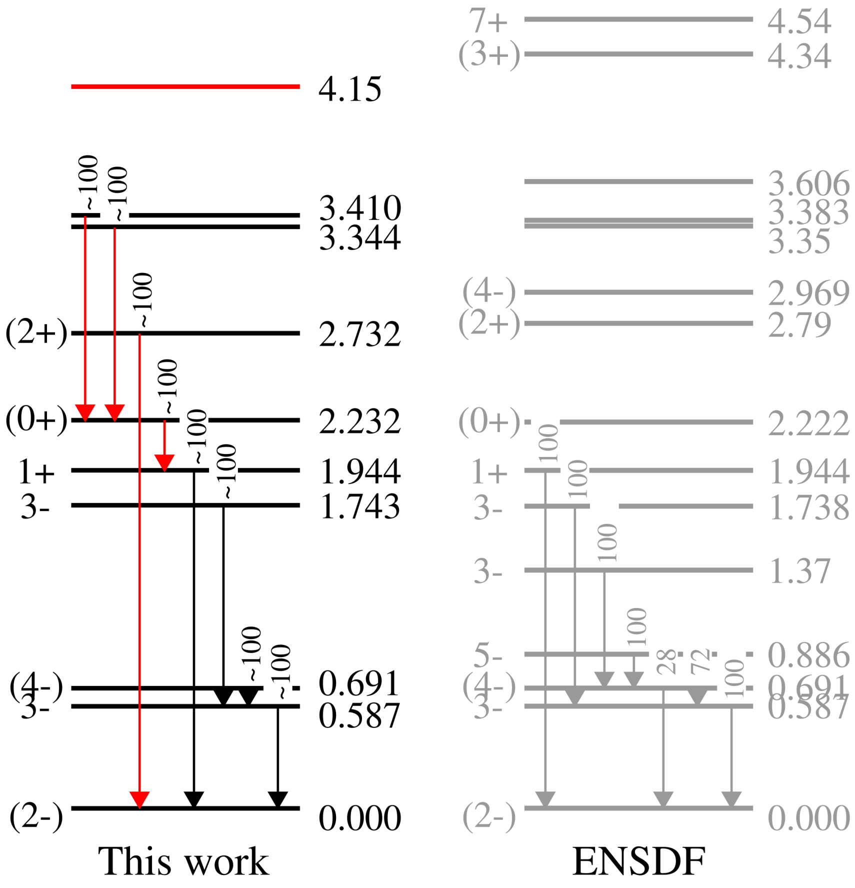


ENSDF



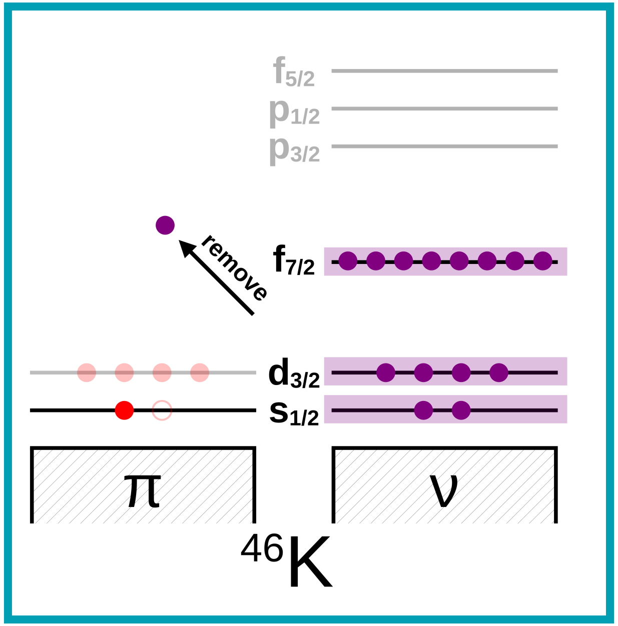


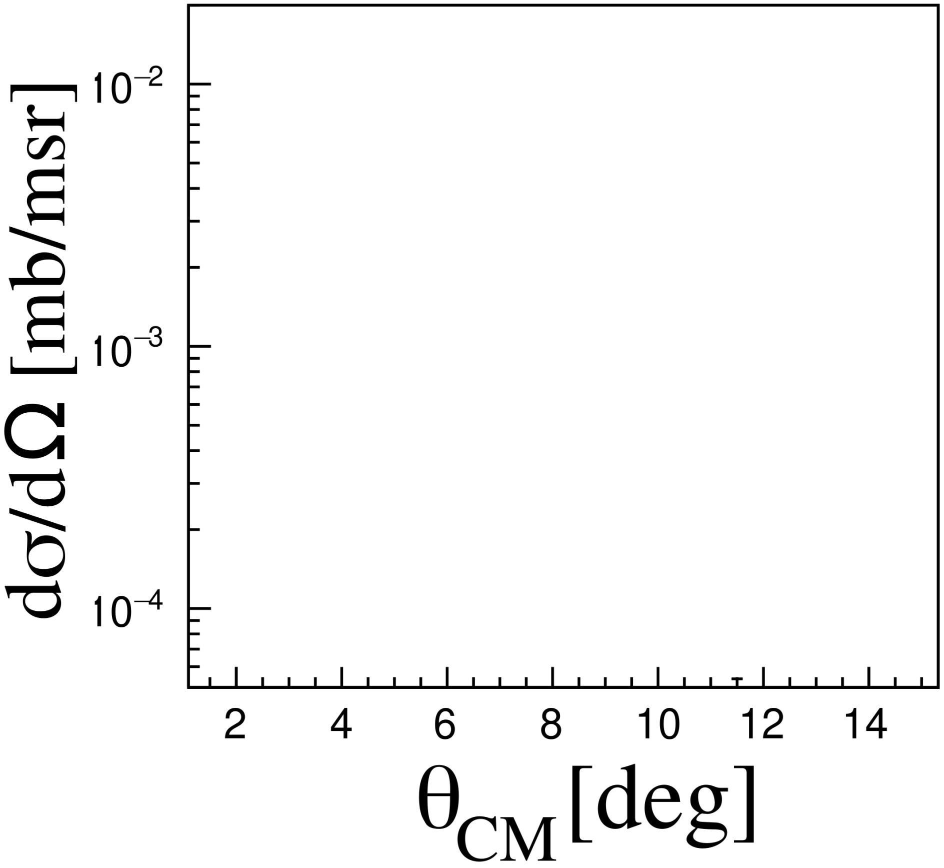
More well-known nucleus than ^{48}K.
First time studied through (d,t).



Angular Distrib.

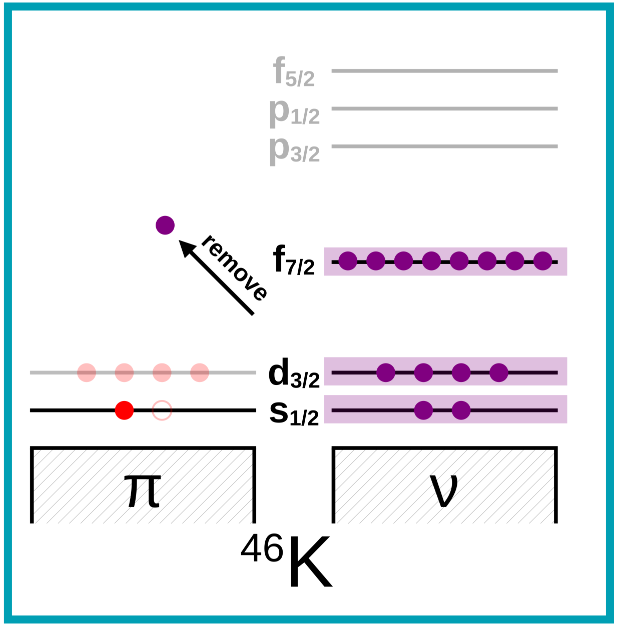
More orbitals to discriminate between;

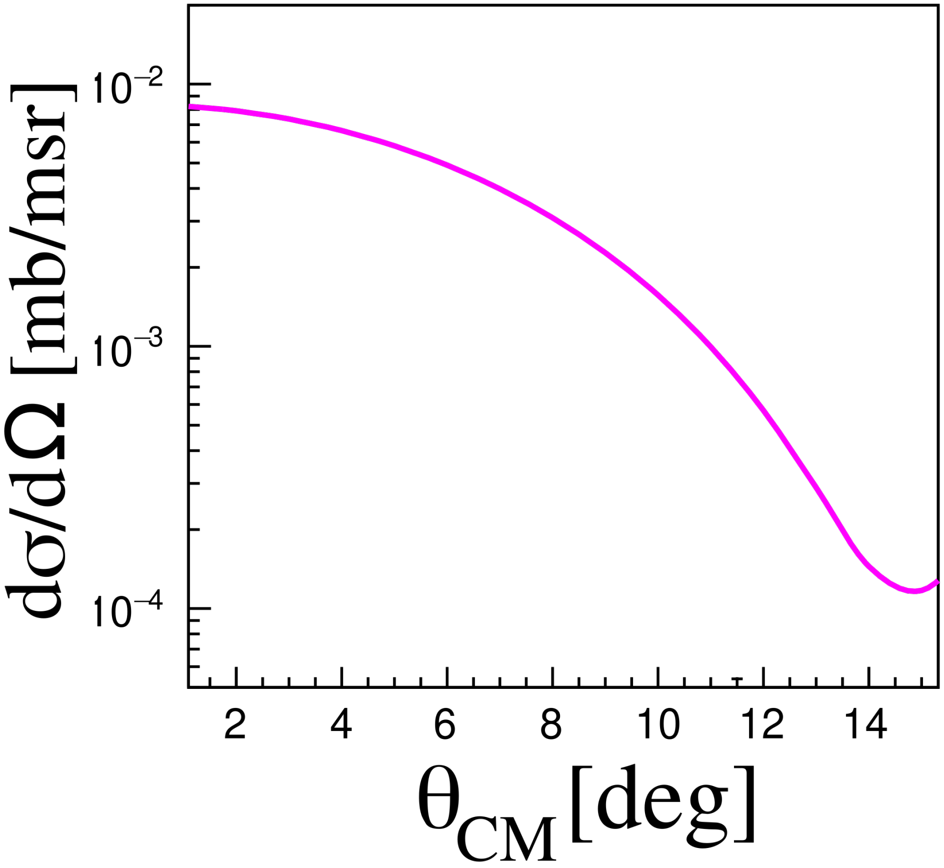




Angular Distrib.

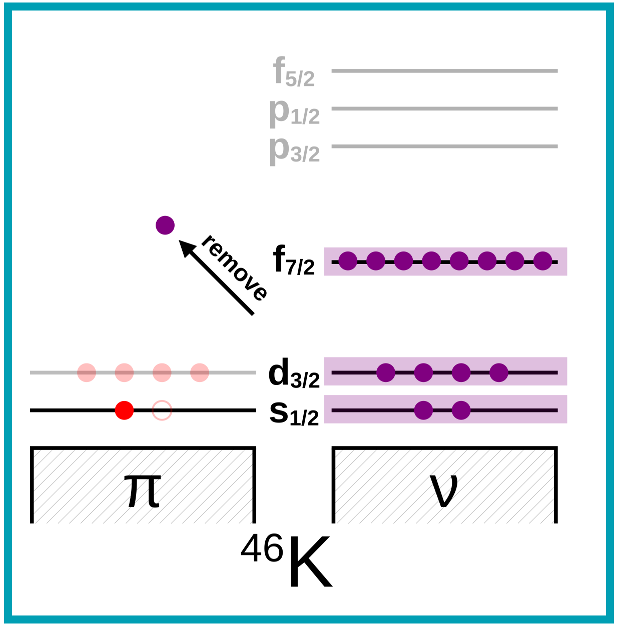
More orbitals to discriminate between;
s-wave (L=0)

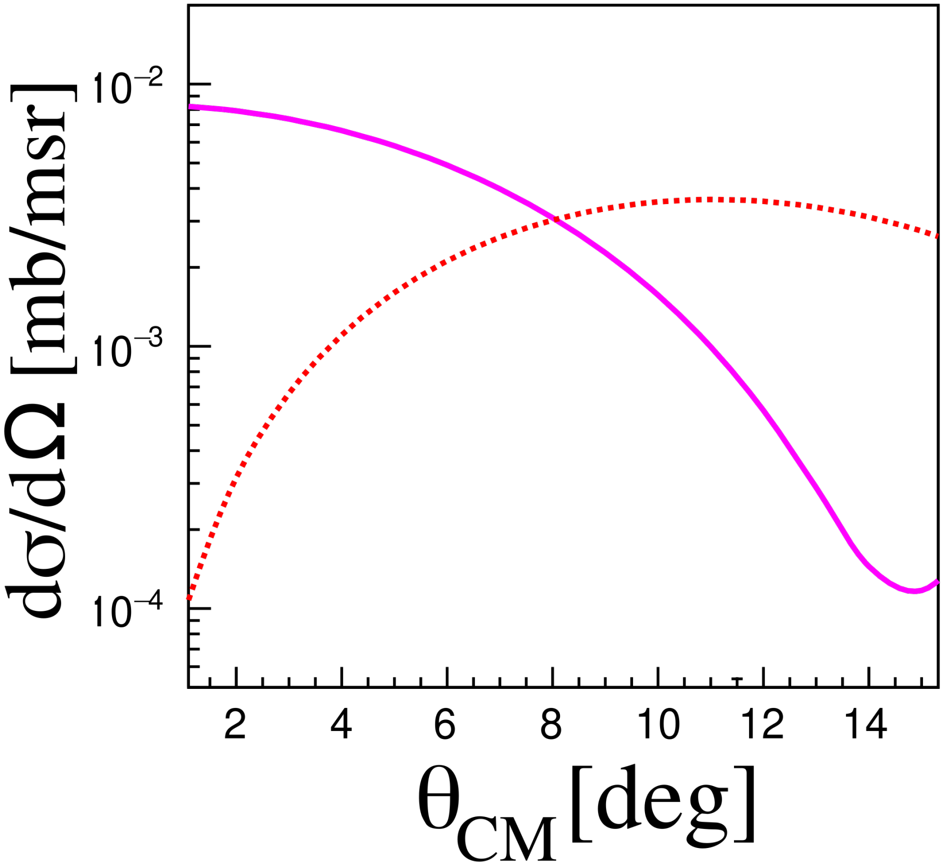




Angular Distrib.

More orbitals to discriminate between;
s-wave (L=0) p-wave (L=1)

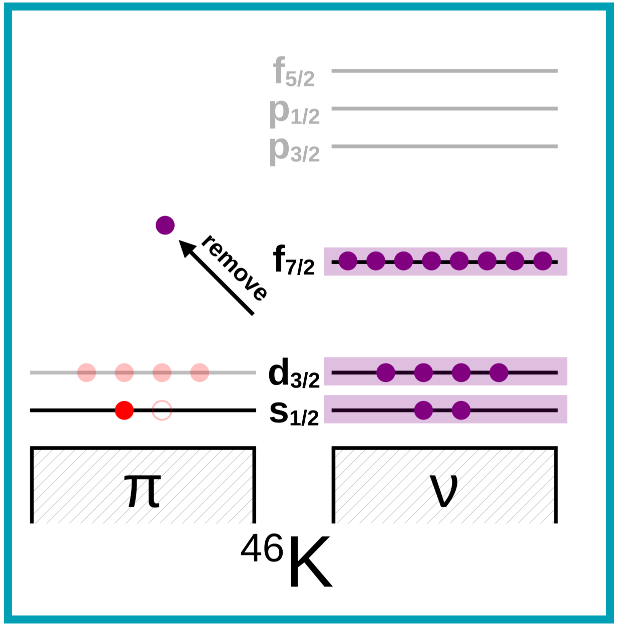


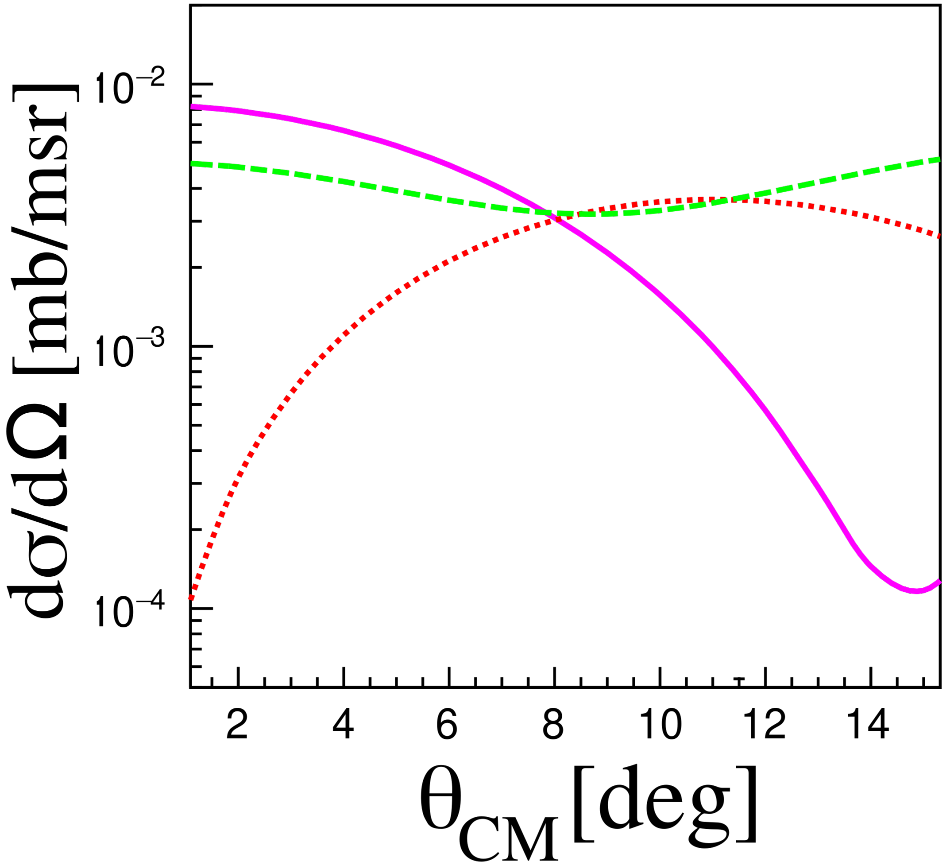


Angular Distrib.

More orbitals to discriminate between;

s-wave (L=0) p-wave (L=1)
d-wave (L=2)

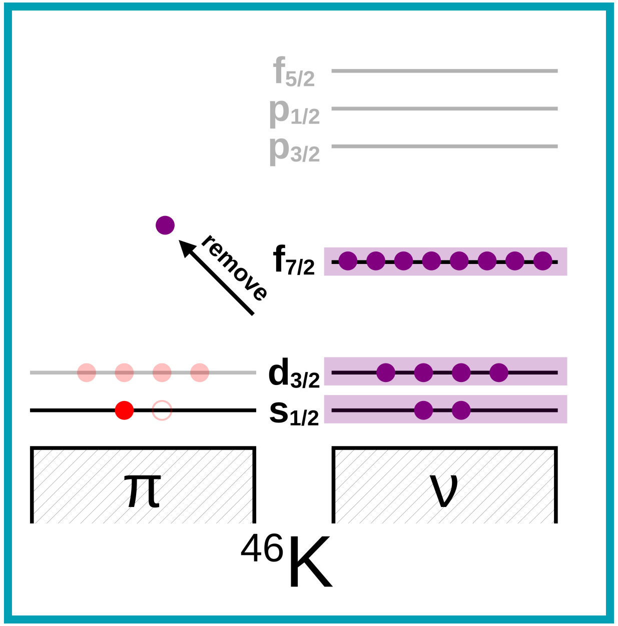


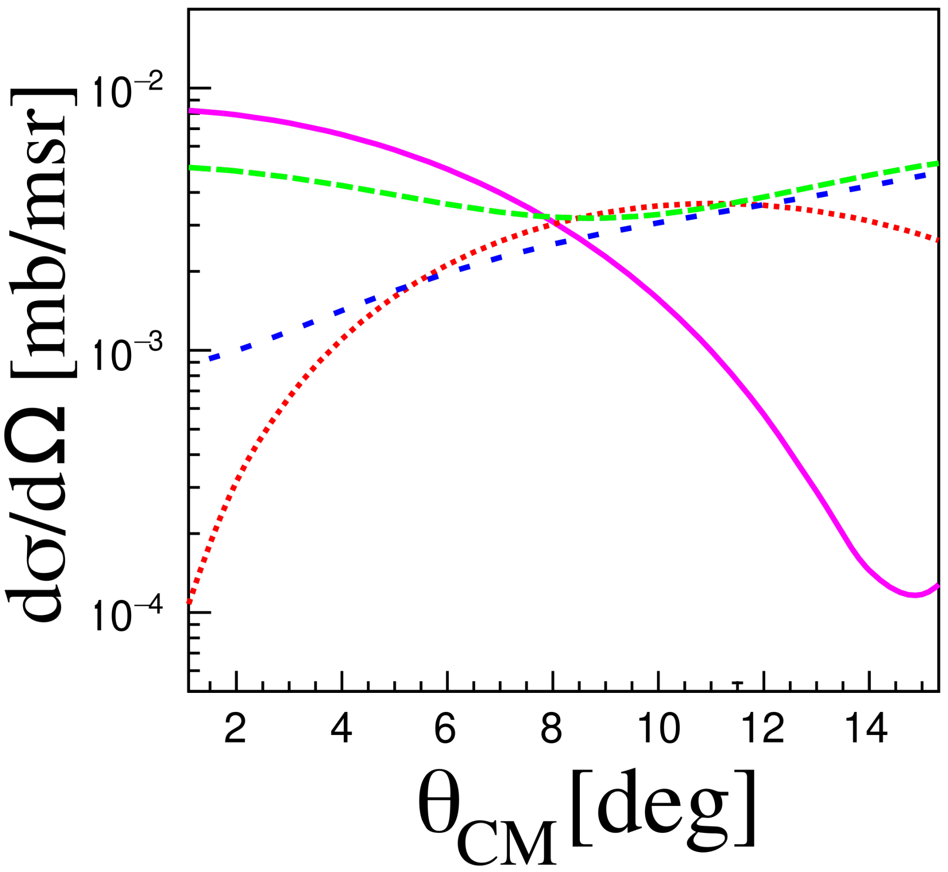


Angular Distrib.

More orbitals to discriminate between;

s-wave (L=0) p-wave (L=1)
d-wave (L=2) f-wave (L=3)

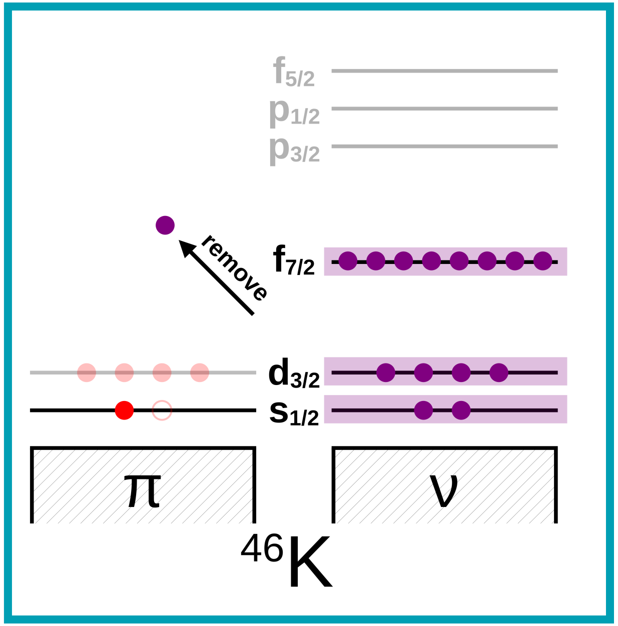


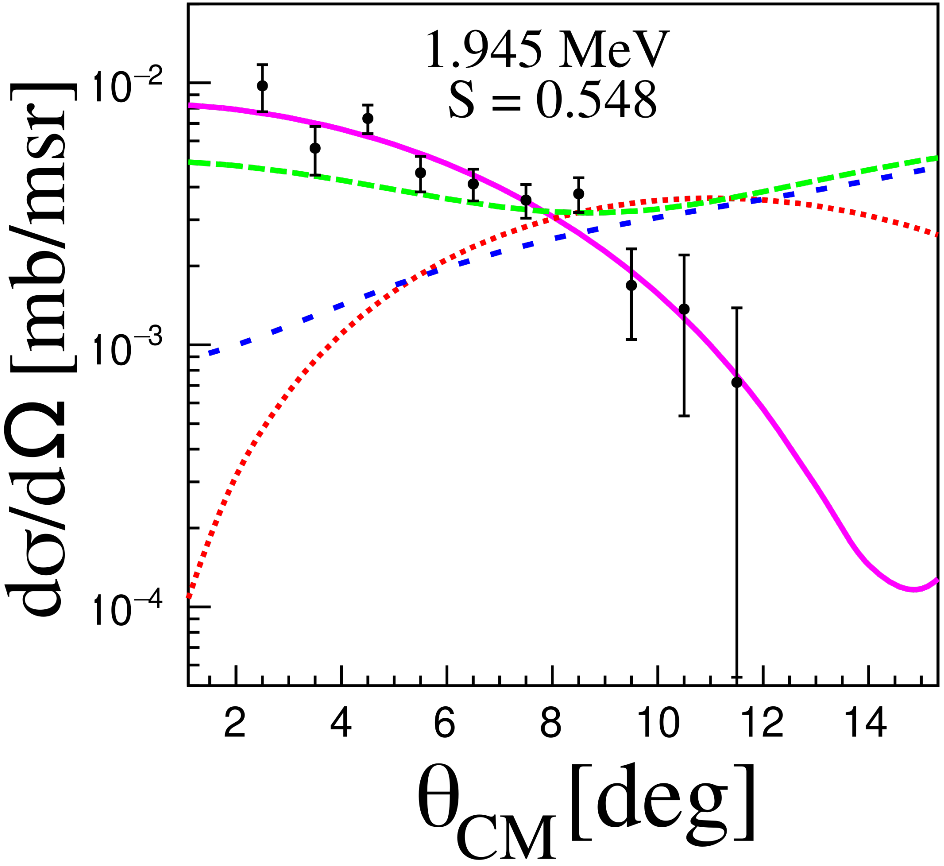


Angular Distrib.

More orbitals to discriminate between;

s-wave	(L=0)	p-wave	(L=1)
d-wave	(L=2)	f-wave	(L=3)





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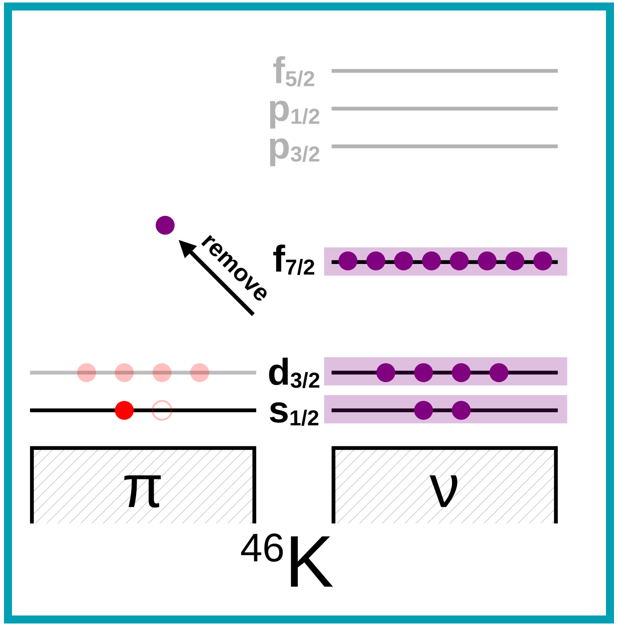
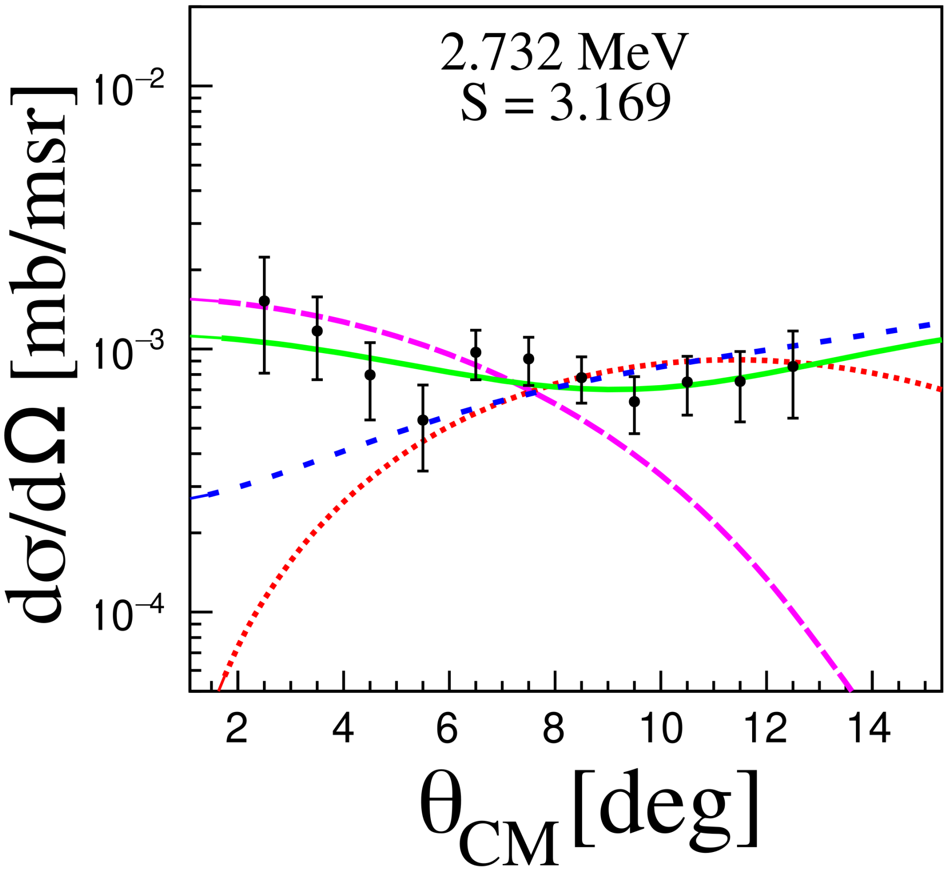
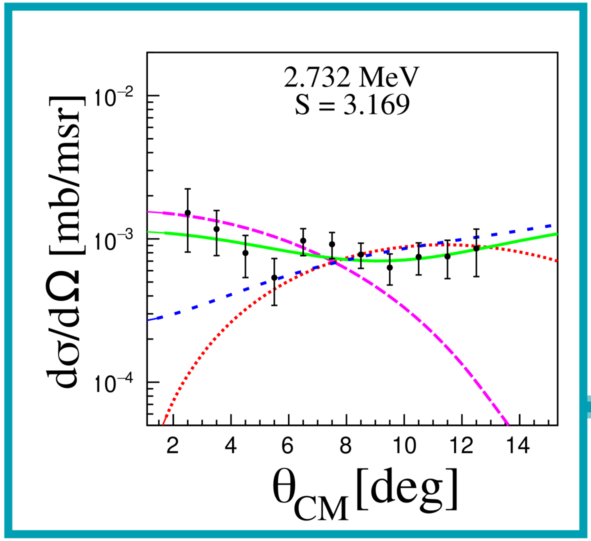
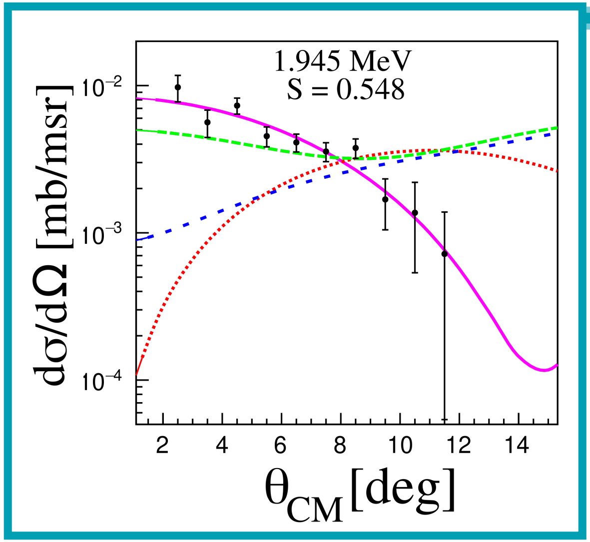
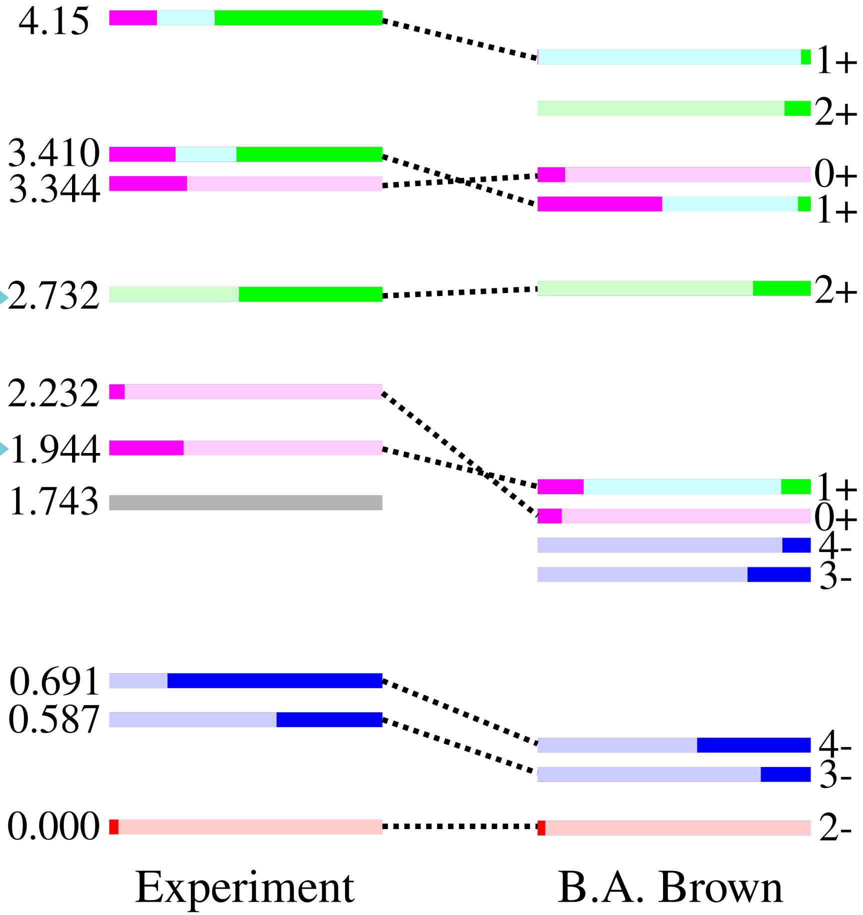


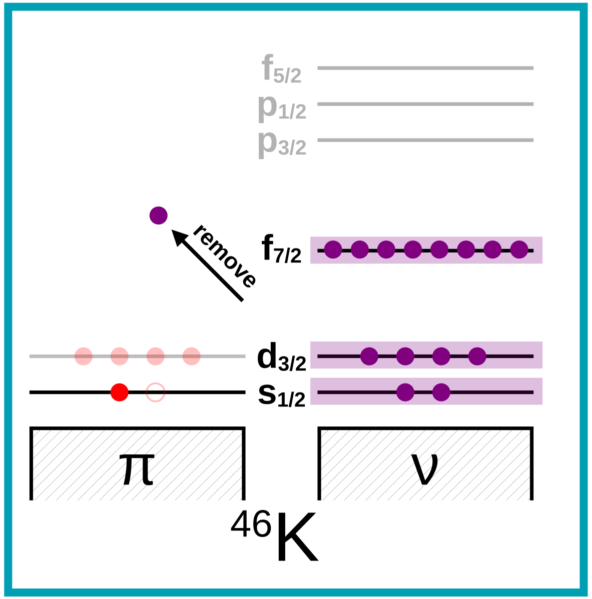


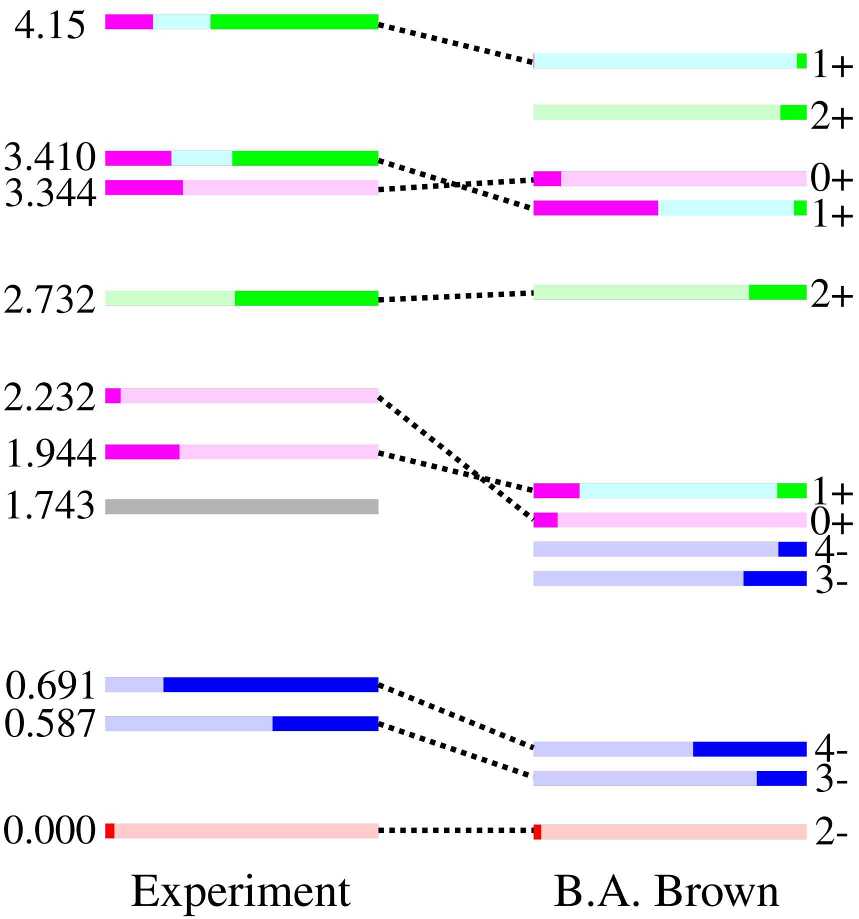

2.732 MeV
S = 3.169
dσ/dΩ [mb/msr]
10^{-2}
10^{-3}
10^{-4}
2 4 6 8 10 12 14
θ_{CM} [deg]


1.945 MeV
S = 0.548
dσ/dΩ [mb/msr]
10^{-2}
10^{-3}
10^{-4}
2 4 6 8 10 12 14
θ_{CM} [deg]


4.15
3.410
3.344
2.732
2.232
1.944
1.743
0.691
0.587
0.000
1+
2+
0+
1+
2+
1+
0+
4-
3-
4-
3-
2-
Experiment
B.A. Brown

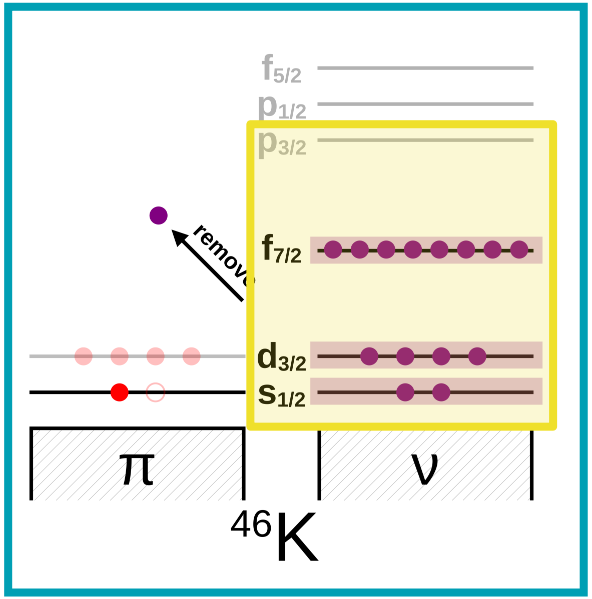
Obs. (d,t)

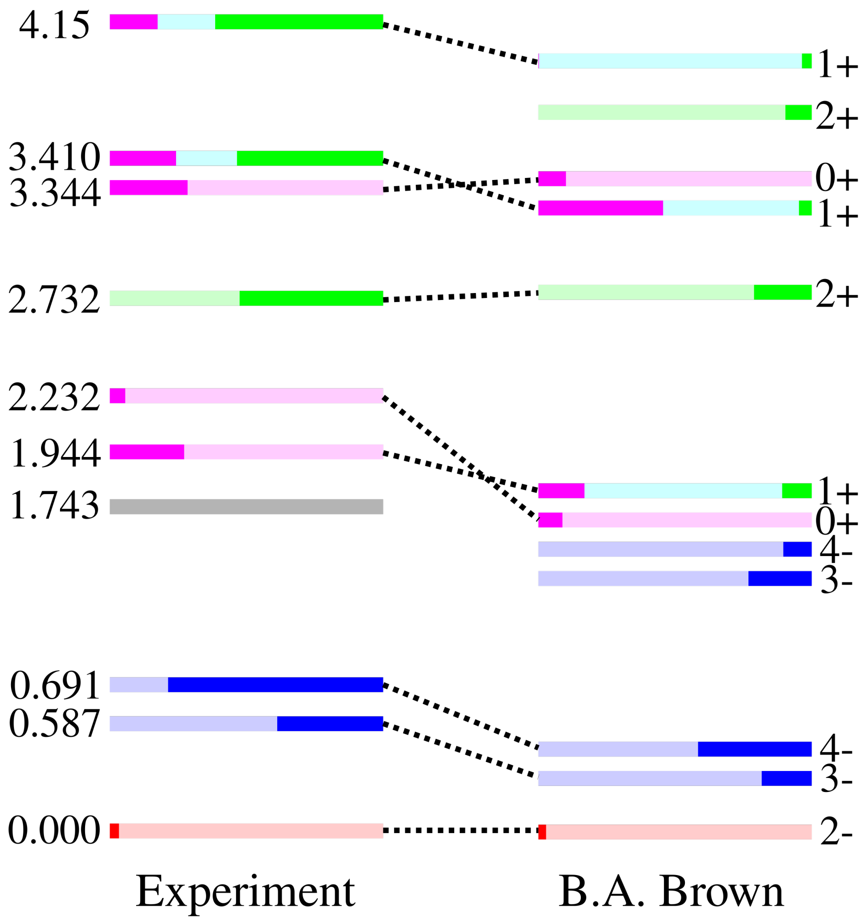




Obs. (d,t)

Shell model is limited by small phase space:

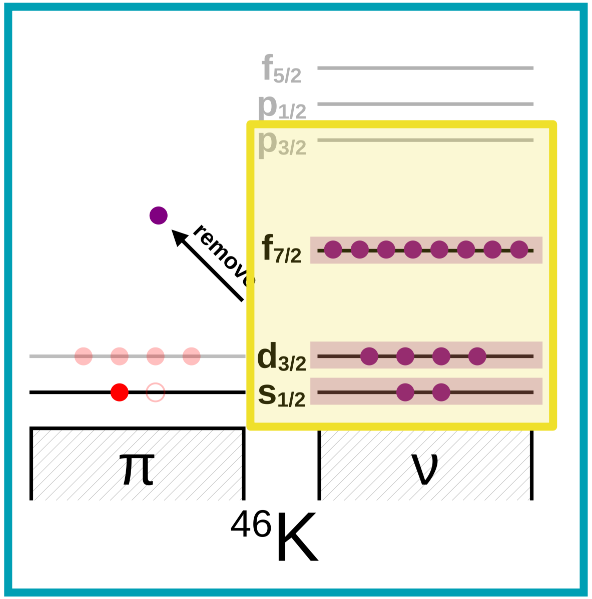


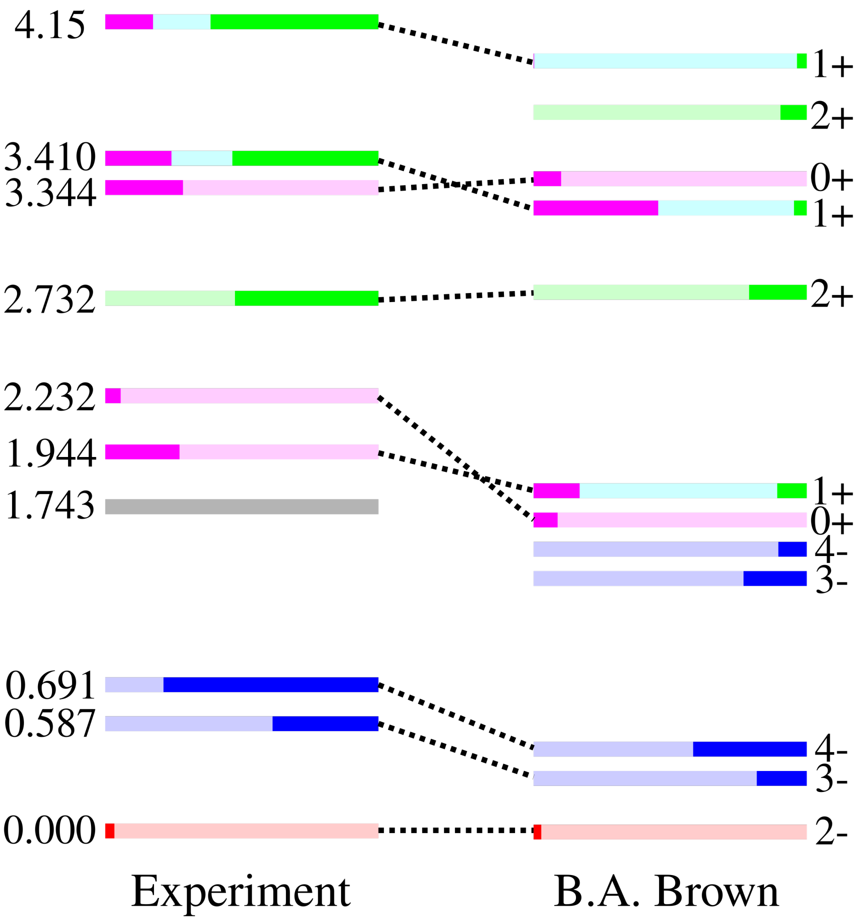


Obs. (d,t)

Shell model is limited by small phase space:

- No deep $\nu(d_{5/2})$
- No high $\nu(p_{1/2})$





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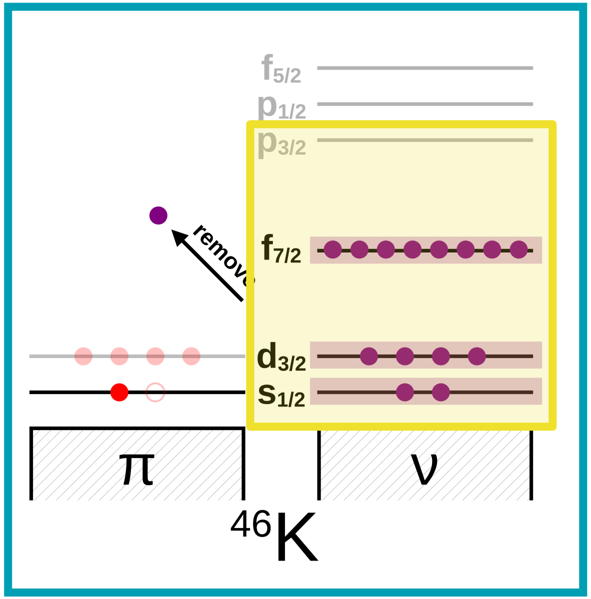
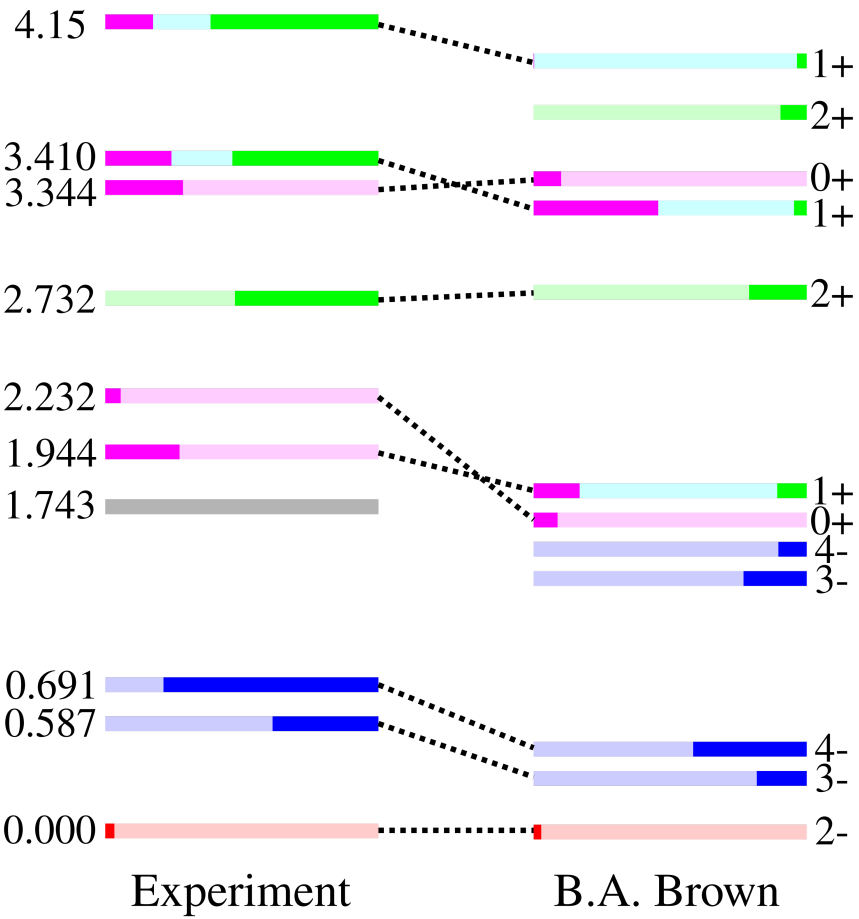
No reduction in (d,t) spectroscopic factor, as observed in (d,p).





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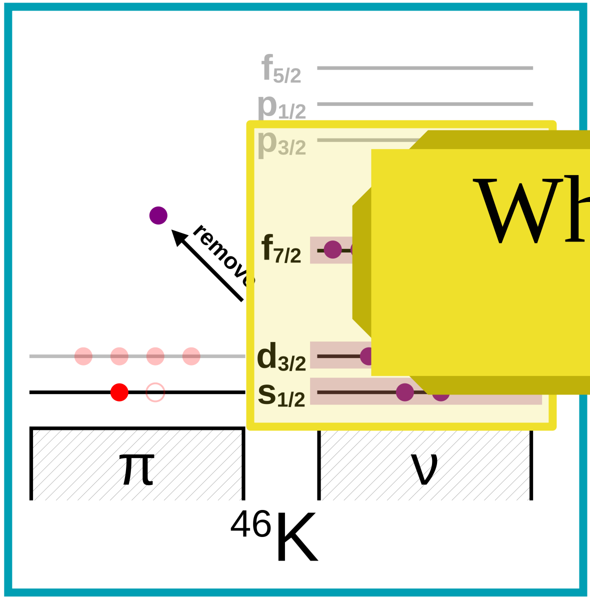

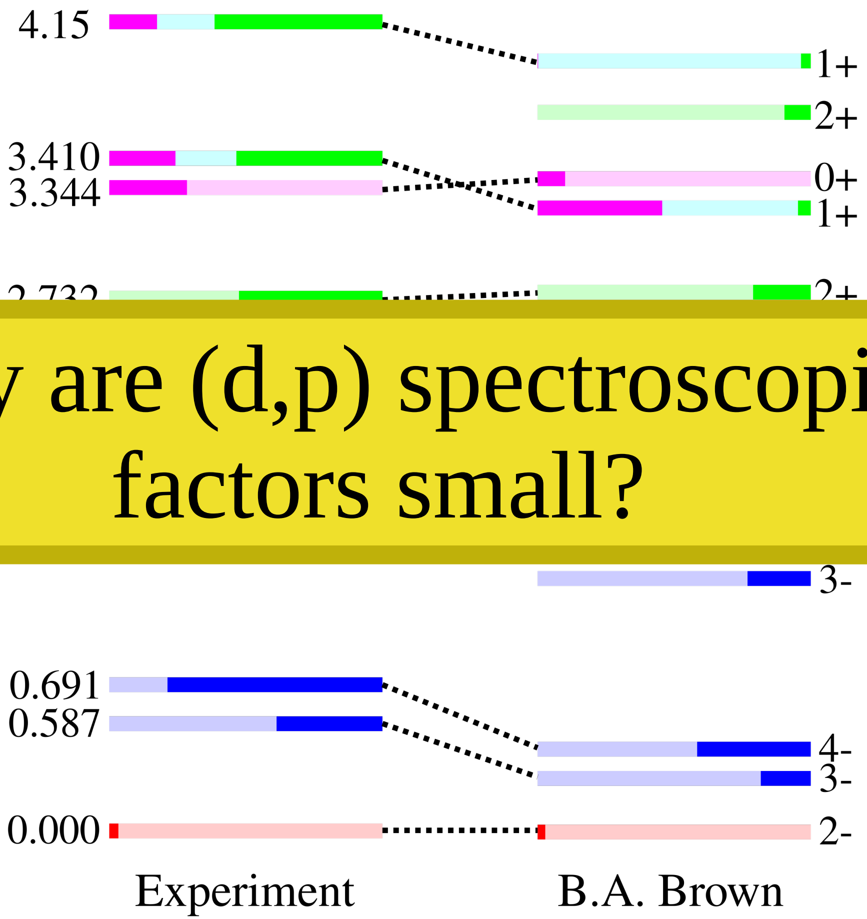

Why are (d,p) spectroscopic factors small?

Obs. (d,t)

Shell model is limited by small phase space:

- No deep $\nu(d_{5/2})$
- No high $\nu(p_{1/2})$

…eduction in (d,t) …roscopic factor, …bserved in (d,p).

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- **Preliminary comparison** with shell models; qualitative observations suggest **overestimation of N=34 gap**.
- **Small (d,p) spectroscopic factors**, exploring possible interpretations.
- **Complementary $^{47}K(d,t\gamma)^{46}K$** results obtained; no evidence to suggest transfer is "blocked".

THANK YOU

C.J. Paxman[1], W.N. Catford[1], A. Matta[2], G. Lotay[1], D.T. Doherty[1], M. Assié[3], E. Clément[4], A. Lemasson[4], D. Ramos[4], F. Galtarossa[3], L. Achouri[2], D. Ackermann[4], D. Beaumel[3], L. Canete[1], P. Delahaye[4], J. Dudouet[5], B. Fernández-Domínguez[6], D. Fernández-Fernández[6], F. Flavigny[2], C. Fougéres[4], G. de France[4], S. Franchoo[3], J. Gibelin[2], V. Girard-Alcindor[4], N. Goyal[4], F. Hammache[3], D.S. Harrouz[3], B. Jacquot[4], L. Lalanne[3,4], C. Lenain[2], J. Lois-Fuentes[6], T. Lokotko[2], F.M. Marqués[2], I. Martel[7], N.A. Orr[2], L. Plagnol[2], D. Regueira-Castro[6], N. de Séréville[3], J.-C. Thomas[4], A. Utepov[4].

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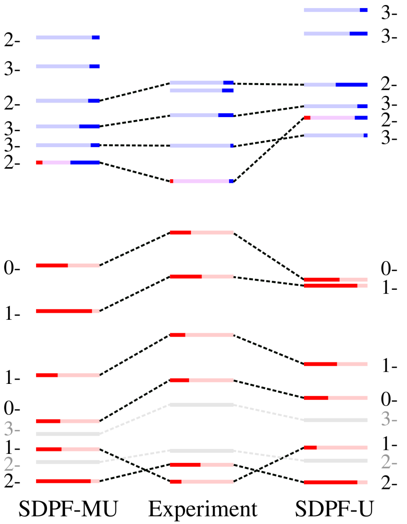
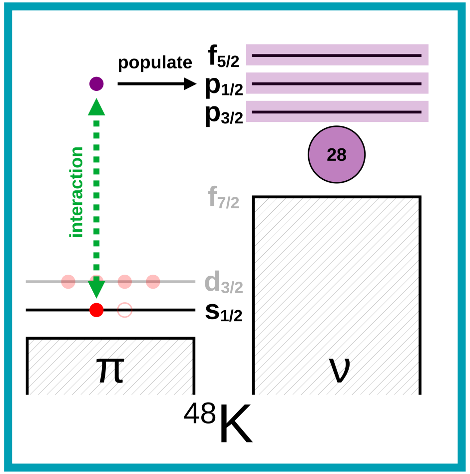
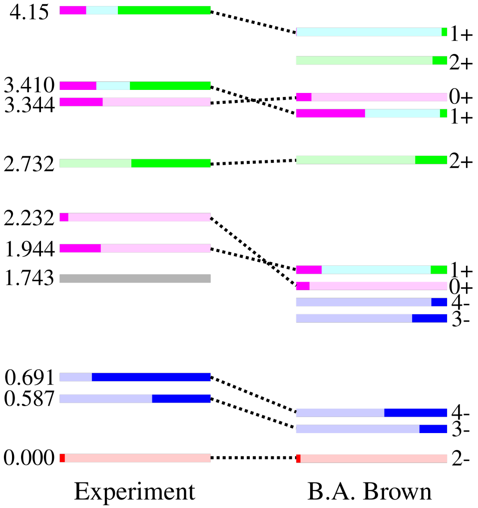
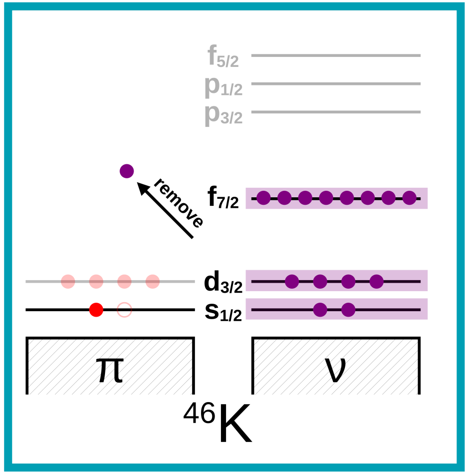
[6] Univ. Santiago de Compostela
[7] Univ. Huelva





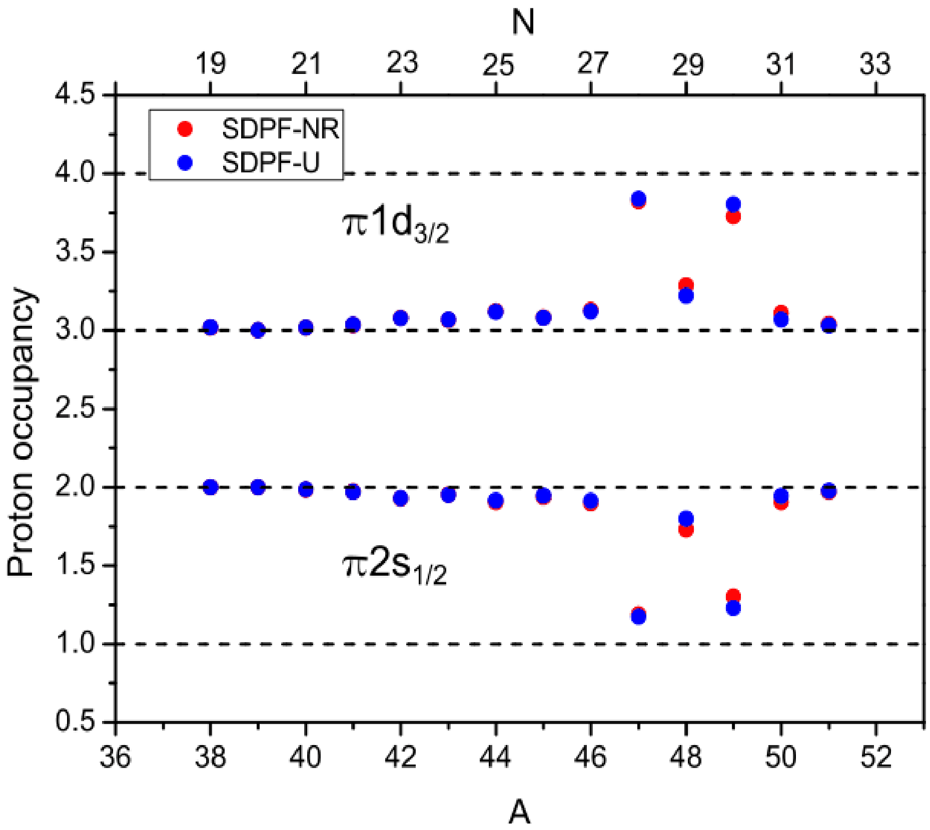




Summary

- First experimental measurement of exotic $\pi(s_{1/2}) \otimes \nu(fp)$ interaction.
- Range of p-wave and f-wave states identified.
- Overestimation of N=34 gap by shell model.
- Small (d,p) spectroscopic factors.
- No evidence to suggest transfer is "blocked".

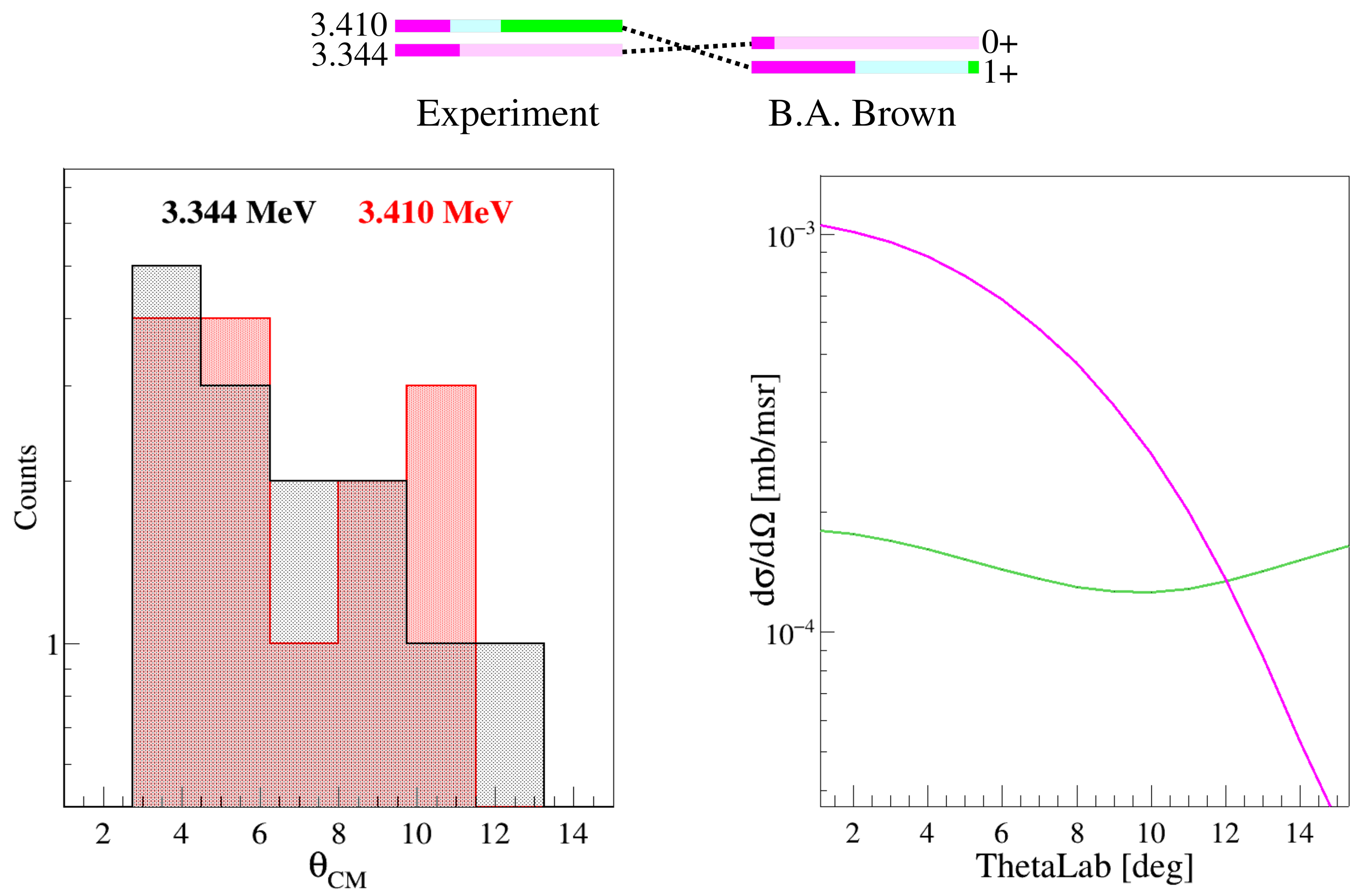
EXTRA SLIDES



J. Papuga *et al.* PRC 90, 034321 (2014)

Laser spec. at COLLAPS

^{47}K structure: $\pi(s_{1/2})^1\ \pi(d_{3/2})^4$



3.410
3.344
0+
1+
Experiment
B.A. Brown
3.344 MeV
3.410 MeV
Counts
1
2
4
6
8
10
12
14
θCM
dσ/dΩ [mb/msr]
10−3
10−4
ThetaLab [deg]

Small spectroscopic factors are not believed to be quenching:

- Papers below find no quenching in transfer reactions.
- 48K not far from stability, so optical potentials are well known

PRL **110,** 122503 (2013) PHYSICAL REVIEW LETTERS week ending 22 MARCH 2013

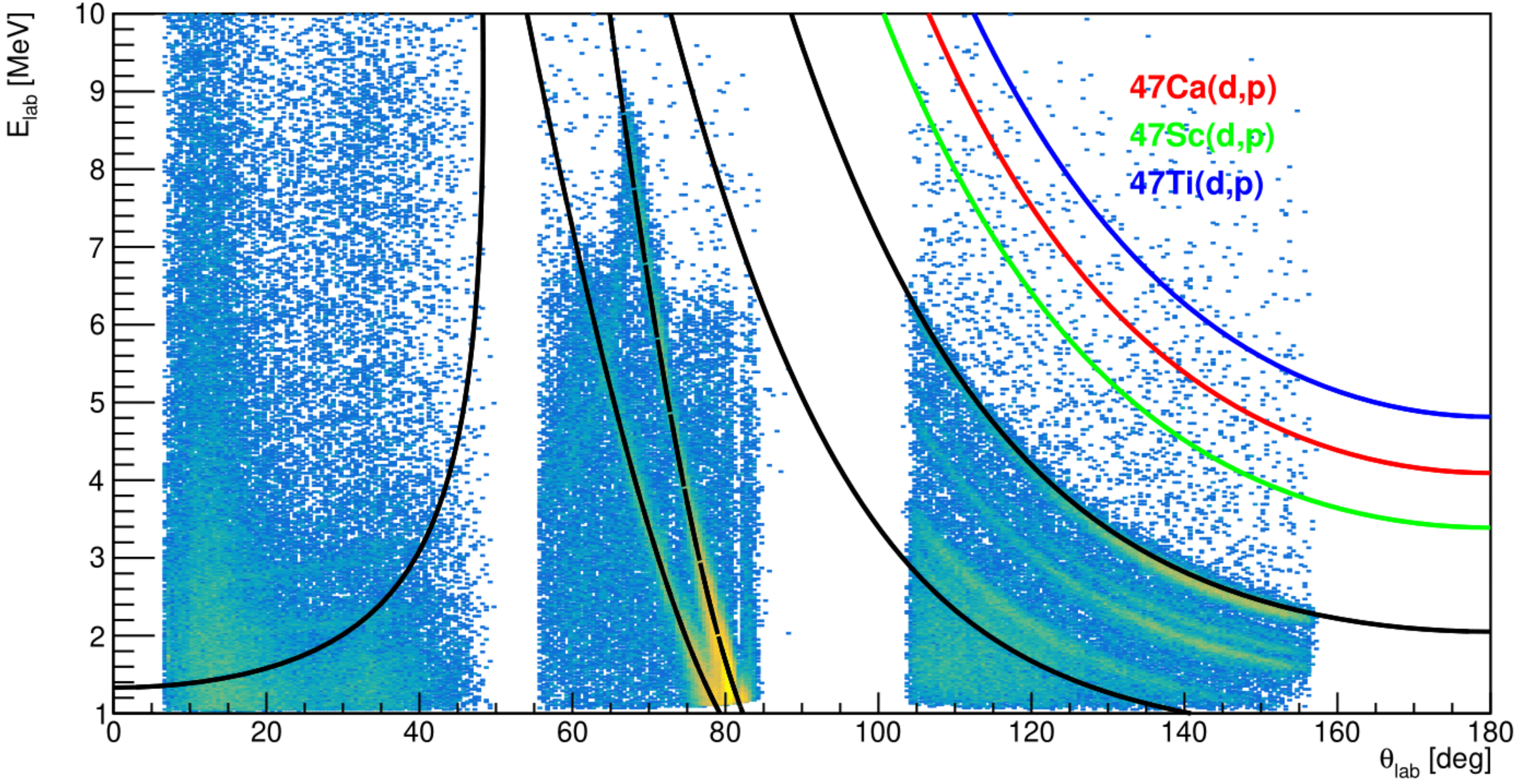
Limited Asymmetry Dependence of Correlations from Single Nucleon Transfer

F. Flavigny,[1,2] A. Gillibert,[1] L. Nalpas,[1] A. Obertelli,[1] N. Keeley,[3] C. Barbieri,[4] D. Beaumel,[5] S. Boissinot,[1] G. Burgunder,[6] A. Cipollone,[4,7,8] A. Corsi,[1] J. Gibelin,[9] S. Giron,[5] J. Guillot,[5] F. Hammache,[5] V. Lapoux,[1] A. Matta,[5] E. C. Pollacco,[1] R. Raabe,[6,2] M. Rejmund,[6] N. de Séreville,[5] A. Shrivastava,[6] A. Signoracci,[1] and Y. Utsuno[10]

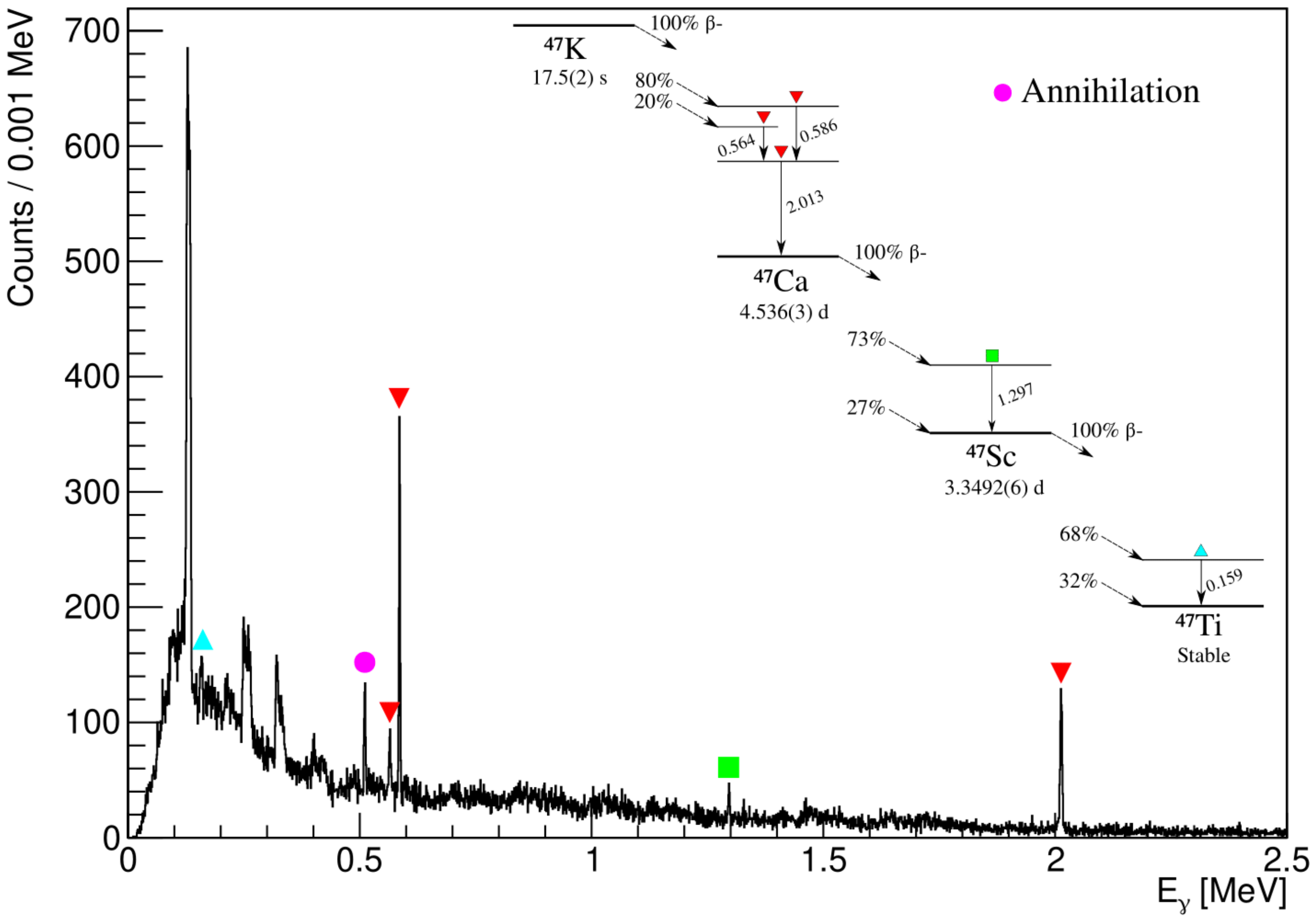
PHYSICAL REVIEW C **92**, 041302(R) (2015)

New findings on structure and production of ^{10}He from ^{11}Li with the (d,^{3}He) reaction

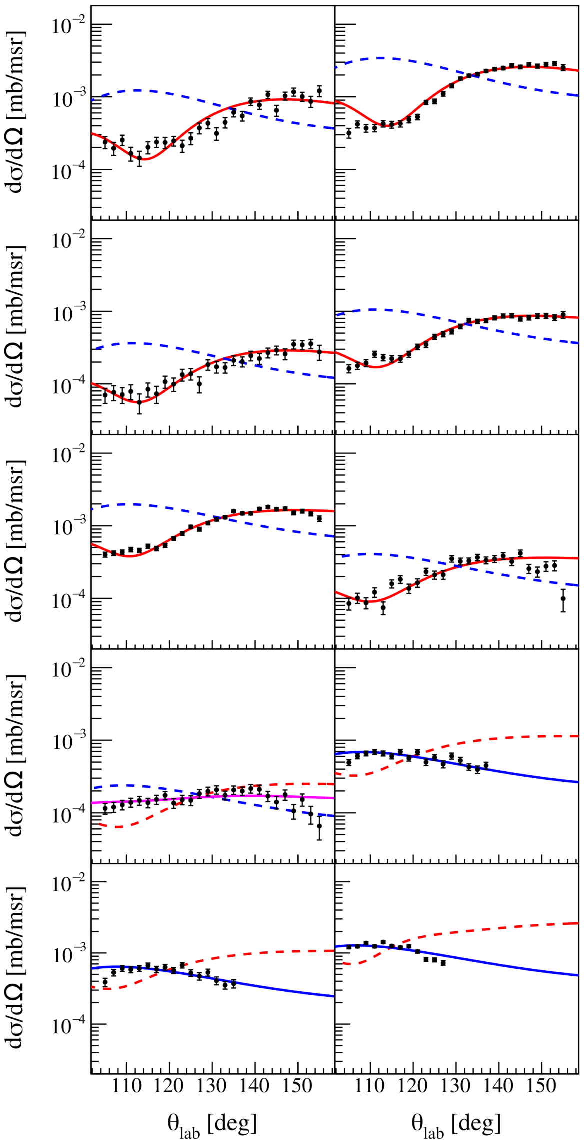
A. Matta,[1,2] D. Beaumel,[1] H. Otsu,[3] V. Lapoux,[4] N. K. Timofeyuk,[2] N. Aoi,[3] M. Assié,[1] H. Baba,[3] S. Boissinot,[4] R. J. Chen,[3] F. Delaunay,[5] N. de Sereville,[1] S. Franchoo,[1] P. Gangnant,[6] J. Gibelin,[5] F. Hammache,[1] Ch. Houarner,[6] N. Imai,[7] N. Kobayashi,[8] T. Kubo,[3] Y. Kondo,[8] Y. Kawada,[8] L. H. Khiem,[9] M. Kurata-Nishimura,[3] E. A. Kuzmin,[13] J. Lee,[3] J. F. Libin,[6] T. Motobayashi,[3] T. Nakamura,[8] L. Nalpas,[4] E. Yu. Nikolskii,[3,13] A. Obertelli,[4] E. C. Pollacco,[4] E. Rindel,[1] Ph. Rosier,[1] F. Saillant,[6] T. Sako,[8] H. Sakurai,[3] A. M. Sánchez-Benítez,[10,11] J-A. Scarpaci,[1] I. Stefan,[1] D. Suzuki,[1] K. Takahashi,[8] M. Takechi,[3] S. Takeuchi,[3] H .Wang,[3] R. Wolski,[12] and K. Yoneda[3]



E_lab [MeV]
θ_lab [deg]
47Ca(d,p)
47Sc(d,p)
47Ti(d,p)
0
20
40
60
80
100
120
140
160
180
1
2
3
4
5
6
7
8
9
10



Counts / 0.001 MeV
E_γ [MeV]
Annihilation
100% β-
47K
17.5(2) s
80%
20%
0.564
0.586
2.013
100% β-
47Ca
4.536(3) d
73%
27%
1.297
100% β-
47Sc
3.3492(6) d
68%
32%
0.159
47Ti
Stable



dσ/dΩ [mb/msr]
10^{-2}
10^{-3}
10^{-4}
110 120 130 140 150
θ_lab [deg]