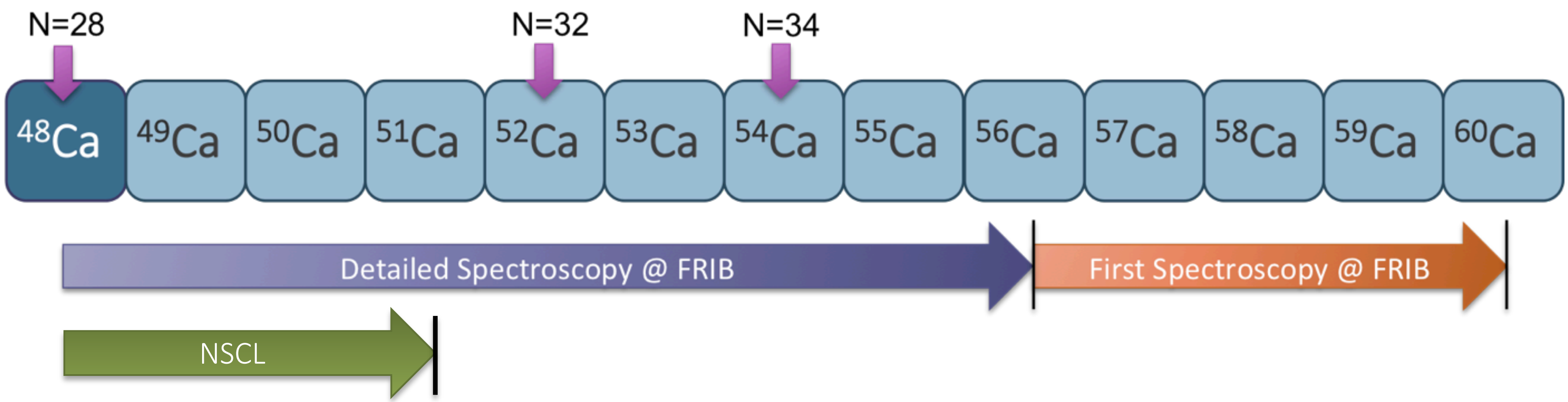
Neutron Knockout to Probe Single Particle Occupancies in the Ca Isotopes

Heather L. Crawford
Nuclear Science Division
Lawrence Berkeley National Laboratory

Overview

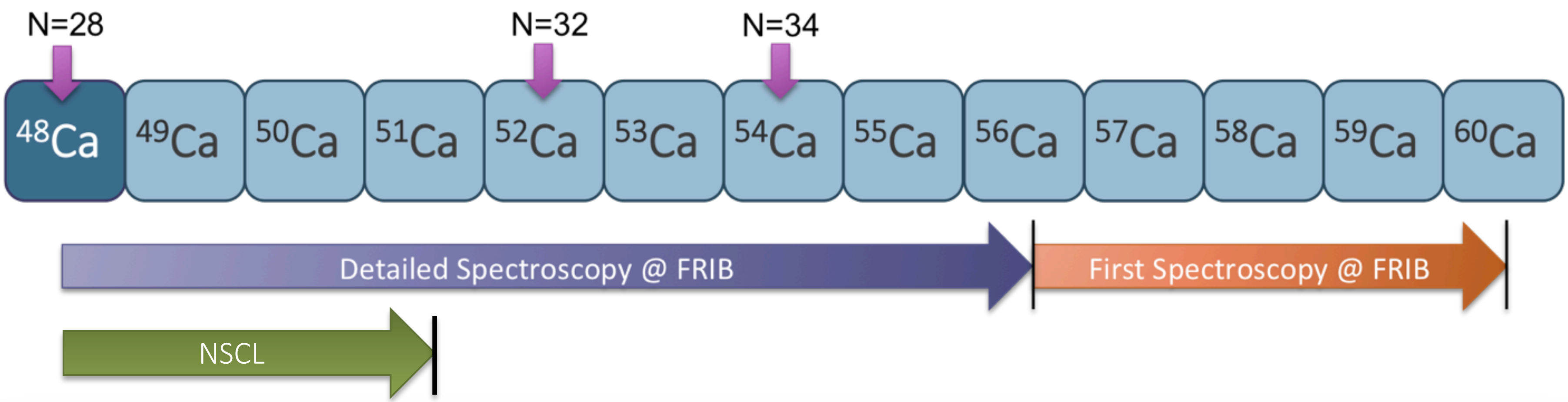
- Current status in the Ca isotopes
- Motivation for a neutron-knockout measurement
- Experimental details (just a few)
- Results
  - Neutron spectroscopic factors for -1n removal in ^{48}Ca and ^{50}Ca
  - Other data to inform the problem (or complicate it)
- Next steps (experimental)
- Summary

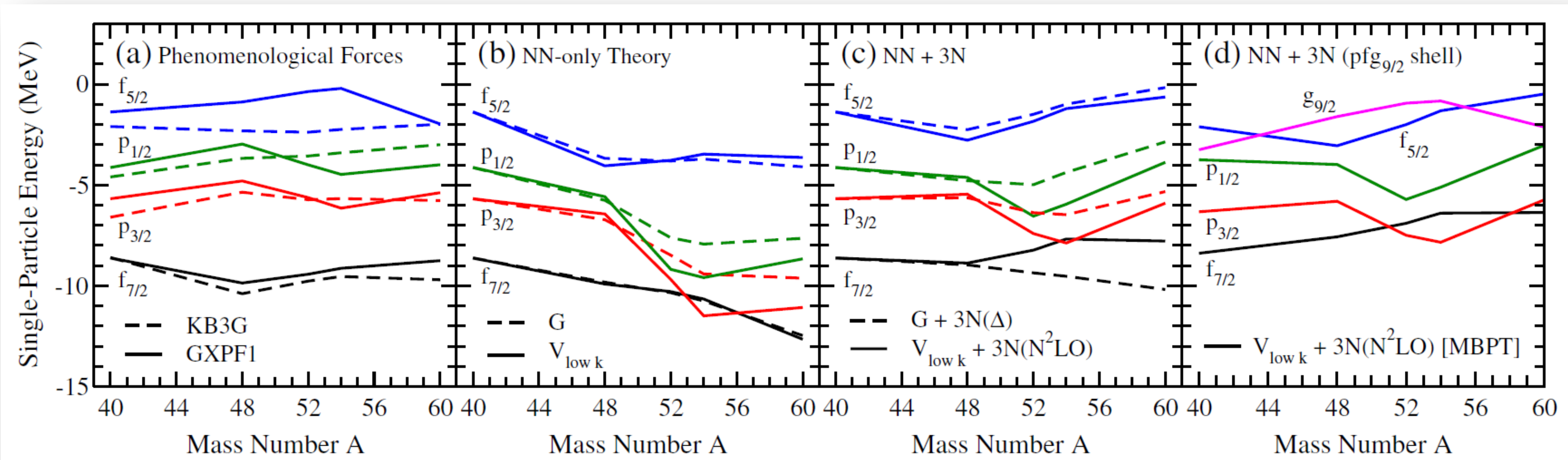
Structure of Neutron-Rich Ca Isotopes



J.D. Holt et al., J. Phys. G: Nucl. Part. Phys. **39**, 085111 (2012).

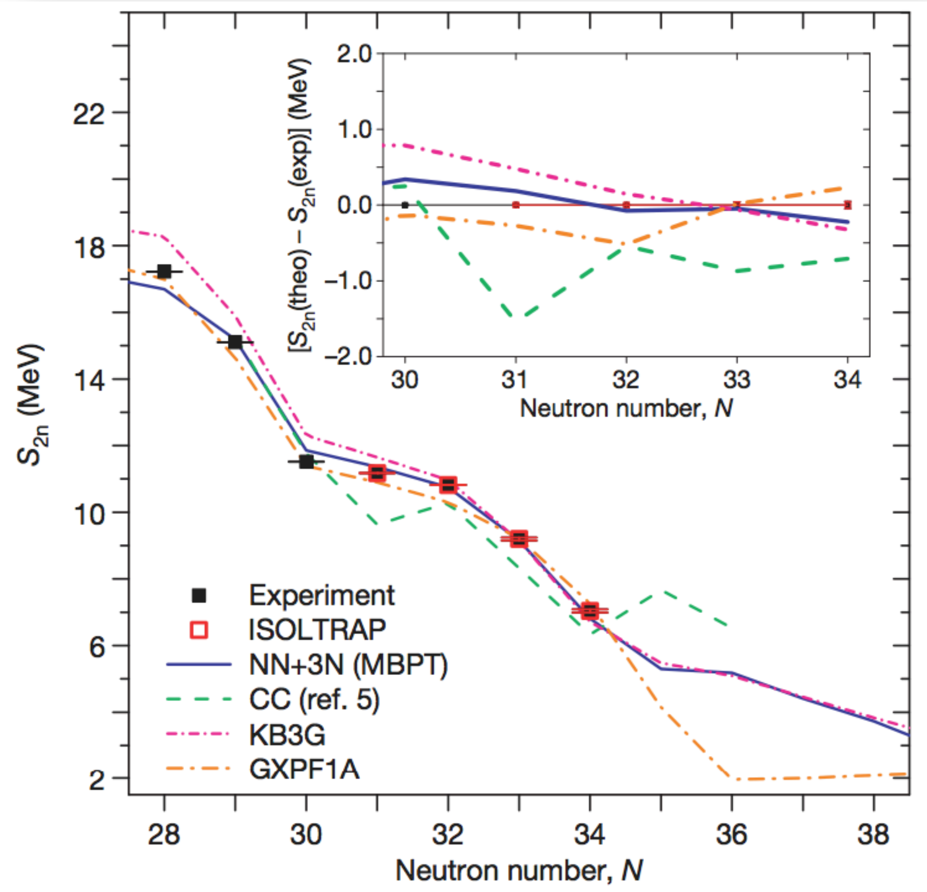
Structure of Neutron-Rich Ca Isotopes





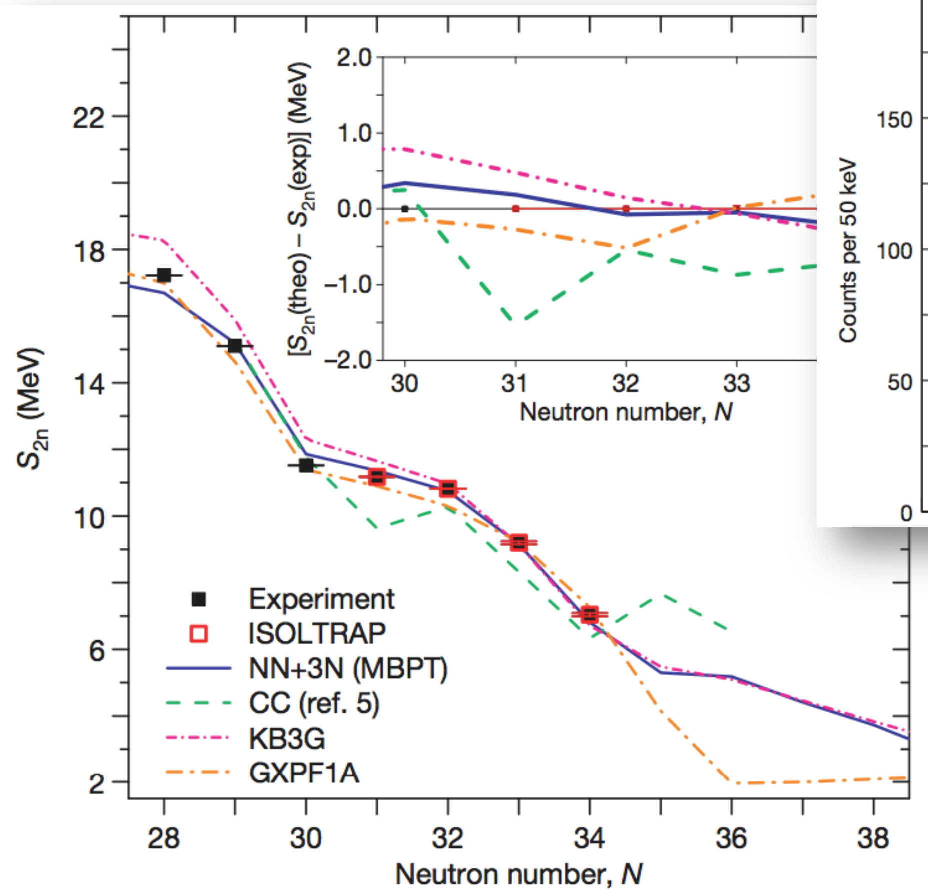
J.D. Holt et al., J. Phys. G: Nucl. Part. Phys. 39, 085111 (2012).

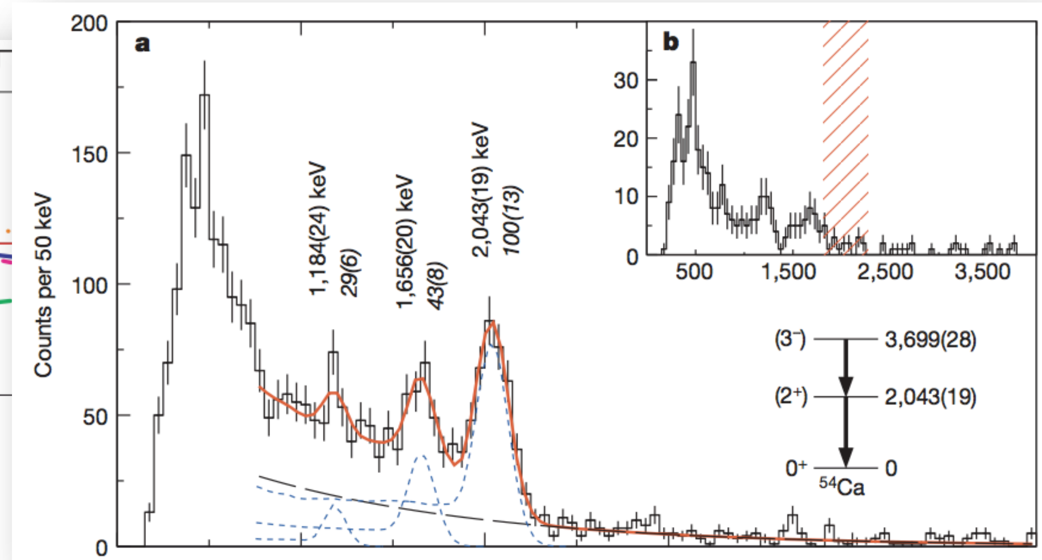
NN + 3N: Success in Ca Isotopes



F. Wienholtz *et al.*, Nature 498, 346 (2013).
D. Steppenbeck *et al.*, Nature 502, 207 (2013).

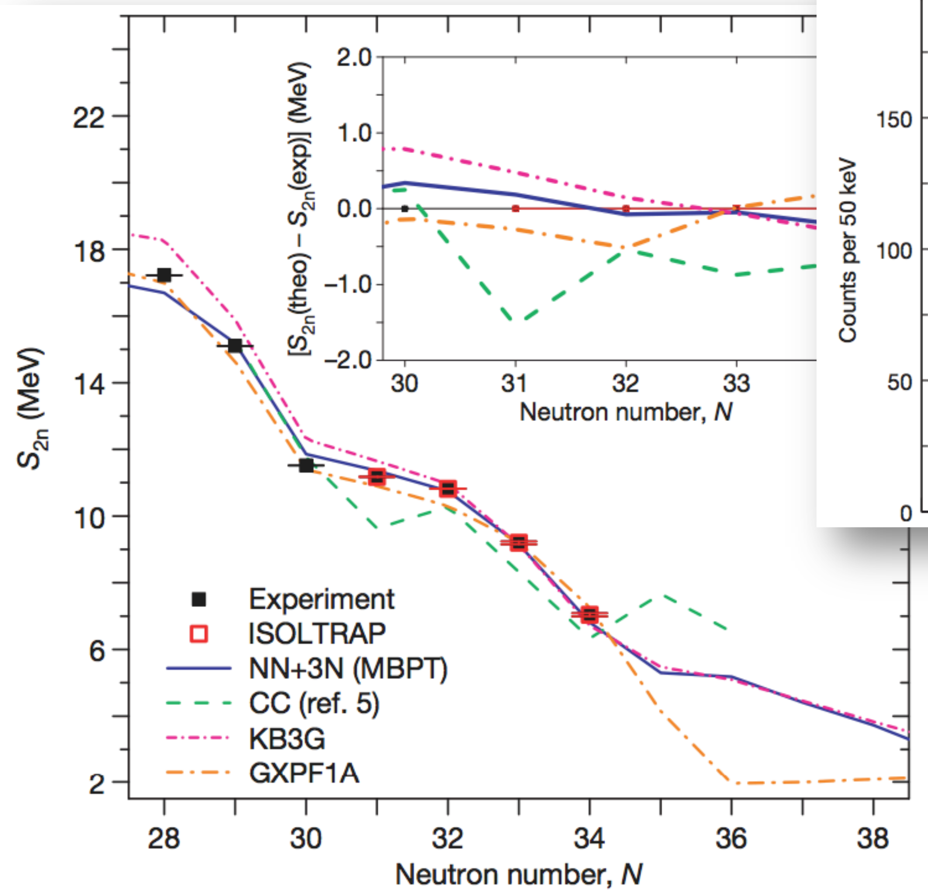
NN + 3N: Success in Ca Isotopes

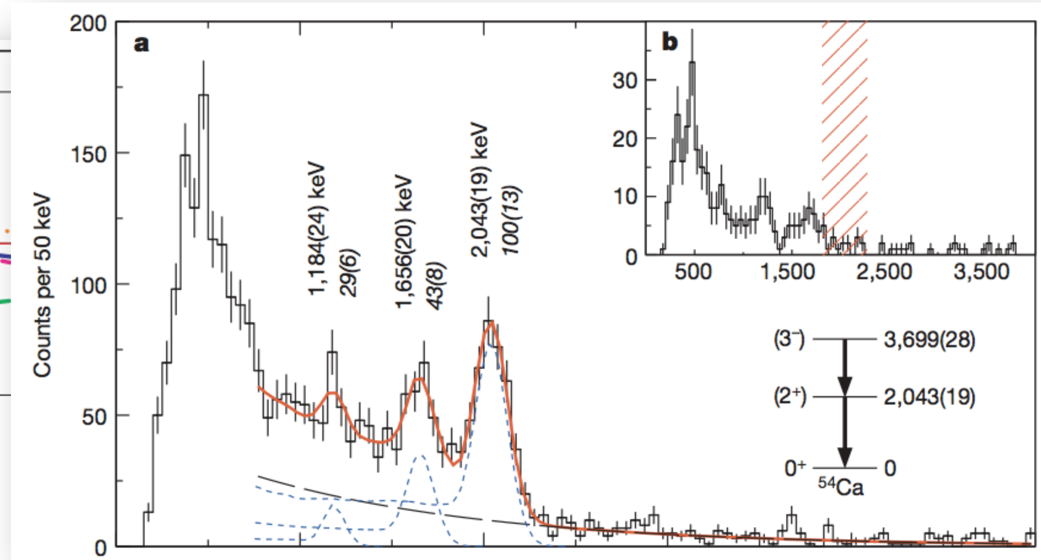


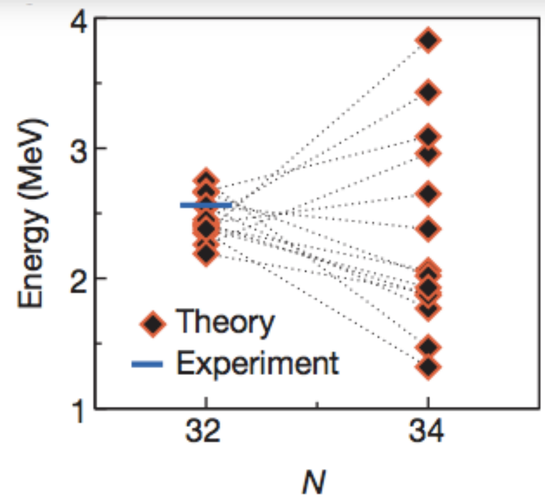


F. Wienholtz *et al.*, Nature 498, 346 (2013).
D. Steppenbeck *et al.*, Nature 502, 207 (2013).

NN + 3N: Success in Ca Isotopes



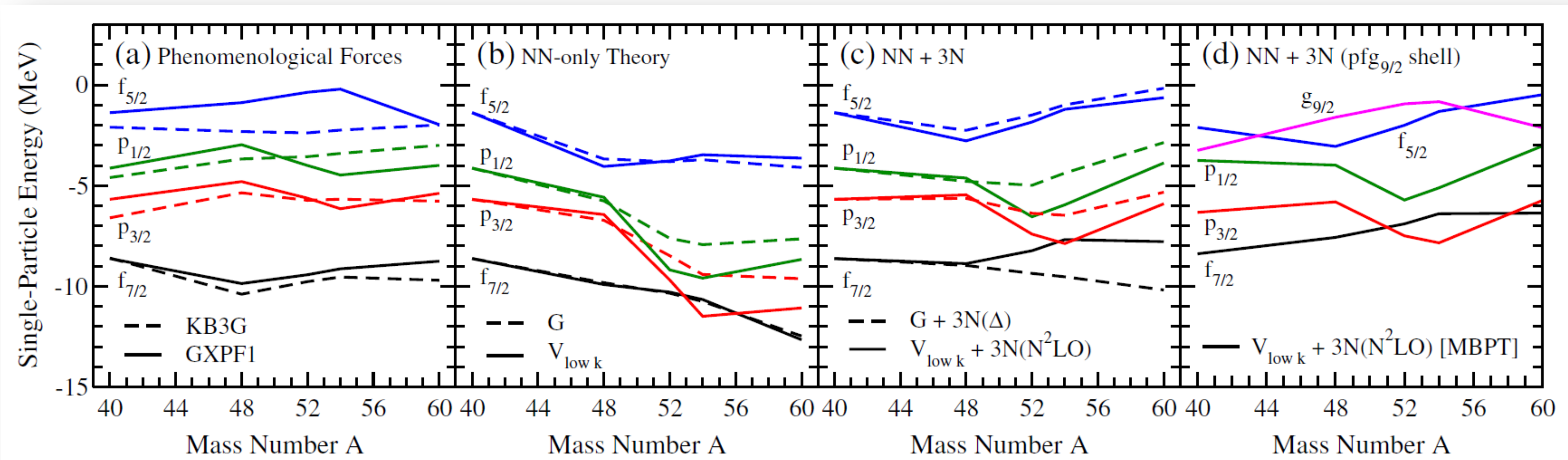




F. Wienholtz *et al.*, Nature **498**, 346 (2013).
D. Steppenbeck *et al.*, Nature **502**, 207 (2013).

Knockout to Probe 3N Forces in Ca Isotopes

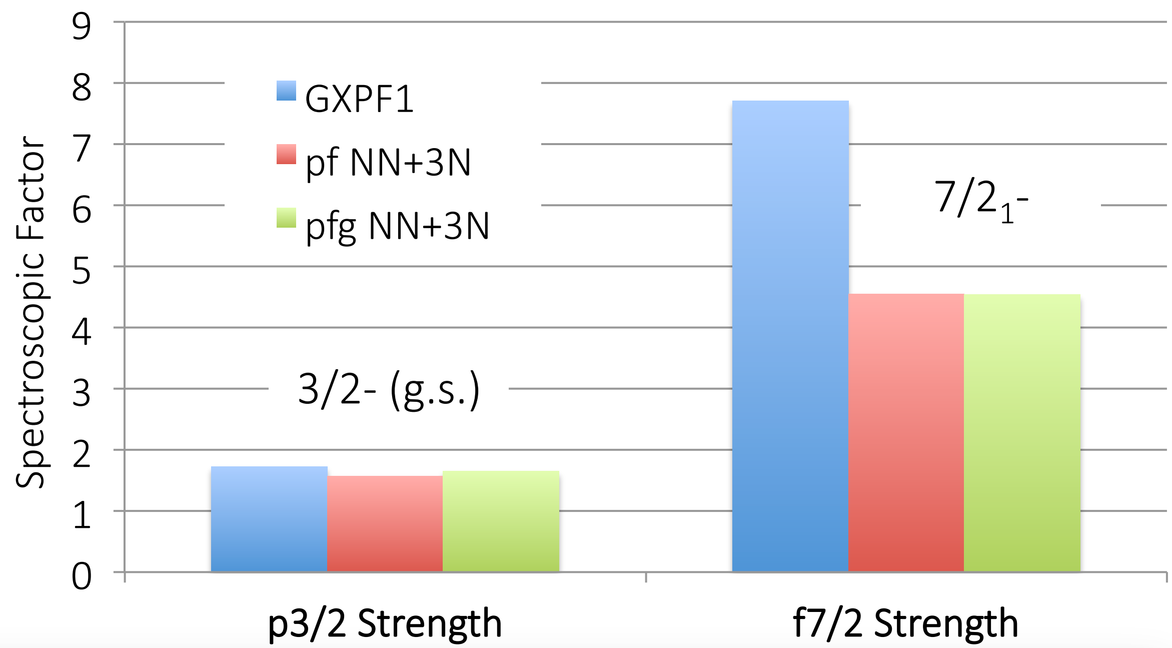
- Single-particle energies as a function of *A* are different between phenomenological forces and the more microscopic interaction --> 'closure' of the *N*=28 gap between $f_{7/2}$ and $p_{3/2}$ orbits
- A difference in the distribution of $1f_{7/2}$ strength is expected between phenomenological forces (GXPF1) and calculations including 3N forces



J. Holt, J. Menendez, A. Schwenk, private communication.

Knockout To Probe 3N Forces in Ca

- Realistic NN + 3N forces substantially fragment the $1f_{7/2}$ strength to higher-lying 7/2- states in knockout from ^{50}Ca to ^{49}Ca

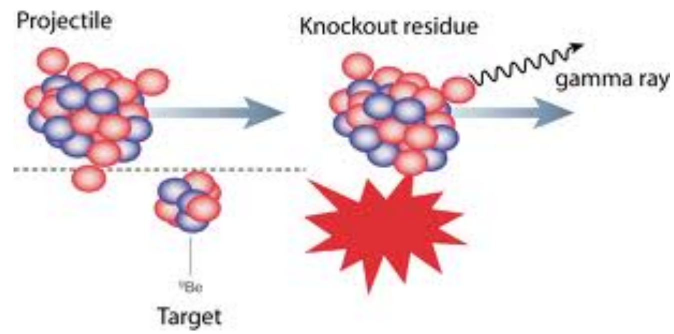


	$^{50}\mathrm{Ca}_{gs} \rightarrow {}^{49}\mathrm{Ca}$ SF$\frac{1}{2J_1+1}$											
	$\frac{3}{2}^-_{gs}$	$\frac{3}{2}^-_1$	$\frac{7}{2}^-_1$	$\frac{7}{2}^-_2$	$\frac{7}{2}^-_3$	$\frac{7}{2}^-_4$	$\frac{5}{2}^-_1$	$\frac{5}{2}^-_2$	$\frac{1}{2}^-_1$	$\frac{1}{2}^-_2$	$\frac{9}{2}^+_1$	$\frac{9}{2}^+_2$
GXPF1	1.73	0.03	7.71	0.00	0.00	0.01	0.00	0.06	0.17	0.00	-	-
(SR)	(1.82)		(7.90)				(0.09)		(0.19)		-	
pf NN+3N	1.57	0.23	4.55	2.03	0.02	0.21	0.03	0.10	0.35	0.01	-	-
(SR)	(1.95)		(7.31)				(0.30)		(0.44)		-	
$\mathrm{pfg}_{9/2}$ NN+3N	1.65	0.09	4.54	1.18	0.00	0.03	0.10	0.01	0.20	0.00	1.26	0.05
(SR)	(1.81)		(6.09)				(0.20)		(0.24)		(1.66)	

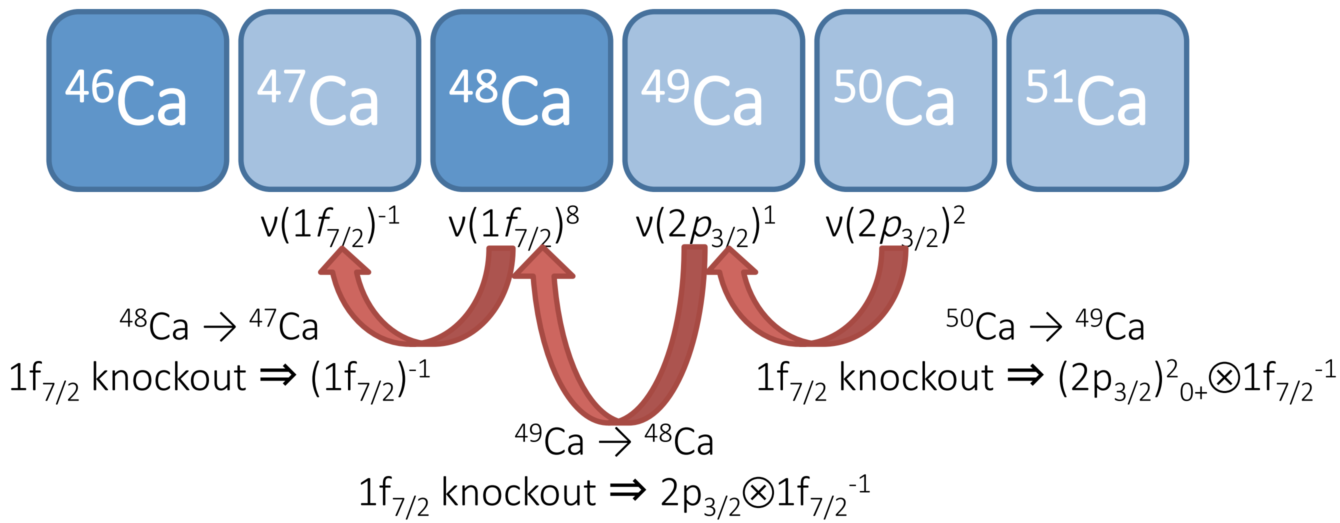
J. Holt, J. Menendez, A. Schwenk, private communication.

E12029: 1n Knockout in the Ca Isotopes

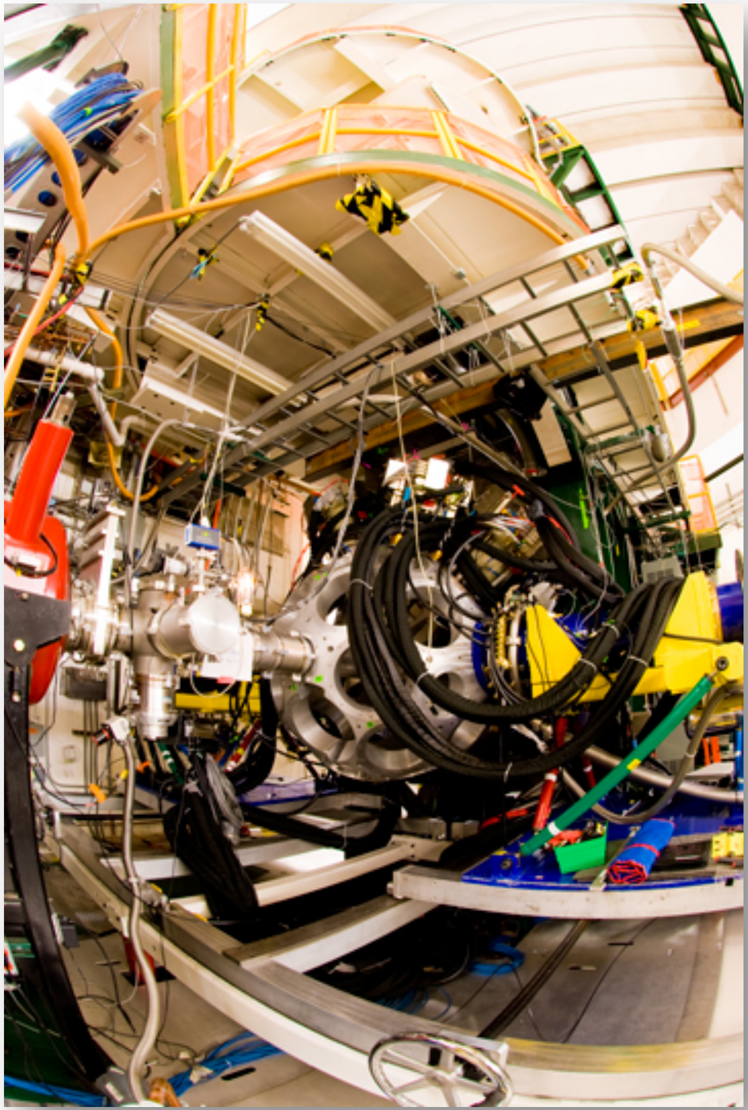
- With GRETINA + S800, a unique opportunity exists to make a high quality measurement, with resolution sufficient to separate closely-spaced transitions, and singles and gamma-gamma efficiency to observe the weakest high-energy transitions, and determine feedings in the level schemes

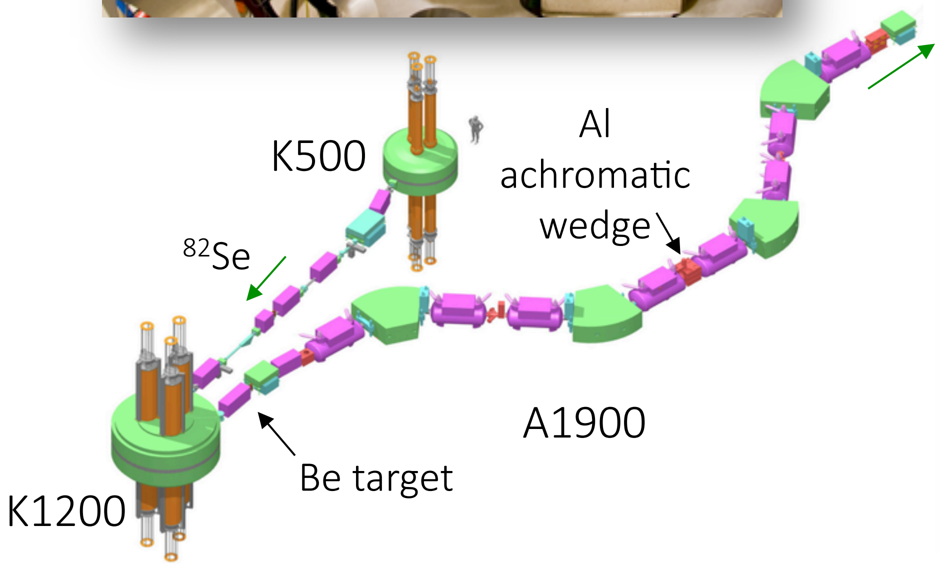


- S800 allows momentum distributions to determine L of knocked-out neutron, GRETINA will allow exclusive momentum distributions

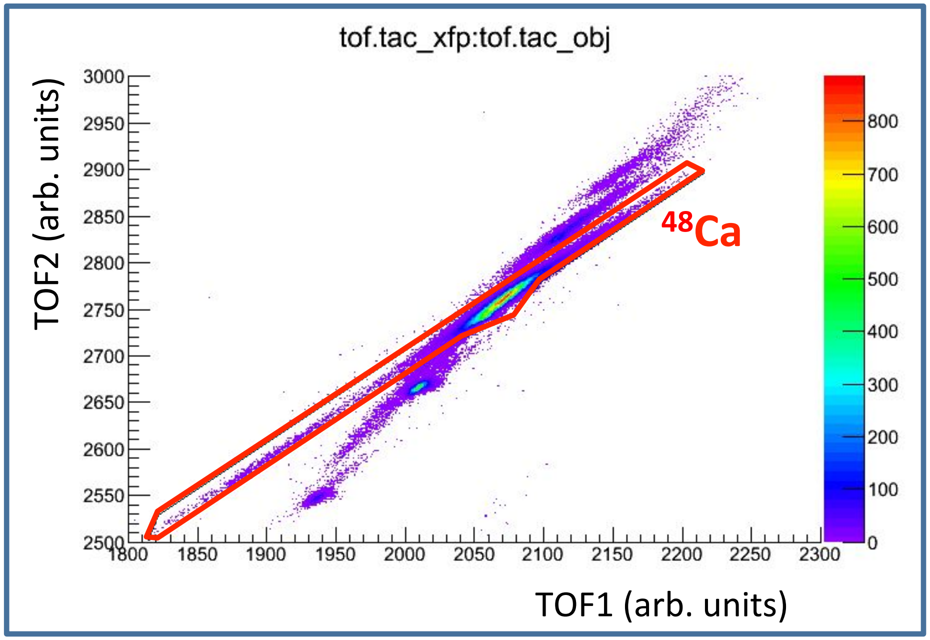


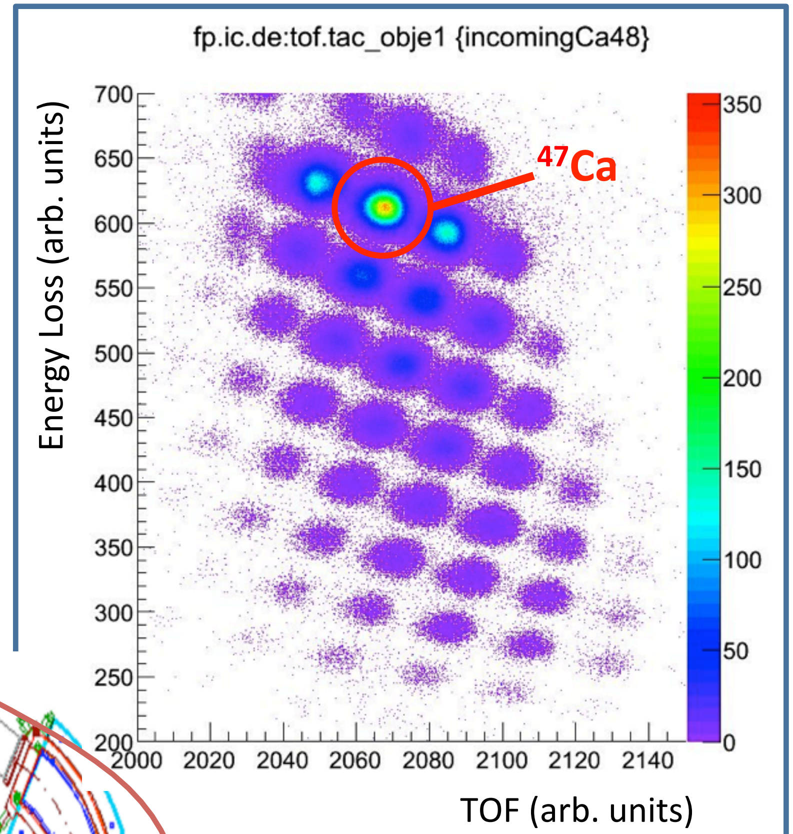
GRETINA + S800: Neutron Knockout in Ca

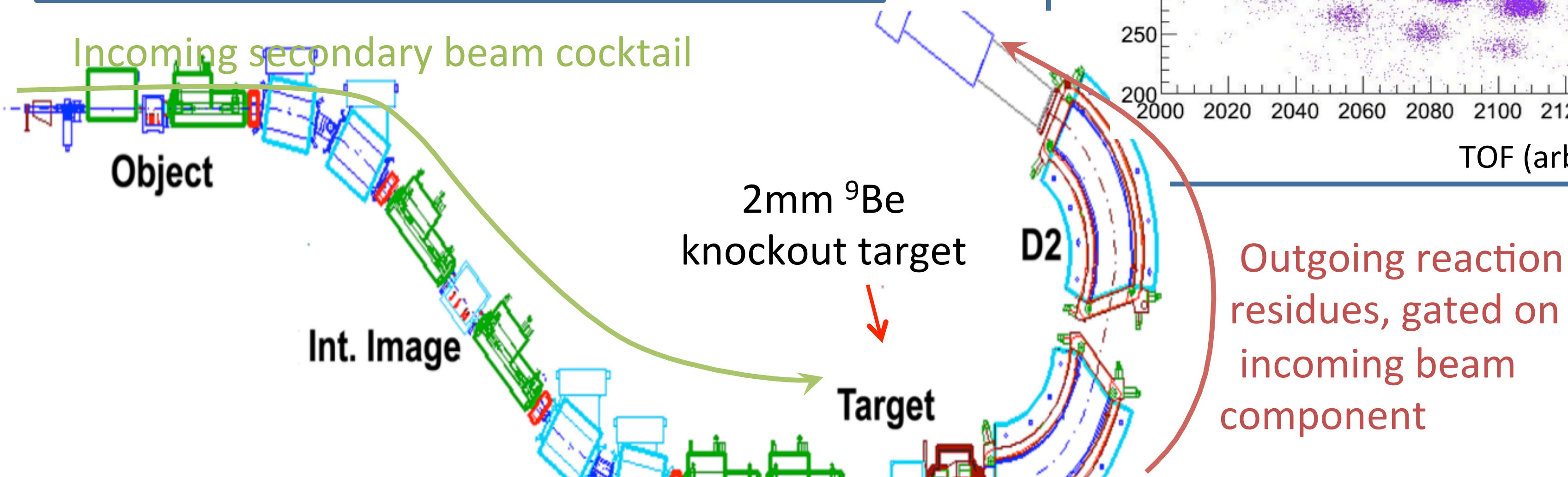




Particle Identification: 1n Knockout from ^{48}Ca





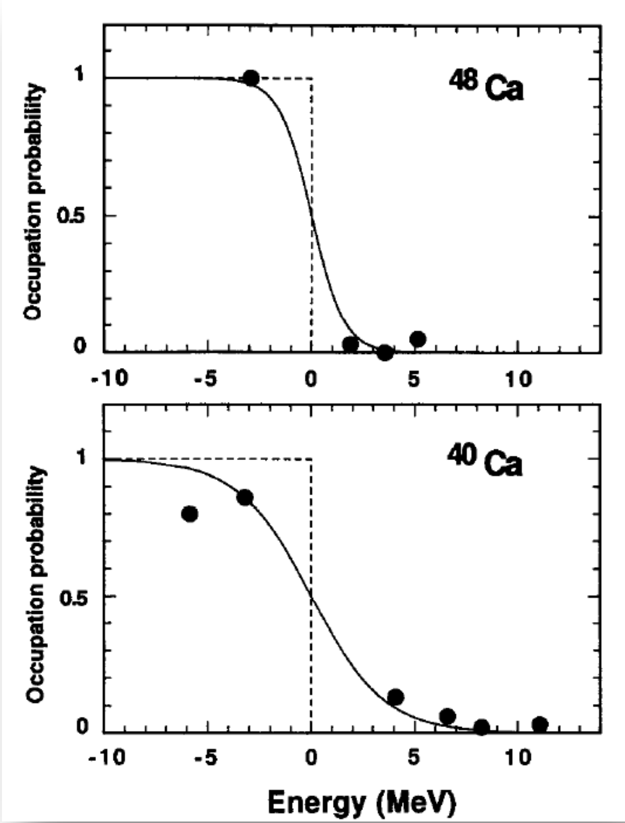


Benchmark against ^{48}Ca(p,d)^{47}Ca

Expectation is ^{48}Ca is good doubly-magic core, and $1f_{7/2}$ occupancy = 8.

Transfer reactions, (p,d) and (d,t) confirm this with large spectroscopic factors for $f_{7/2}$ transfer.

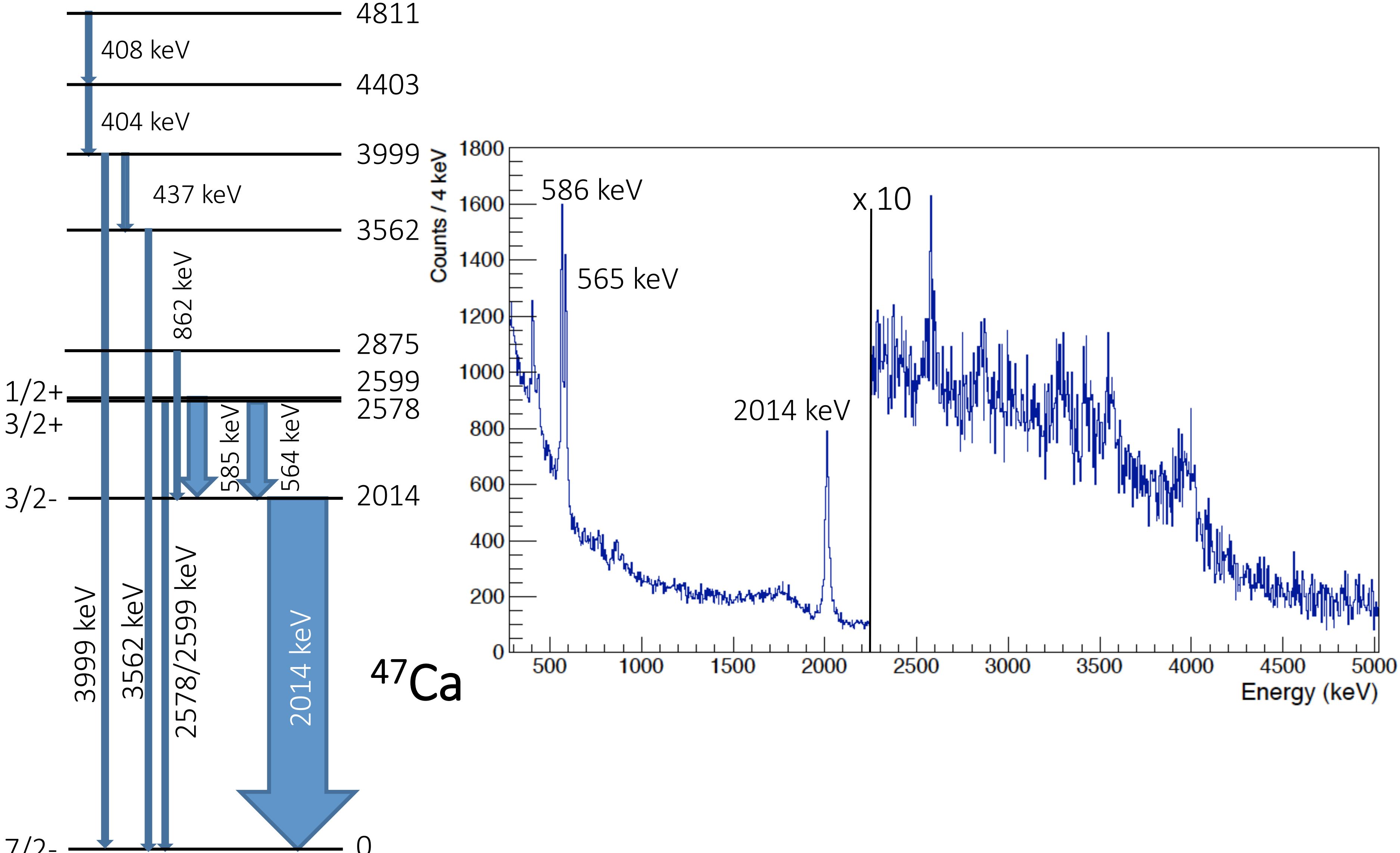
Energy (keV)	J^{π}	Configuration	C^2S^a	C^2S^b
0 (g.s)	7/2-	$(1f_{7/2})^{-1}$	6.7	6.22
2020	3/2-	$[(1f_{7/2})^{-2}(2p_{3/2})^{1}]_{3/2-}$	0.02	0.10
2580	3/2+	$(1d_{3/2})^{-1}$	3.6	1.18
2600	1/2+	$(2s_{1/2})^{-1}$	1.8	1.28



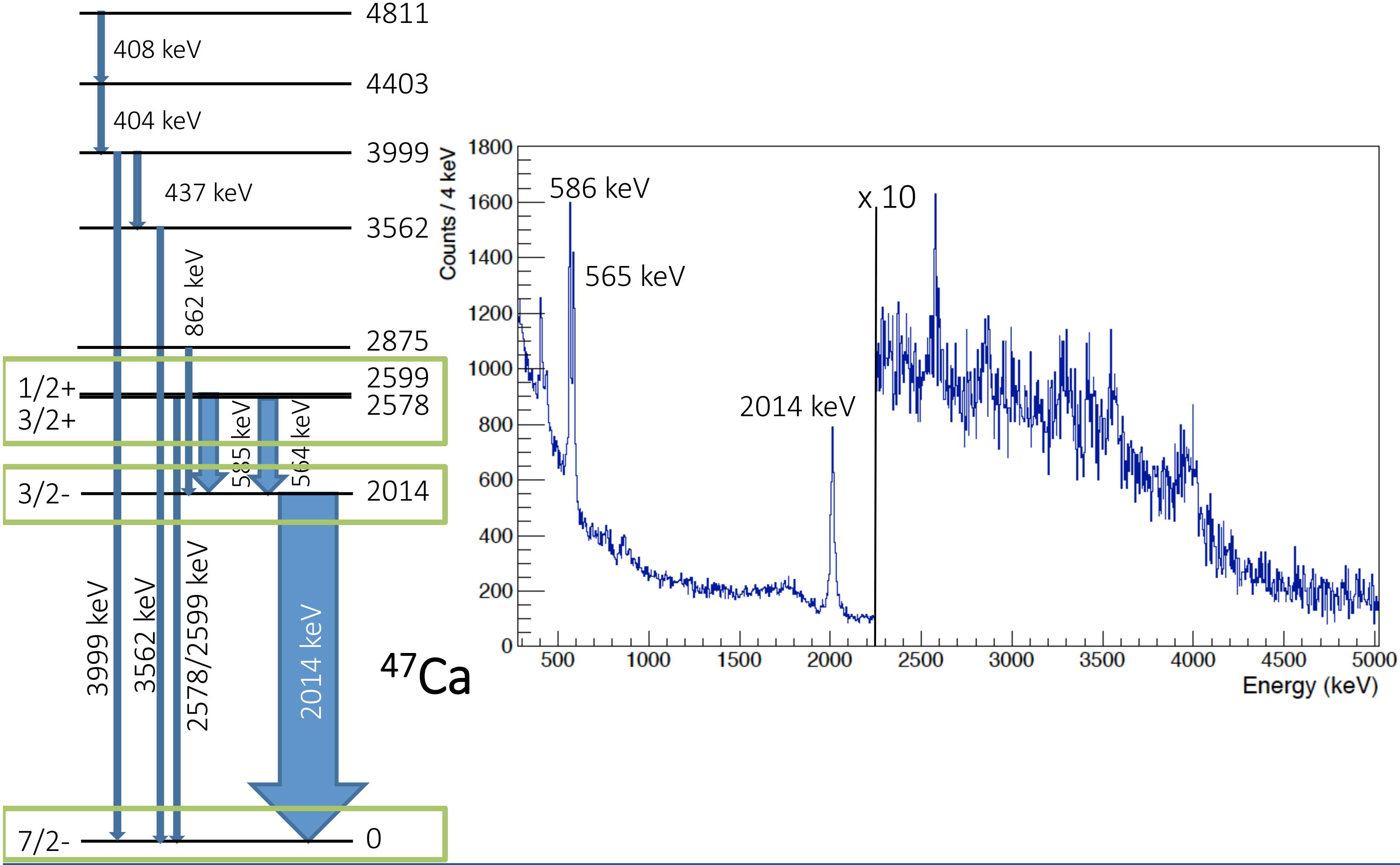
Y. Uozumi *et al.*, Nucl. Phys. A576, 123 (1994).

(a) P. Martin et al., Nuclear Physics A185, 465 (1972). -- (p,d)
(b) M.E. Williams-Norton and R. Abegg, Nuclear Physics A291, 429 (1977). – (d,t)

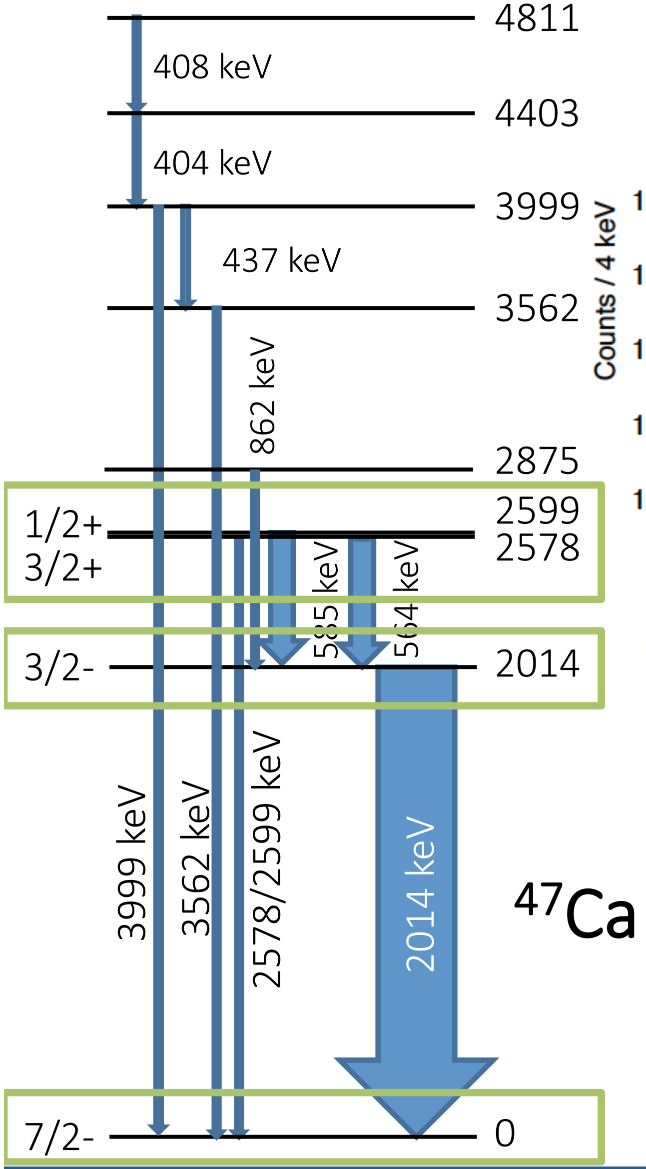
Benchmark against $^{48}Ca(p,d)^{47}Ca$

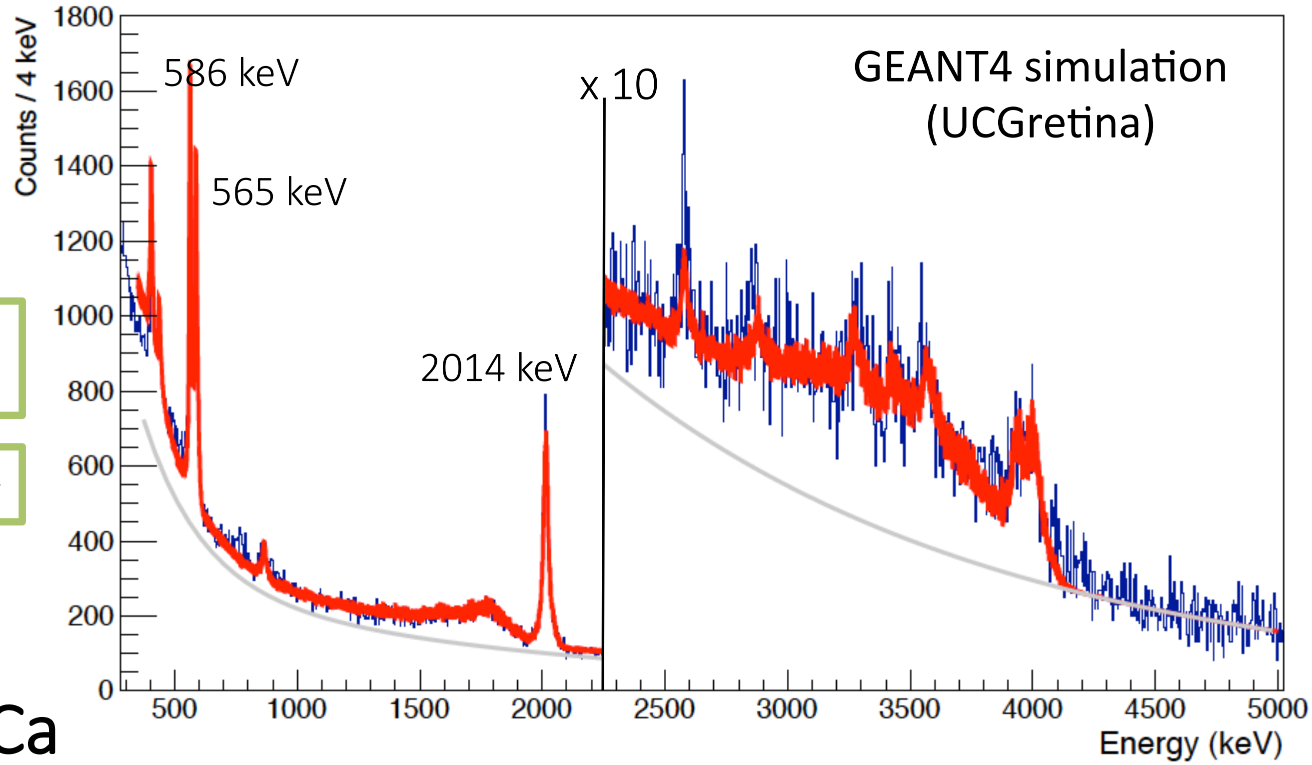


Benchmark against $^{48}Ca(p,d)^{47}Ca$

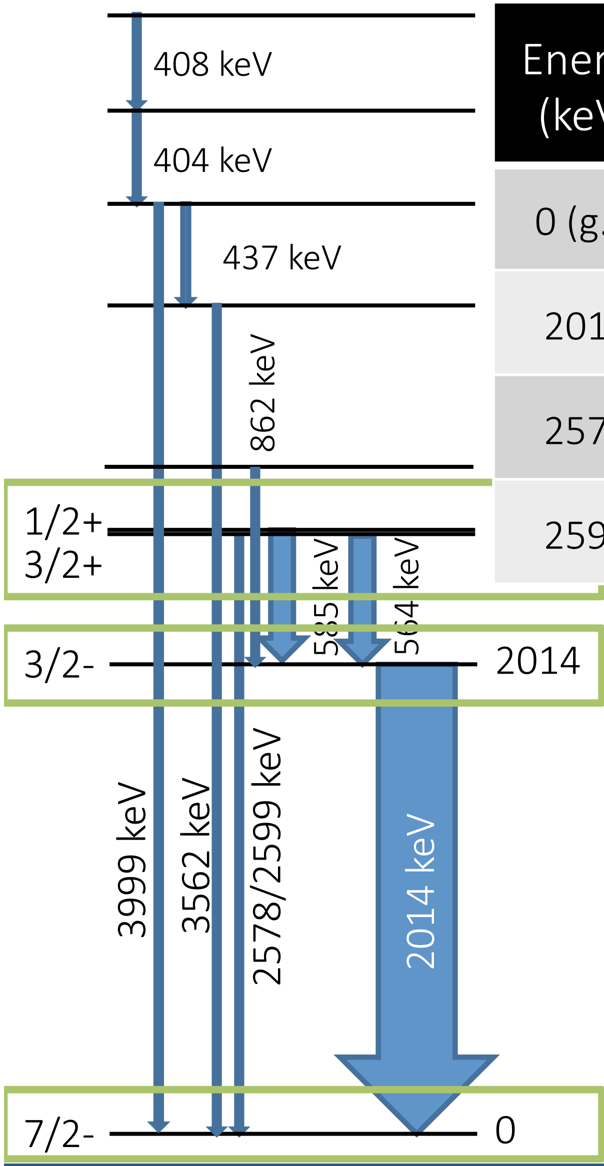


Benchmark against $^{48}Ca(p,d)^{47}Ca$





Benchmark against $^{48}Ca(p,d)^{47}Ca$



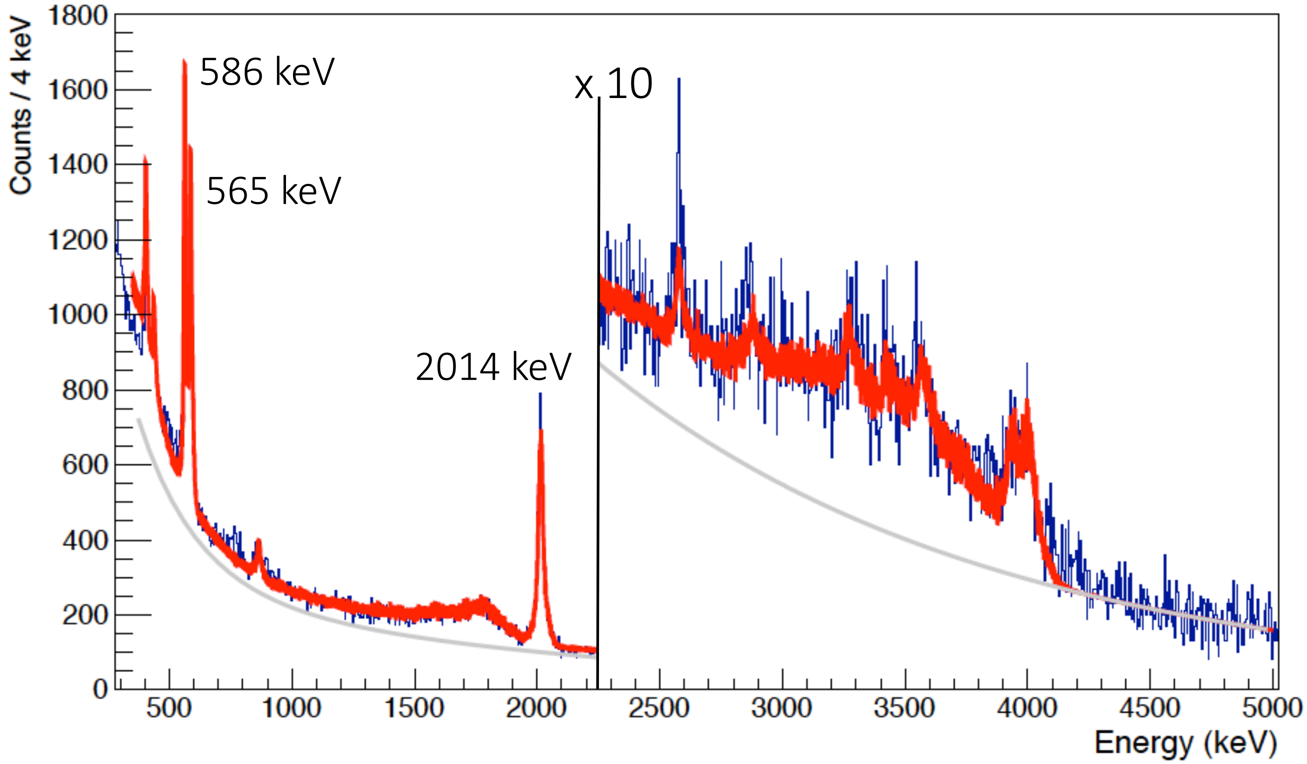
Energy (keV)	Jπ	Configuration	C^2S^a	C^2S^b	σ (mb)	C^2S
0 (g.s)	7/2-	$(1f_{7/2})^{-1}$	6.7	6.22	76.2±4.0	6.9±0.4
2014	3/2-	$[(1f_{7/2})^{-2}(2p_{3/2})^{1}]_{3/2-}$	0.02	0.10	6.9±1.6	0.6±0.1
2578	3/2+	$(1d_{3/2})^{-1}$	3.6	1.18	9.7±1.8	1.3±0.2
2599	1/2+	$(2s_{1/2})^{-1}$	1.8	1.28	11.1±2.0	0.9±0.2

- Level scheme agrees with literature; few high energy gamma-rays were placed directly feeding the ^{47}Ca g.s.
- Fit with GEANT4 simulation provides absolute gamma-ray intensities – determine feeding to individual states and extract cross-sections

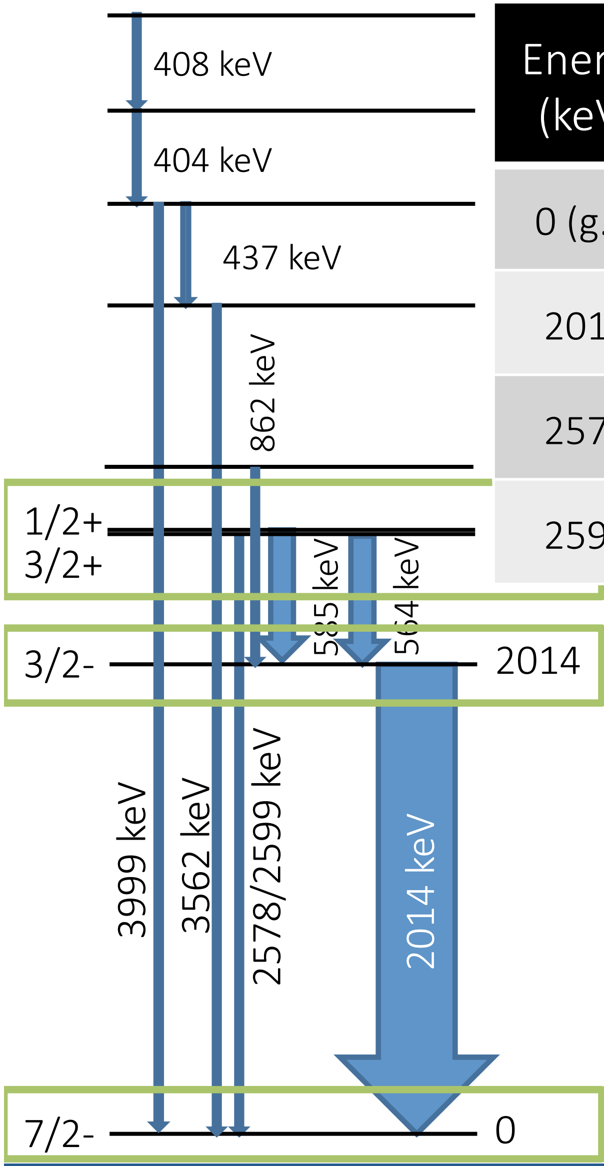
(a) P. Martin et al., Nuclear Physics A185, 465 (1972). -- (p,d)
(b) M.E. Williams-Norton and R. Abegg, Nuclear Physics A291, 429 (1977). – (d,t)

Unresolved Feeding

- Experimentally, there will be unresolved feeding from highly fragmented states ($d_{5/2}$)
- Work is ongoing to finalize errors in cross-section resulting from unresolved strength, but the physics is unchanged
- We can estimate a systematic uncertainty for the measurement



Benchmark against $^{48}Ca(p,d)^{47}Ca$

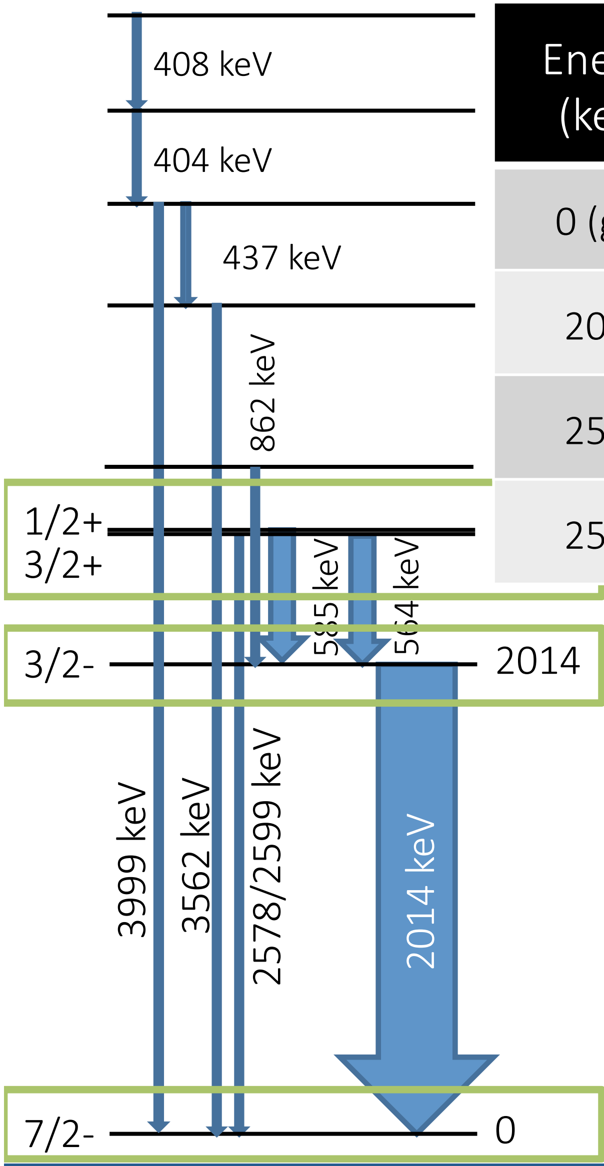


Energy (keV)	Jπ	Configuration	C^2S^a	C^2S^b	σ (mb)	C^2S
0 (g.s)	7/2-	$(1f_{7/2})^{-1}$	6.7	6.22	76.2±4.0	6.9±0.4
2014	3/2-	$[(1f_{7/2})^{-2}(2p_{3/2})^{1}]_{3/2-}$	0.02	0.10	6.9±1.6	0.6±0.1
2578	3/2+	$(1d_{3/2})^{-1}$	3.6	1.18	9.7±1.8	1.3±0.2
2599	1/2+	$(2s_{1/2})^{-1}$	1.8	1.28	11.1±2.0	0.9±0.2

- Level scheme agrees with literature; few high energy gamma-rays were placed directly feeding the ^{47}Ca g.s.
- Fit with GEANT4 simulation provides absolute gamma-ray intensities – determine feeding to individual states and extract cross-sections

(a) P. Martin et al., Nuclear Physics A185, 465 (1972). -- (p,d)
(b) M.E. Williams-Norton and R. Abegg, Nuclear Physics A291, 429 (1977). – (d,t)

Benchmark against $^{48}Ca(p,d)^{47}Ca$

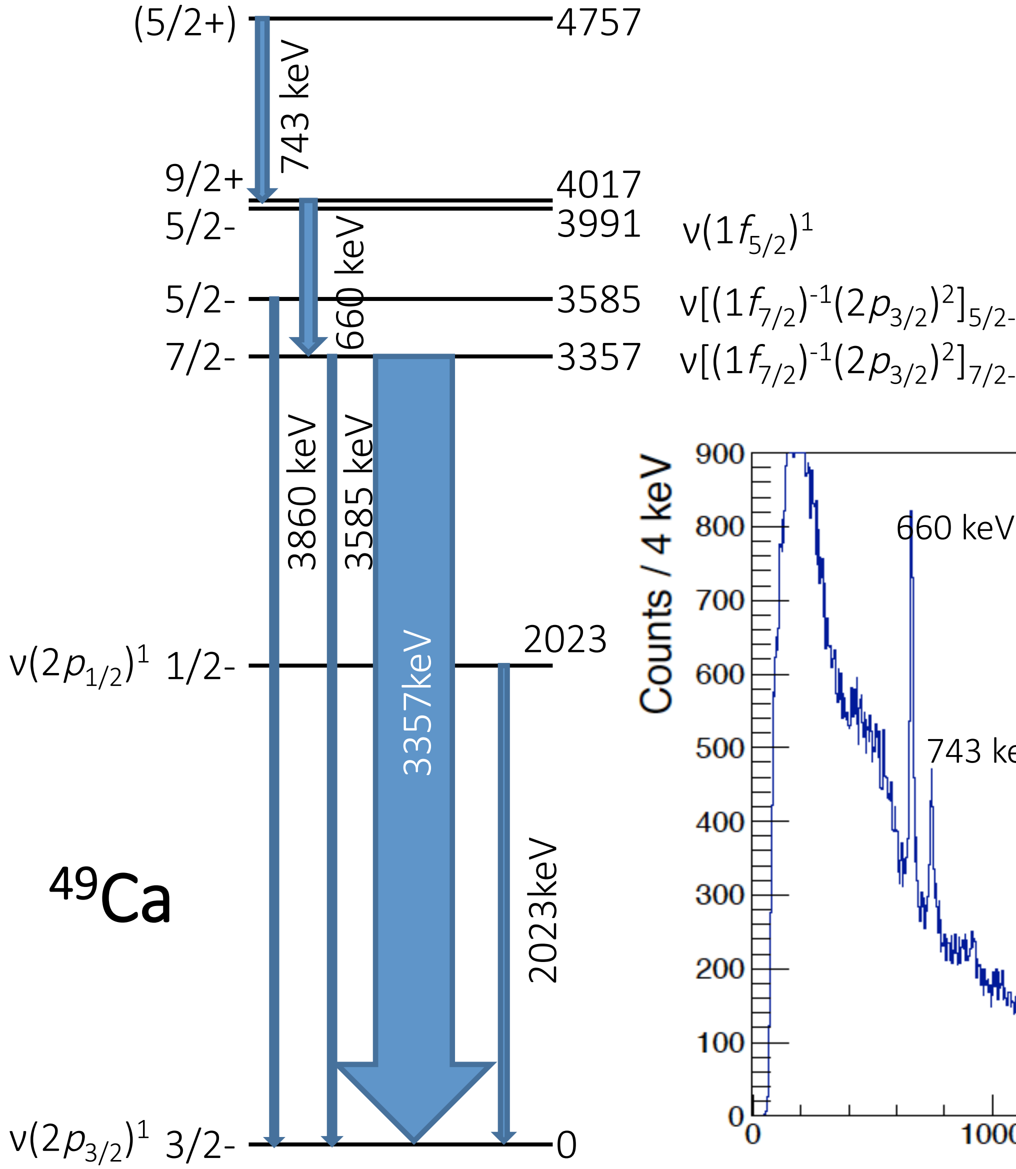


Energy (keV)	J^{π}	Configuration	C^2S	Relative C^2S
0 (g.s)	7/2-	$(1f_{7/2})^{-1}$	6.9±0.4	$8.0 \pm (0.4)_{stat} \pm (0.6)_{sys}$
2014	3/2-	$[(1f_{7/2})^{-2}(2p_{3/2})^{1}]_{3/2-}$	0.6±0.1	$0.7 \pm (0.1)_{stat} \pm (0.7)_{sys}$
2578	3/2+	$(1d_{3/2})^{-1}$	1.3±0.2	$1.7 \pm (0.2)_{stat} \pm (0.9)_{sys}$
2599	1/2+	$(2s_{1/2})^{-1}$	0.9±0.2	$1.2 \pm (0.2)_{stat} \pm (0.5)_{sys}$

- Level scheme agrees with literature; few high energy gamma-rays were placed directly feeding the ^{47}Ca g.s.
- Fit with GEANT4 simulation provides absolute gamma-ray intensities – determine feeding to individual states and extract cross-sections

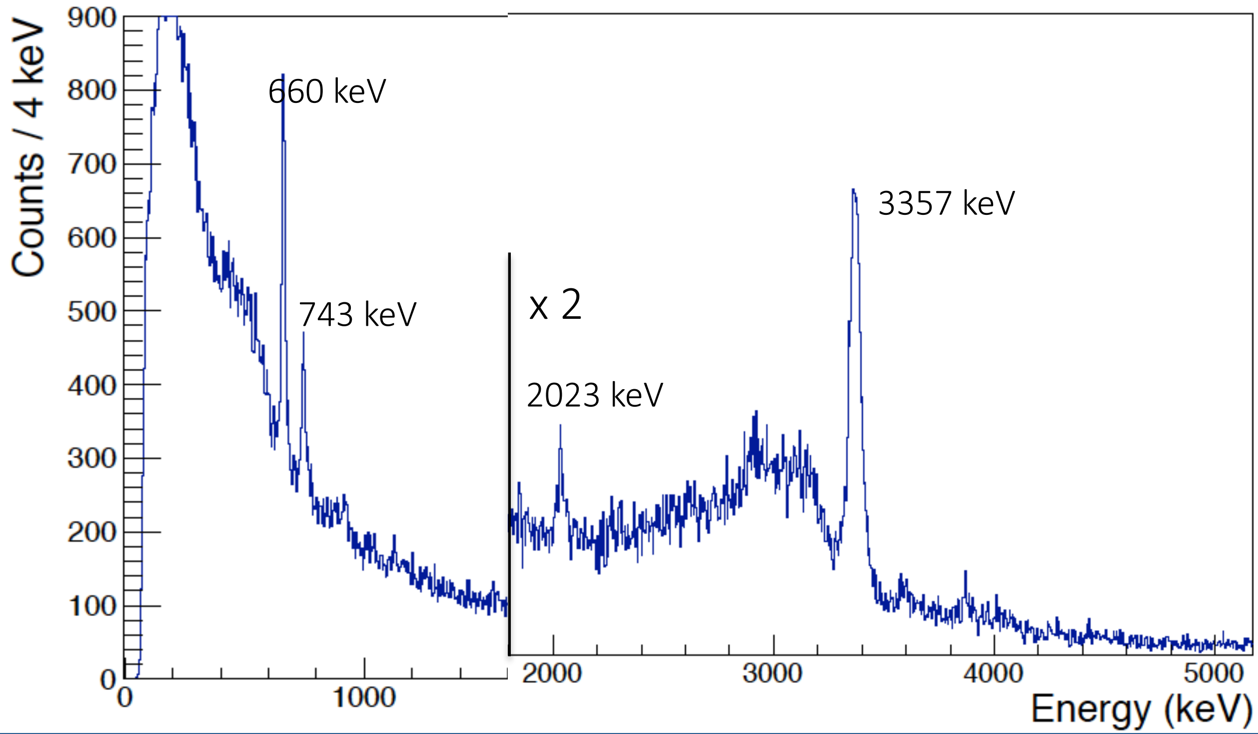
(a) P. Martin et al., Nuclear Physics A185, 465 (1972). -- (p,d)
(b) M.E. Williams-Norton and R. Abegg, Nuclear Physics A291, 429 (1977). – (d,t)

Measuring the $f_{7/2}$ Strength: ^{50}Ca

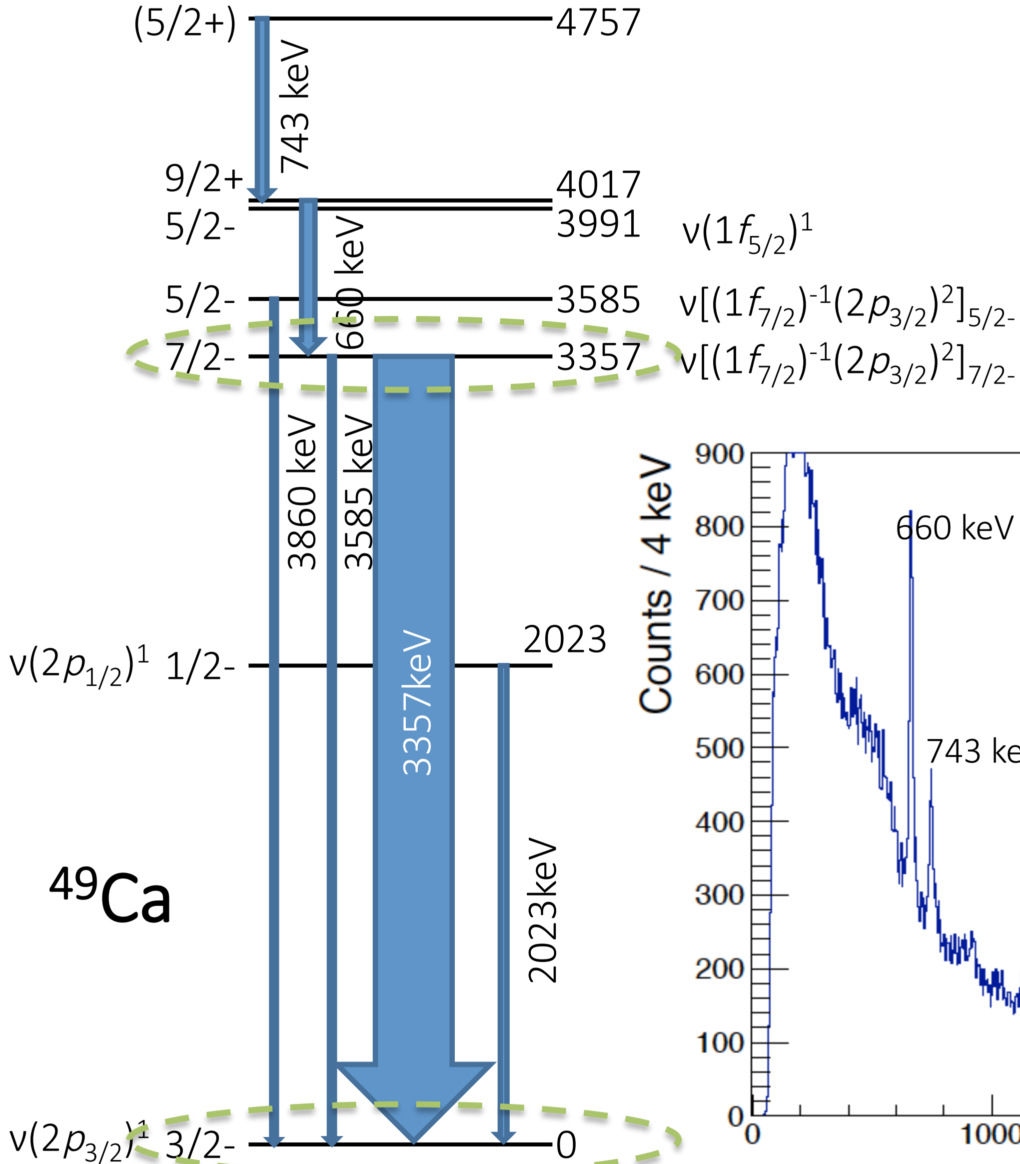


^{50}Ca knockout from $(2p_{3/2})^2$ ground state

In the ^{50}Ca ground state, two $p_{3/2}$ neutron are coupled to 0+; knockout of a $1f_{7/2}$ neutron should essentially exclusively populate the first 7/2- state, with $\nu[(1f_{7/2})^{-1}(2p_{3/2})^2]_{7/2-}$

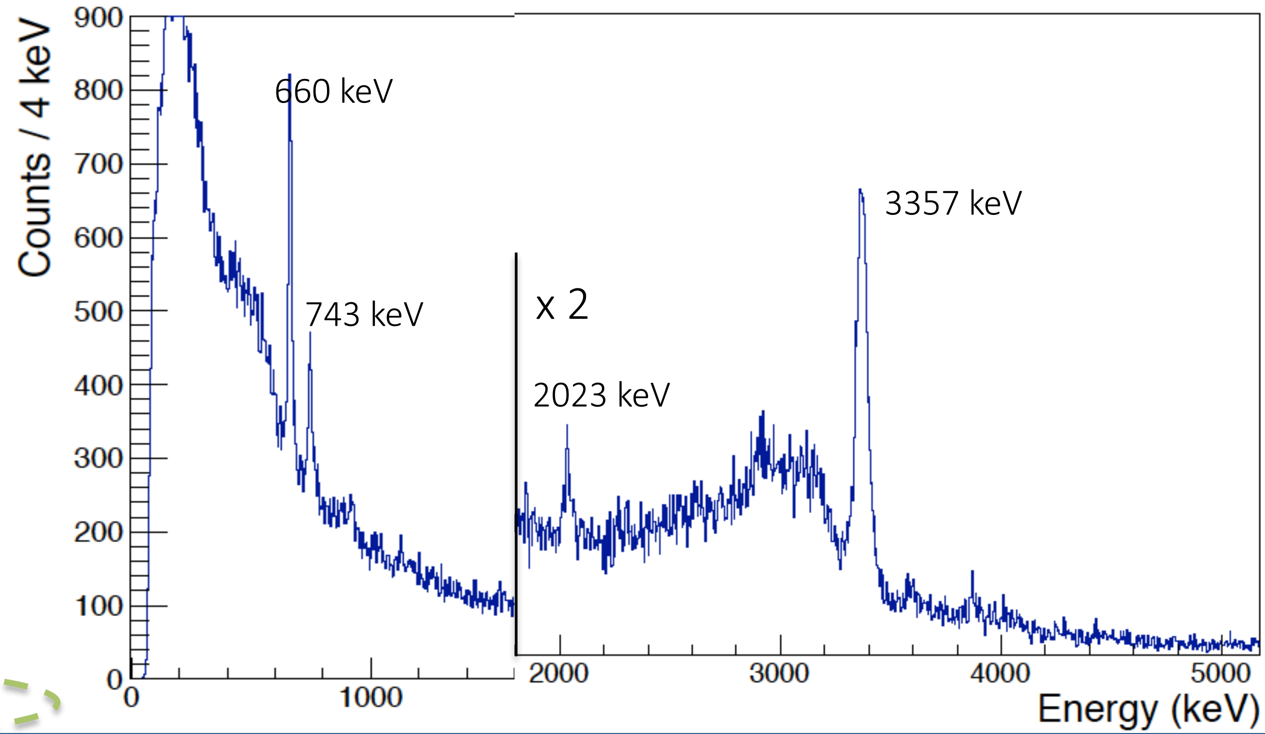


Measuring the $f_{7/2}$ Strength: ^{50}Ca

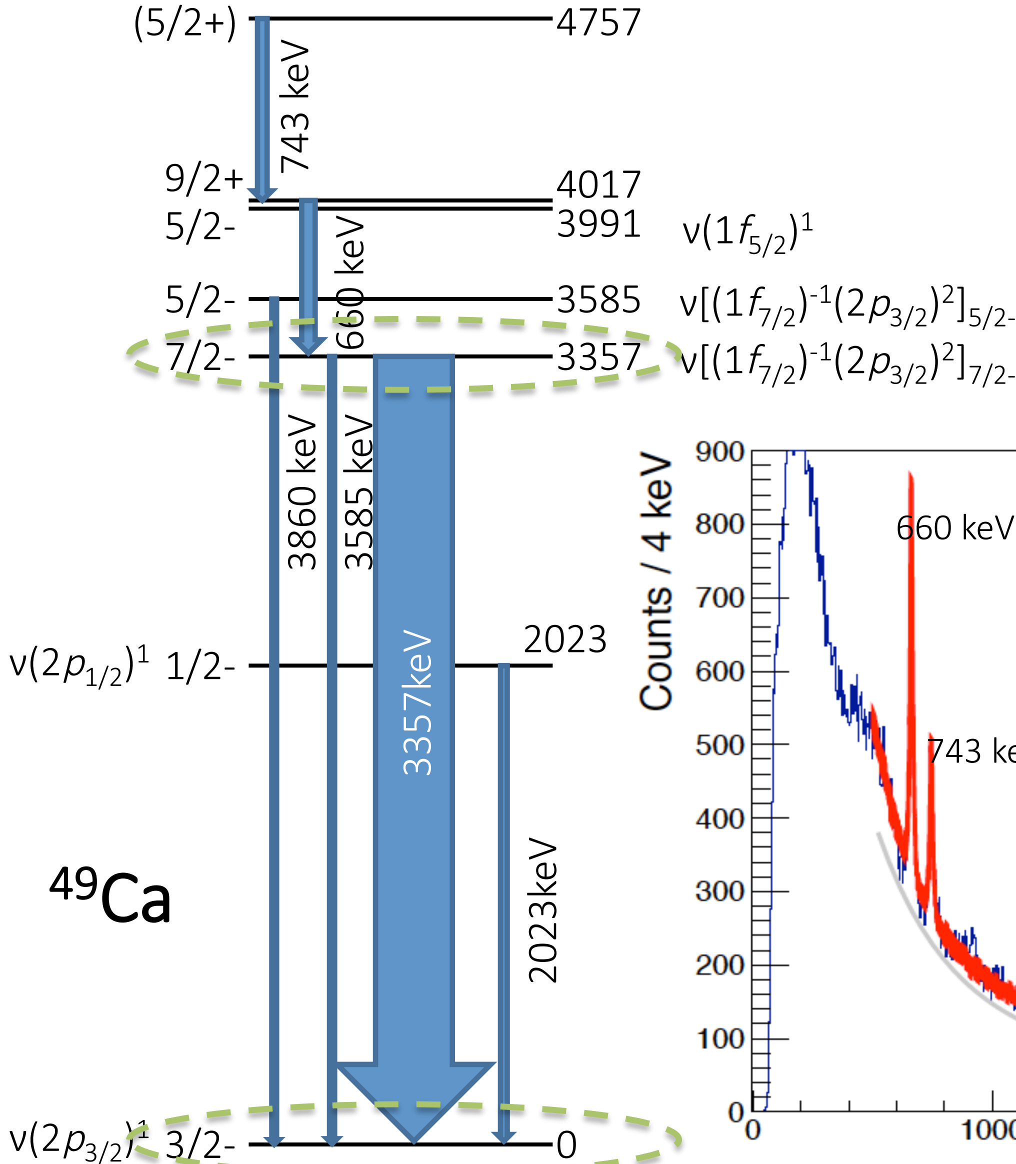


^{50}Ca knockout from $(2p_{3/2})^2$ ground state

In the ^{50}Ca ground state, two $p_{3/2}$ neutron are coupled to 0+; knockout of a $1f_{7/2}$ neutron should essentially exclusively populate the first 7/2- state, with $\nu[(1f_{7/2})^{-1}(2p_{3/2})^2]_{7/2-}$

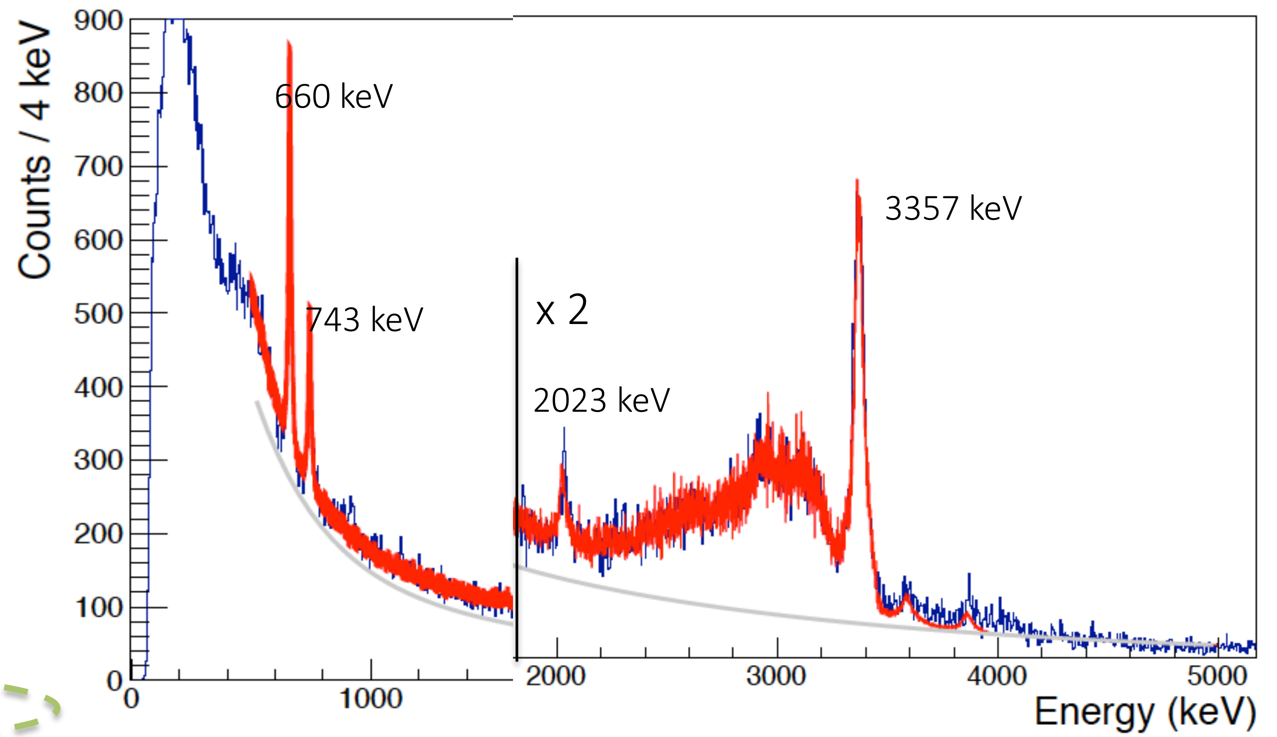


Measuring the $f_{7/2}$ Strength: ^{50}Ca

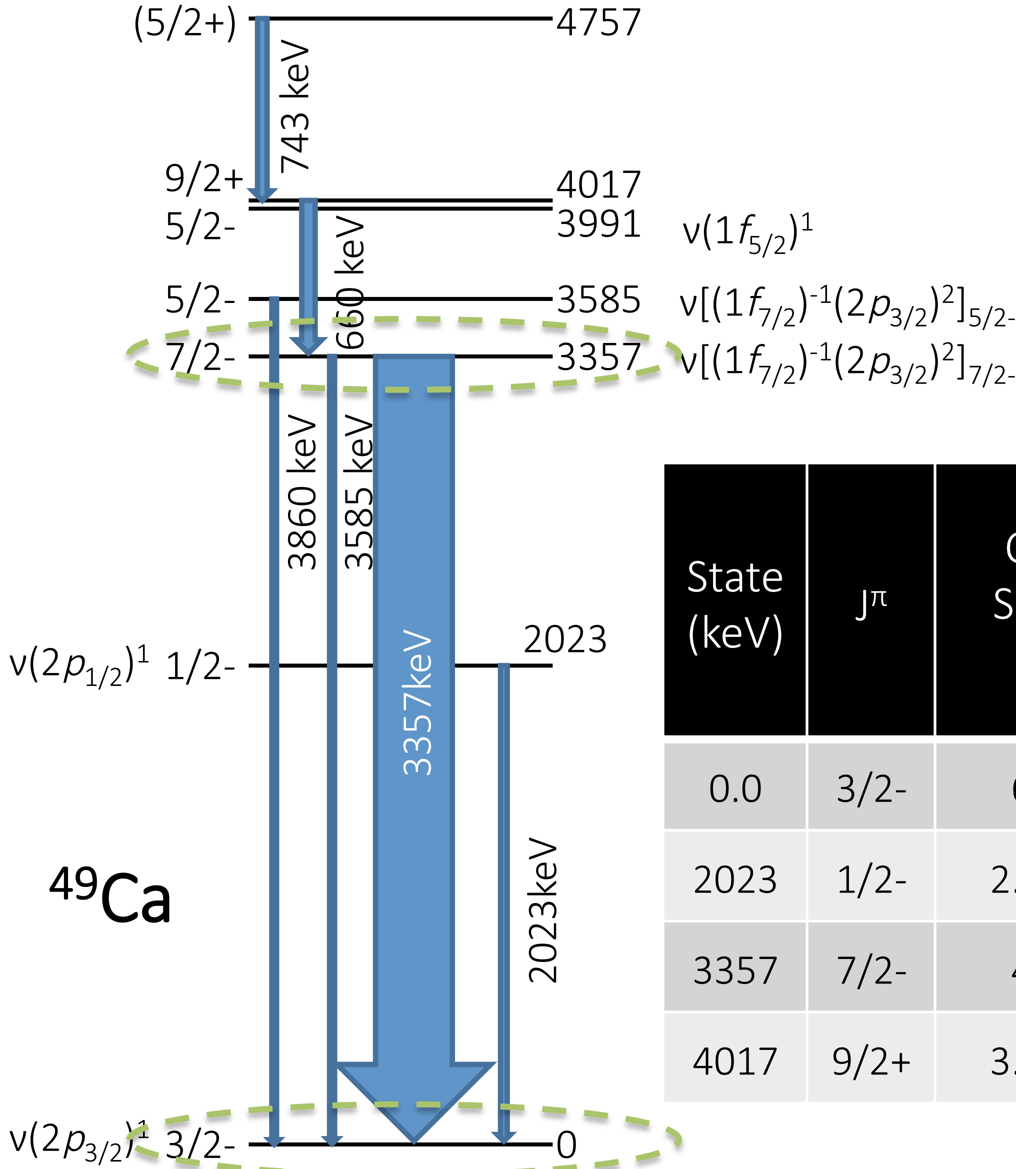


^{50}Ca knockout from $(2p_{3/2})^2$ ground state

In the ^{50}Ca ground state, two $p_{3/2}$ neutron are coupled to 0+; knockout of a $1f_{7/2}$ neutron should essentially exclusively populate the first 7/2- state, with $\nu[(1f_{7/2})^{-1}(2p_{3/2})^2]_{7/2-}$



Measuring the $f_{7/2}$ Strength: ^{50}Ca

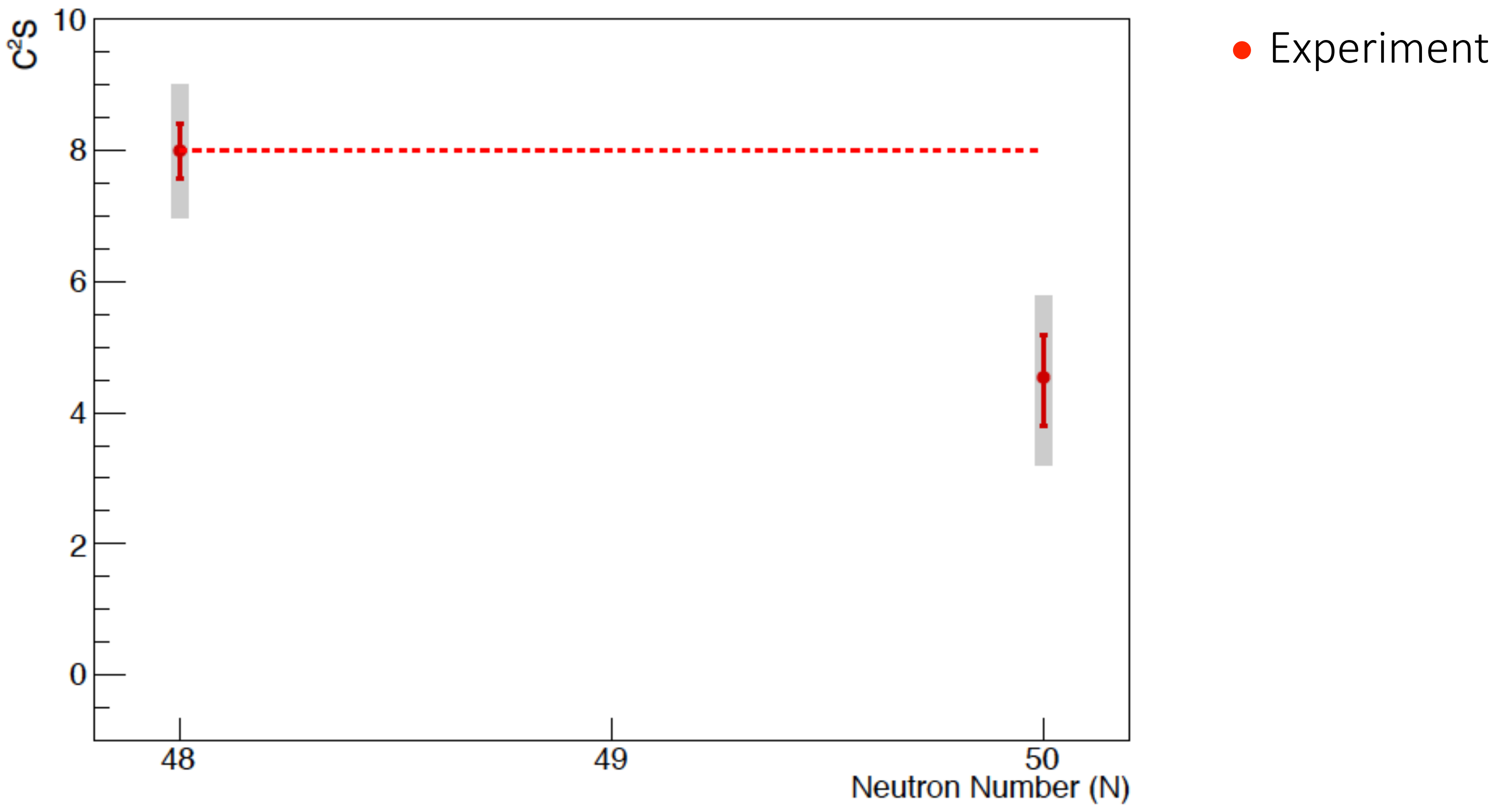


^{50}Ca knockout from $(2p_{3/2})^2$ ground state

In the ^{50}Ca ground state, two $p_{3/2}$ neutron are coupled to 0+; knockout of a $1f_{7/2}$ neutron should essentially exclusively populate the first 7/2- state, with $\nu[(1f_{7/2})^{-1}(2p_{3/2})^2]_{7/2-}$

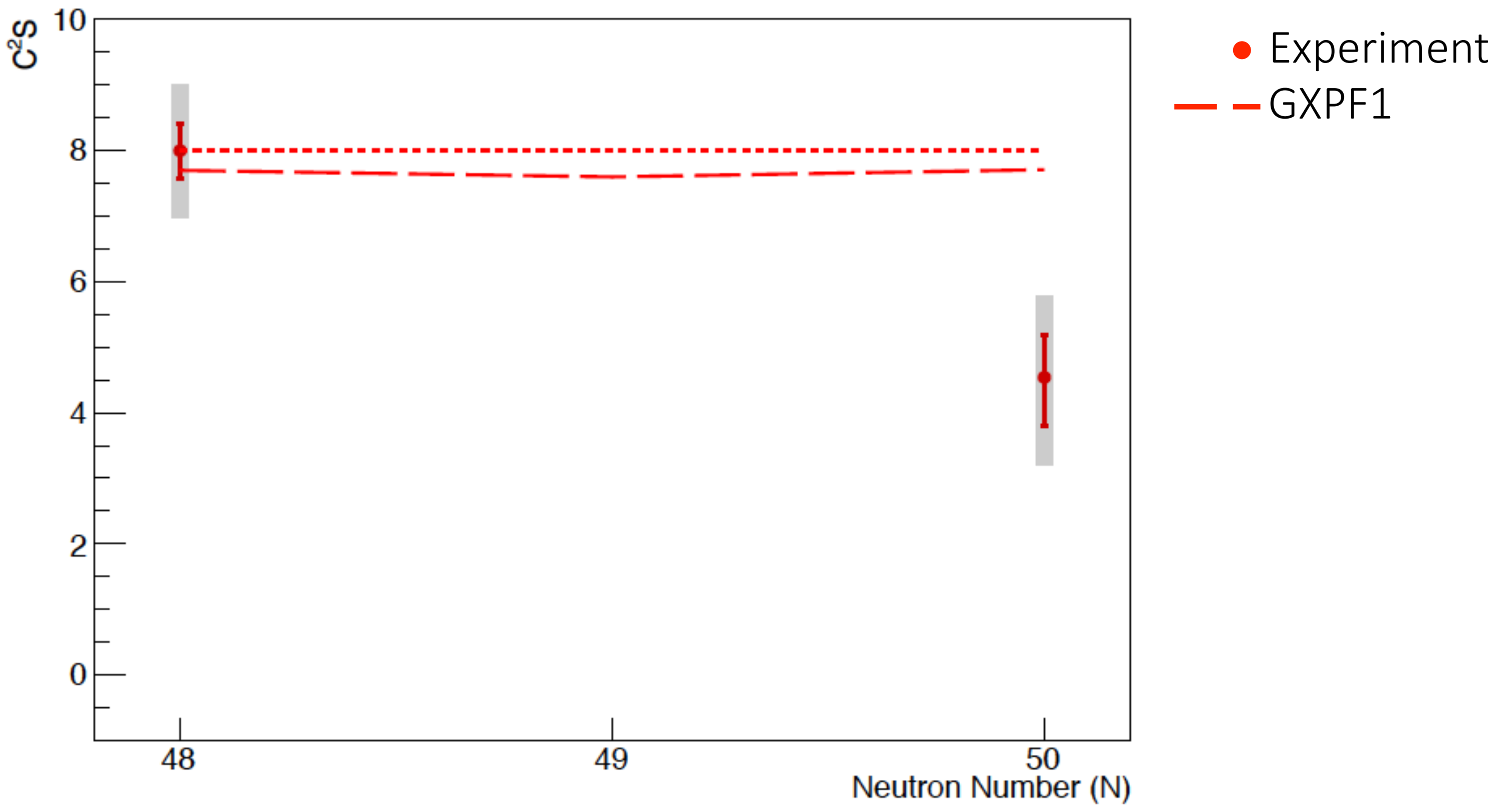
State (keV)	J^π	Cross-Section (mb)	'Raw' C^2S	Relative C^2S
0.0	3/2-	60 ± 5	3.2 ± 0.3	$3.7 \pm (0.4)_{stat} \pm (0.4)_{sys}$
2023	1/2-	2.7 ± 0.6	0.2 ± 0.1	$0.2 \pm (0.1)_{stat} \pm (0.4)_{sys}$
3357	7/2-	42 ± 5	3.8 ± 0.5	$4.6 \pm (0.7)_{stat} \pm (0.6)_{sys}$
4017	9/2+	3.2 ± 0.8	0.3 ± 0.1	$0.3 \pm (0.1)_{stat} \pm (0.6)_{sys}$

Occupation of the $1f_{7/2}$ Along $Z = 20$



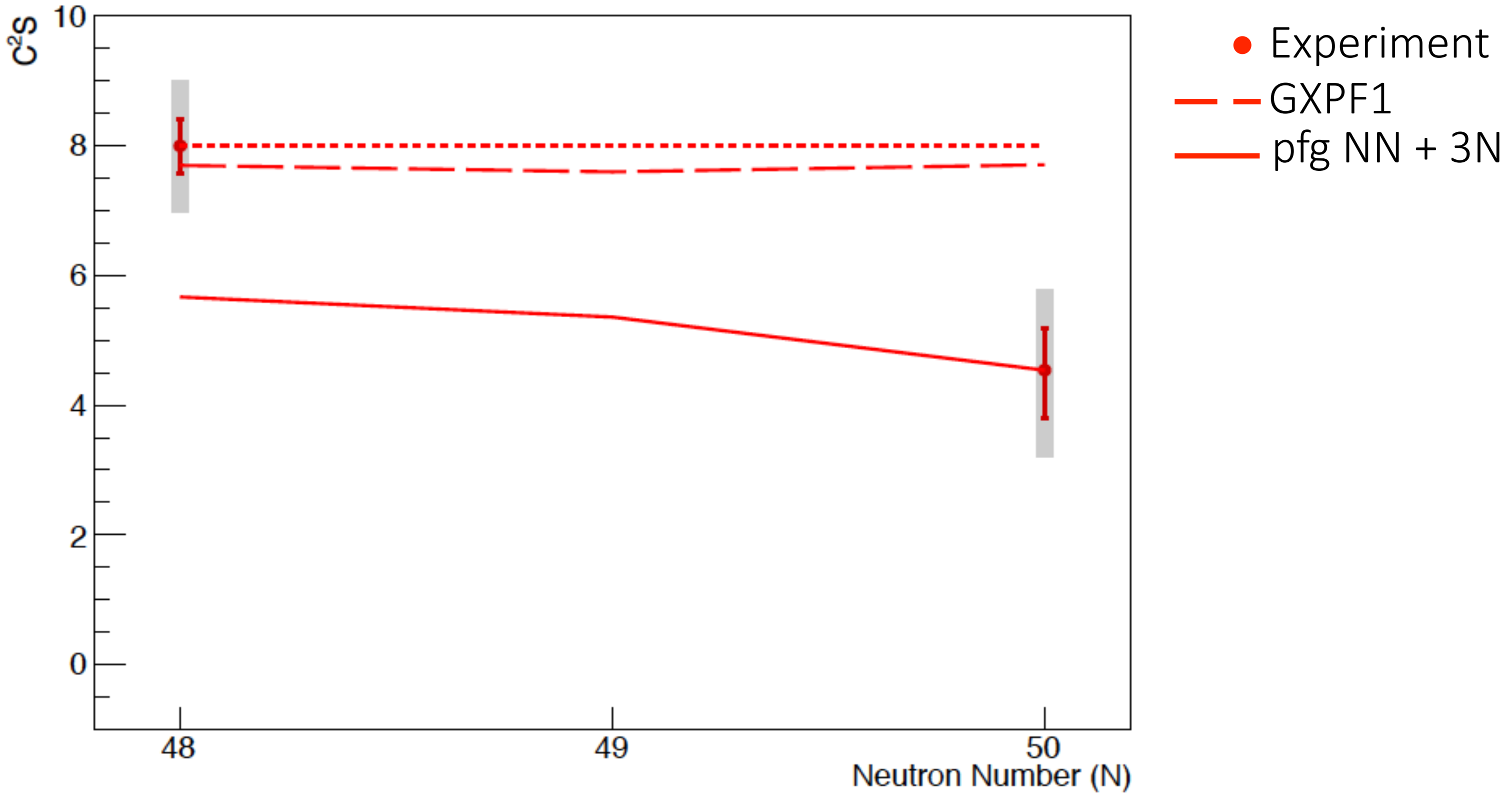
Using calculated $1f_{7/2}$ single-particle cross-sections and the experimental cross-sections to the expected $f_{7/2}$ states, we see a decrease in strength to the lowest $f_{7/2}$ level from ^{48}Ca to ^{50}Ca

Occupation of the $1f_{7/2}$ Along $Z = 20$



Using calculated $1f_{7/2}$ single-particle cross-sections and the experimental cross-sections to the expected $f_{7/2}$ states, we see a decrease in strength to the lowest $f_{7/2}$ level from ^{48}Ca to ^{50}Ca

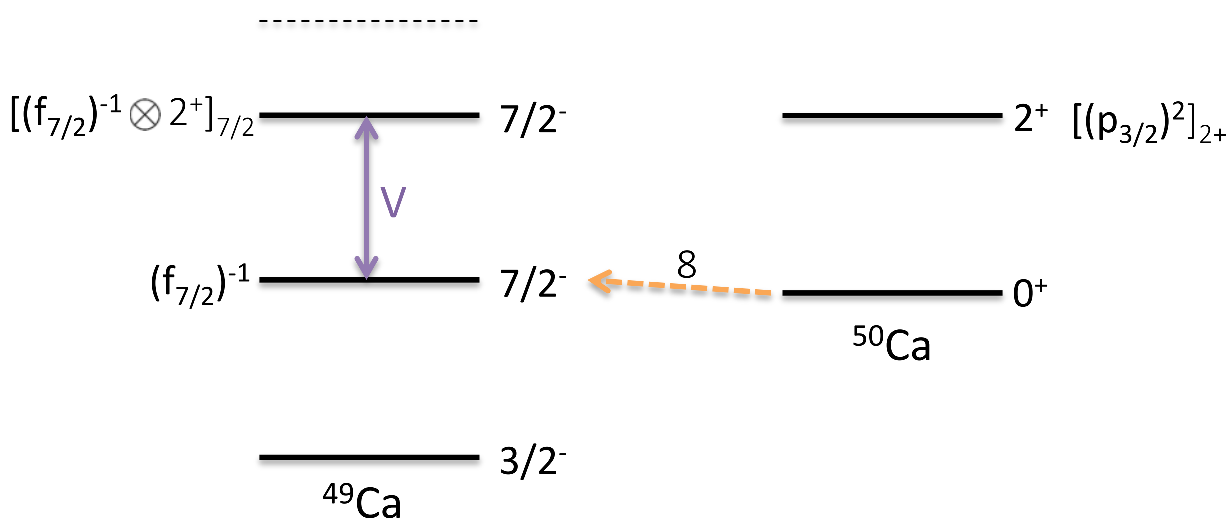
Occupation of the $1f_{7/2}$ Along $Z = 20$



Using calculated $1f_{7/2}$ single-particle cross-sections and the experimental cross-sections to the expected $f_{7/2}$ states, we see a decrease in strength to the lowest $f_{7/2}$ level from ^{48}Ca to ^{50}Ca

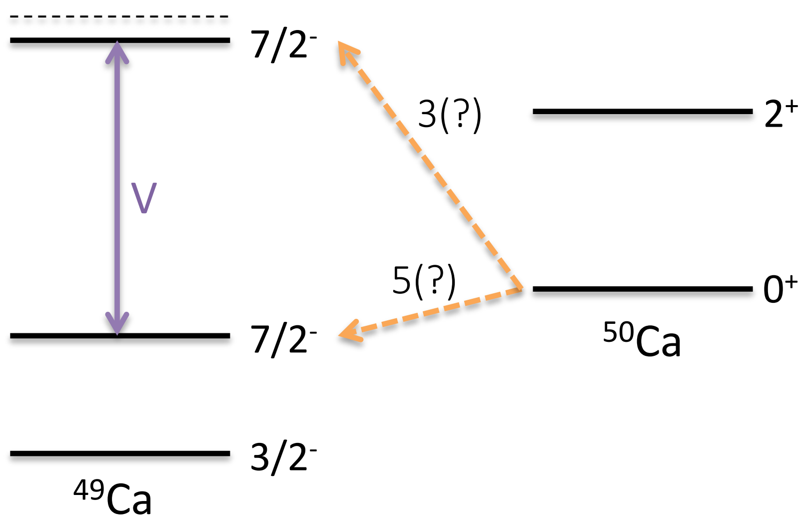
Fragmentation of $f_{7/2}$ Strength: Why?

	$^{50}Ca_{gs} \rightarrow {}^{49}Ca$ SF $\frac{1}{2J_1+1}$											
	$\frac{3}{2}^-_{gs}$	$\frac{3}{2}^-_1$	$\frac{7}{2}^-_1$	$\frac{7}{2}^-_2$	$\frac{7}{2}^-_3$	$\frac{7}{2}^-_4$	$\frac{5}{2}^-_1$	$\frac{5}{2}^-_2$	$\frac{1}{2}^-_1$	$\frac{1}{2}^-_2$	$\frac{9}{2}^+_1$	$\frac{9}{2}^+_2$
GXPF1	1.73	0.03	7.71	0.00	0.00	0.01	0.00	0.06	0.17	0.00	-	-
(SR)	(1.82)		(7.90)				(0.09)		(0.19)		-	
pf NN+3N	1.57	0.23	4.55	2.03	0.02	0.21	0.03	0.10	0.35	0.01	-	-
(SR)	(1.95)		(7.31)				(0.30)		(0.44)		-	
$pfg_{9/2}$ NN+3N	1.65	0.09	4.54	1.18	0.00	0.03	0.10	0.01	0.20	0.00	1.26	0.05
(SR)	(1.81)		(6.09)				(0.20)		(0.24)		(1.66)	



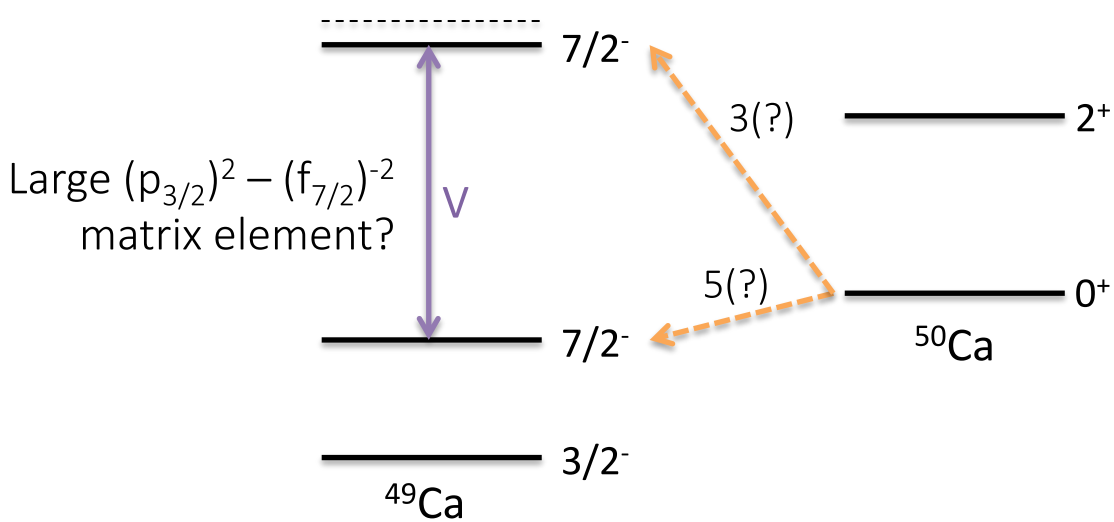
Fragmentation of $f_{7/2}$ Strength: Why?

	$^{50}\mathrm{Ca}_{gs} \rightarrow {}^{49}\mathrm{Ca}$ SF$_{\frac{1}{2J_1+1}}$											
	$\frac{3}{2}^-_{gs}$	$\frac{3}{2}^-_1$	$\frac{7}{2}^-_1$	$\frac{7}{2}^-_2$	$\frac{7}{2}^-_3$	$\frac{7}{2}^-_4$	$\frac{5}{2}^-_1$	$\frac{5}{2}^-_2$	$\frac{1}{2}^-_1$	$\frac{1}{2}^-_2$	$\frac{9}{2}^+_1$	$\frac{9}{2}^+_2$
GXPF1	1.73	0.03	7.71	0.00	0.00	0.01	0.00	0.06	0.17	0.00	-	-
(SR)	(1.82)		(7.90)				(0.09)		(0.19)		-	
pf NN+3N	1.57	0.23	4.55	2.03	0.02	0.21	0.03	0.10	0.35	0.01	-	-
(SR)	(1.95)		(7.31)				(0.30)		(0.44)		-	
pfg$_{9/2}$ NN+3N	1.65	0.09	4.54	1.18	0.00	0.03	0.10	0.01	0.20	0.00	1.26	0.05
(SR)	(1.81)		(6.09)				(0.20)		(0.24)		(1.66)	



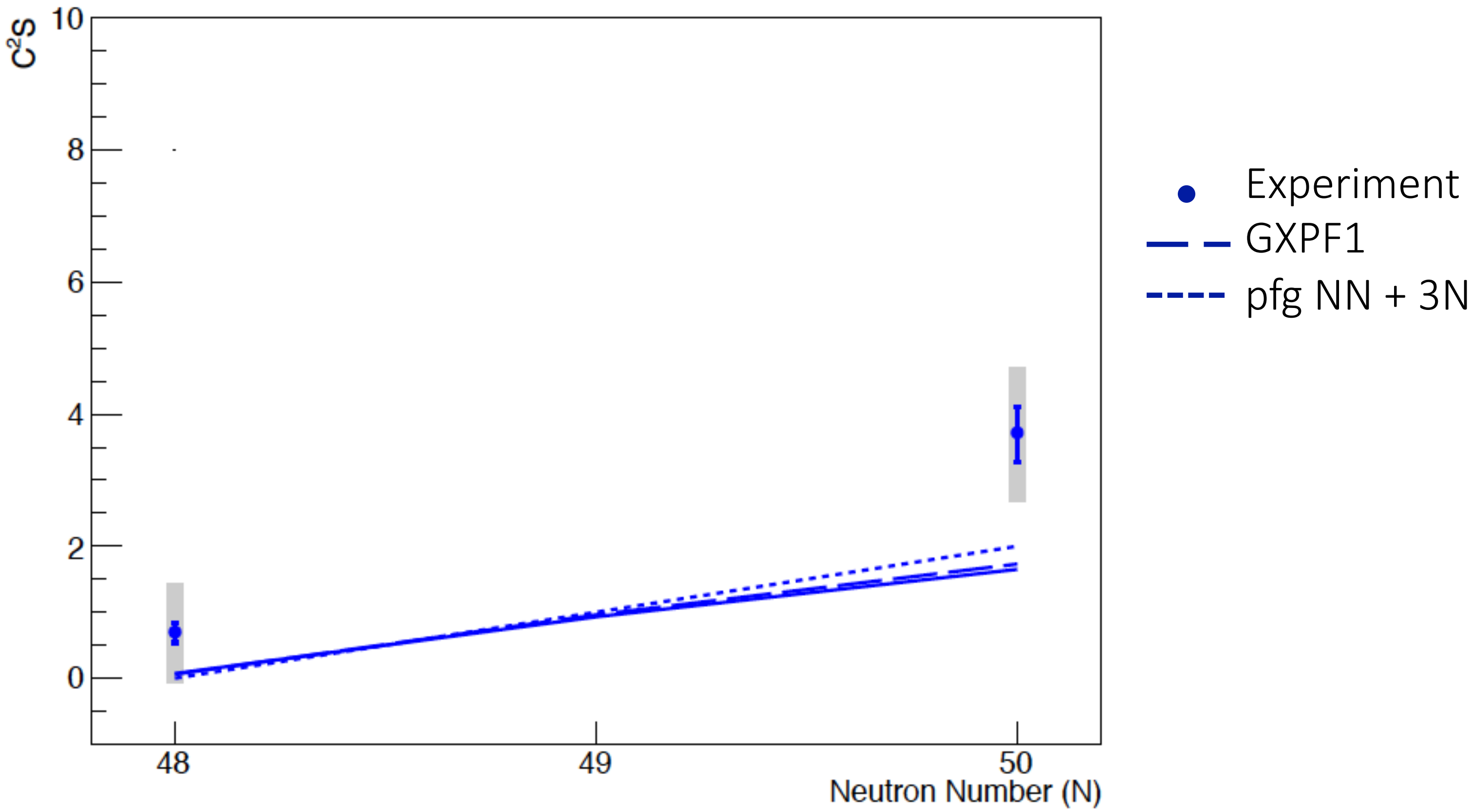
Fragmentation of $f_{7/2}$ Strength: Why?

	$^{50}Ca_{gs} \rightarrow ^{49}Ca$ SF $\frac{1}{2J_1+1}$											
	$\frac{3}{2}^-_{gs}$	$\frac{3}{2}^-_1$	$\frac{7}{2}^-_1$	$\frac{7}{2}^-_2$	$\frac{7}{2}^-_3$	$\frac{7}{2}^-_4$	$\frac{5}{2}^-_1$	$\frac{5}{2}^-_2$	$\frac{1}{2}^-_1$	$\frac{1}{2}^-_2$	$\frac{9}{2}^+_1$	$\frac{9}{2}^+_2$
GXPF1	1.73	0.03	7.71	0.00	0.00	0.01	0.00	0.06	0.17	0.00	-	-
(SR)	(1.82)		(7.90)				(0.09)		(0.19)		-	
pf NN+3N	1.57	0.23	4.55	2.03	0.02	0.21	0.03	0.10	0.35	0.01	-	-
(SR)	(1.95)		(7.31)				(0.30)		(0.44)		-	
$pfg_{9/2}$ NN+3N	1.65	0.09	4.54	1.18	0.00	0.03	0.10	0.01	0.20	0.00	1.26	0.05
(SR)	(1.81)		(6.09)				(0.20)		(0.24)		(1.66)	

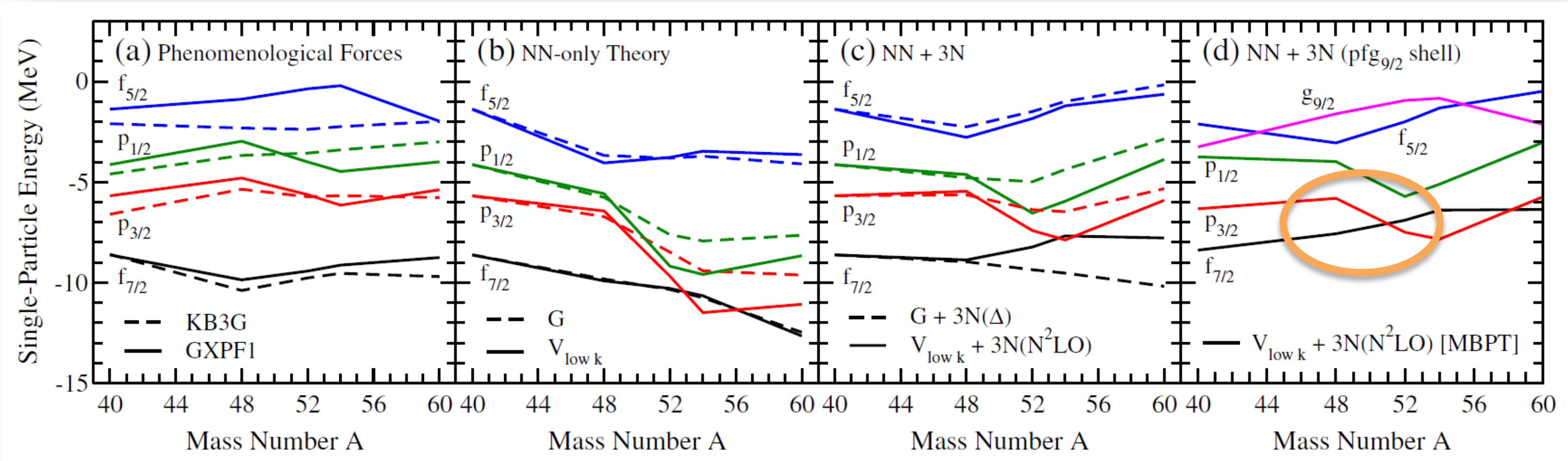


And the $p_{3/2}$?

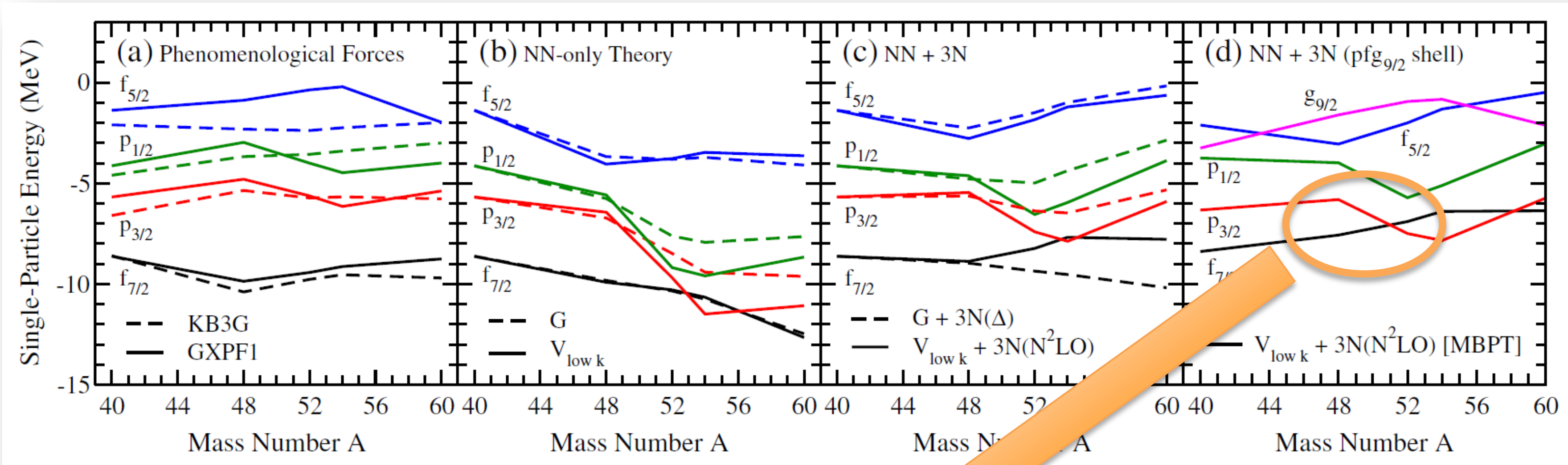
All theoretical predictions for $p_{3/2}$ occupancy in ^{50}Ca are approx. 2
The data suggests an enhancement in the occupation of the $p_{3/2}$ orbital.

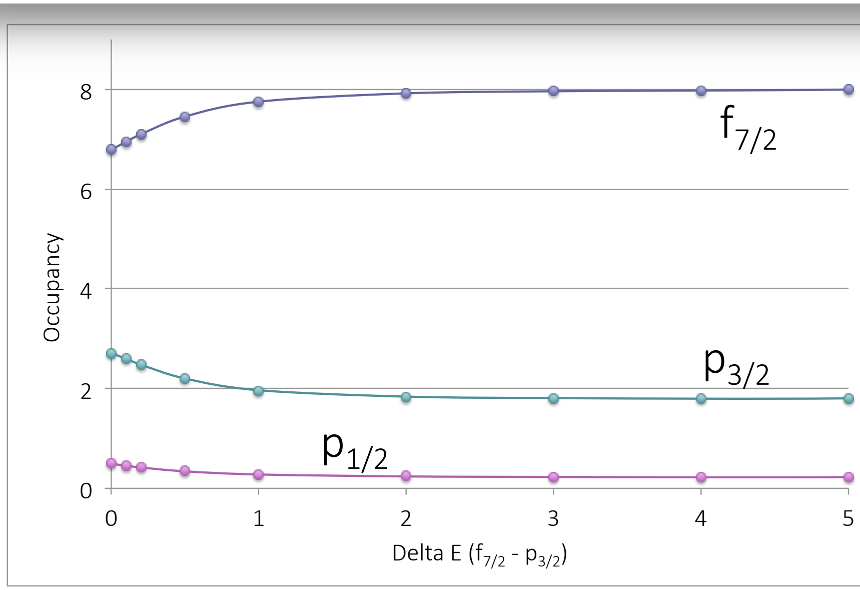


Mixing of the $f_{7/2}$ and $p_{3/2}$?



Mixing of the $f_{7/2}$ and $p_{3/2}$?



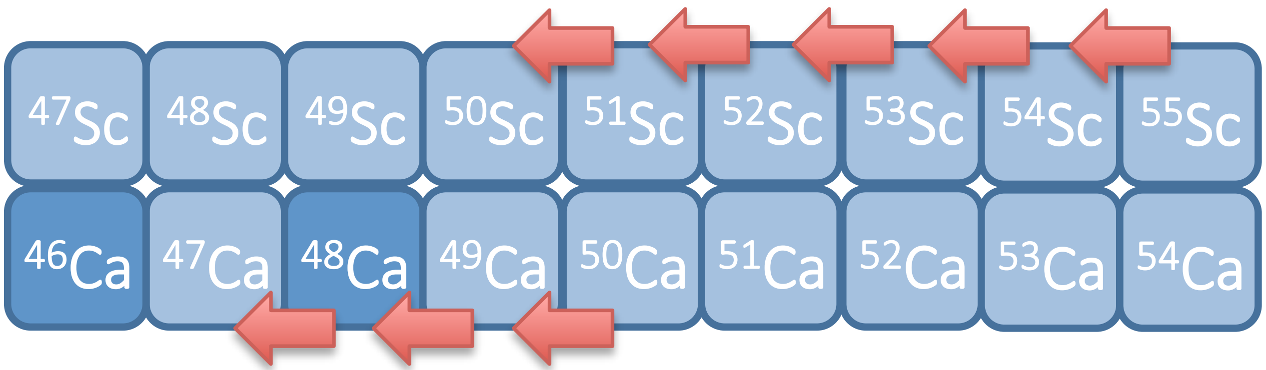


Mixing may provide at least a partial explanation for depletion of the $f_{7/2}$ strength and enhancement of the $p_{3/2}$ occupancy

Reduction of the total observed $f_{7/2}$ strength related to fragmentation of strength to higher states as predicted by the microscopic calculations?

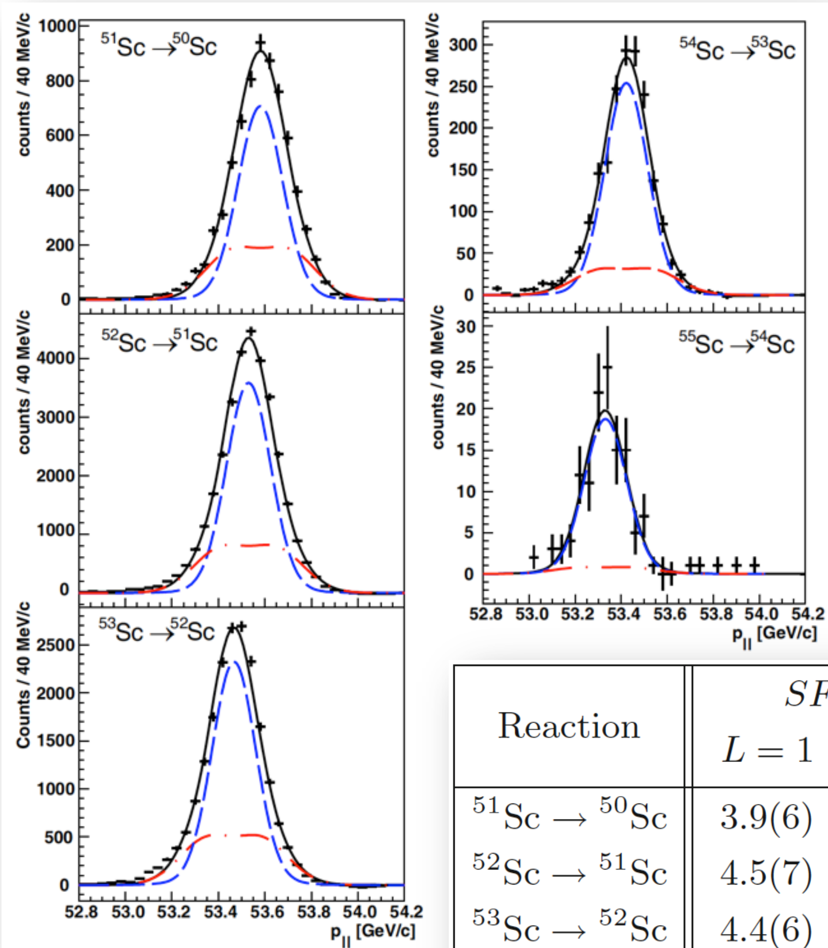
What Else Is Known?

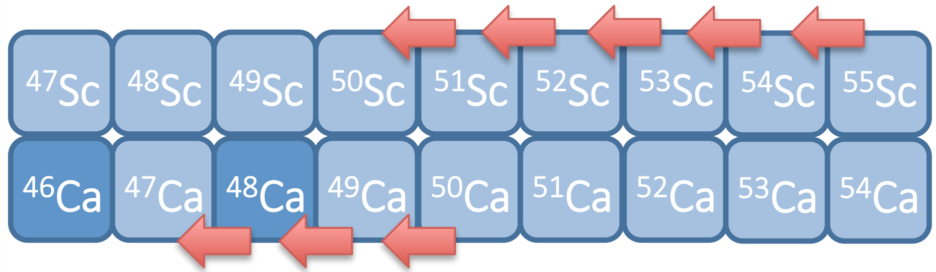
Knockout in the Sc Isotopes at GSI



S. Schwertel *et al.*, Eur. Phys. J. A **48**, 191 (2012)

Knockout in the Sc Isotopes at GSI

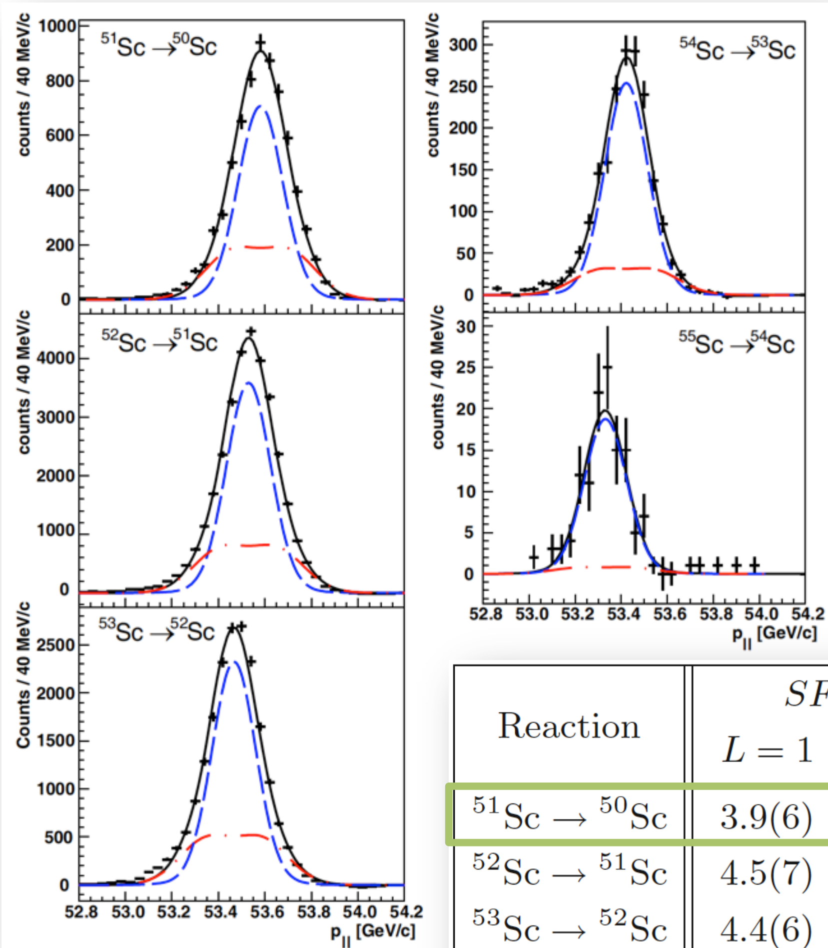


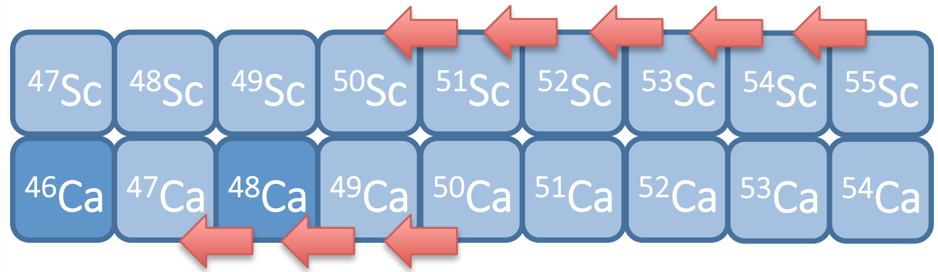


Reaction	SF_{exp}		SF_{th}			
	$L=1$	$L=3$	$\nu p_{3/2}$	$\nu p_{1/2}$	$\nu f_{7/2}$	$\nu f_{5/2}$
$^{51}Sc \to {}^{50}Sc$	3.9(6)	2.4(4)	1.78	0.16	7.32	0.10
$^{52}Sc \to {}^{51}Sc$	4.5(7)	3.5(5)	2.71	0.15	7.17	0.08
$^{53}Sc \to {}^{52}Sc$	4.4(6)	3.5(5)	3.46	0.32	7.13	0.12
$^{54}Sc \to {}^{53}Sc$	6.7(10)	3.1(7)	3.67	1.00	2.87	0.07
$^{55}Sc \to {}^{54}Sc$	4.1(9)	0.3(9)	3.62	1.86	0.44	0.13

S. Schwertel *et al.*, Eur. Phys. J. A **48**, 191 (2012)

Knockout in the Sc Isotopes at GSI

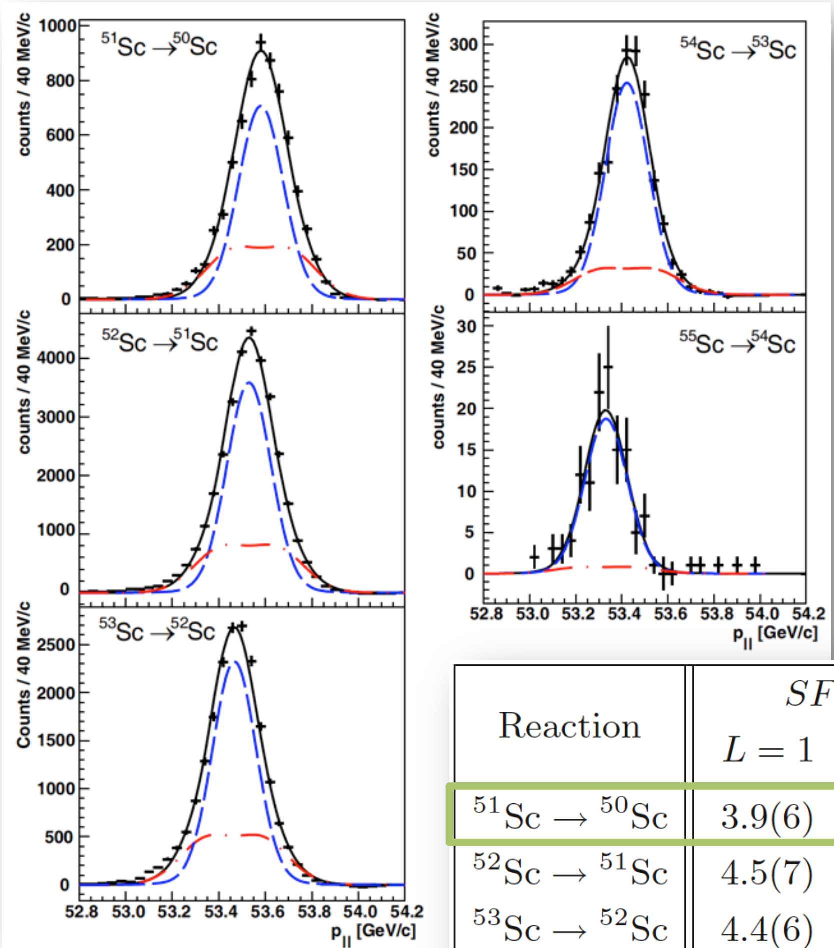


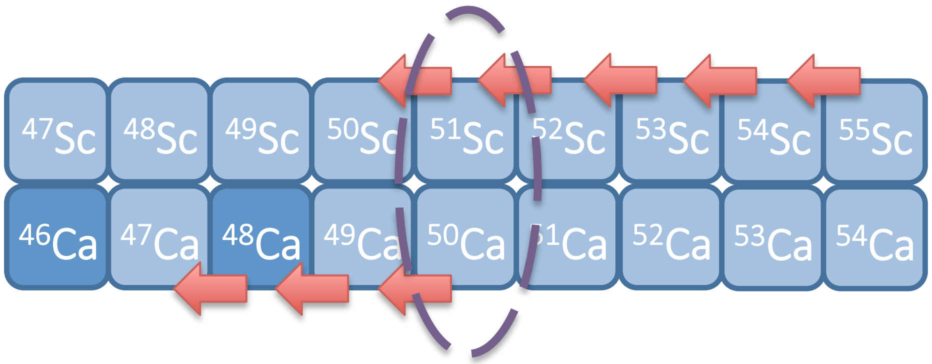


Reaction	SF_{exp}		SF_{th}			
	$L=1$	$L=3$	$\nu p_{3/2}$	$\nu p_{1/2}$	$\nu f_{7/2}$	$\nu f_{5/2}$
^{51}Sc → ^{50}Sc	3.9(6)	2.4(4)	1.78	0.16	7.32	0.10
^{52}Sc → ^{51}Sc	4.5(7)	3.5(5)	2.71	0.15	7.17	0.08
^{53}Sc → ^{52}Sc	4.4(6)	3.5(5)	3.46	0.32	7.13	0.12
^{54}Sc → ^{53}Sc	6.7(10)	3.1(7)	3.67	1.00	2.87	0.07
^{55}Sc → ^{54}Sc	4.1(9)	0.3(9)	3.62	1.86	0.44	0.13

S. Schwertel *et al.*, Eur. Phys. J. A 48, 191 (2012)

Knockout in the Sc Isotopes at GSI

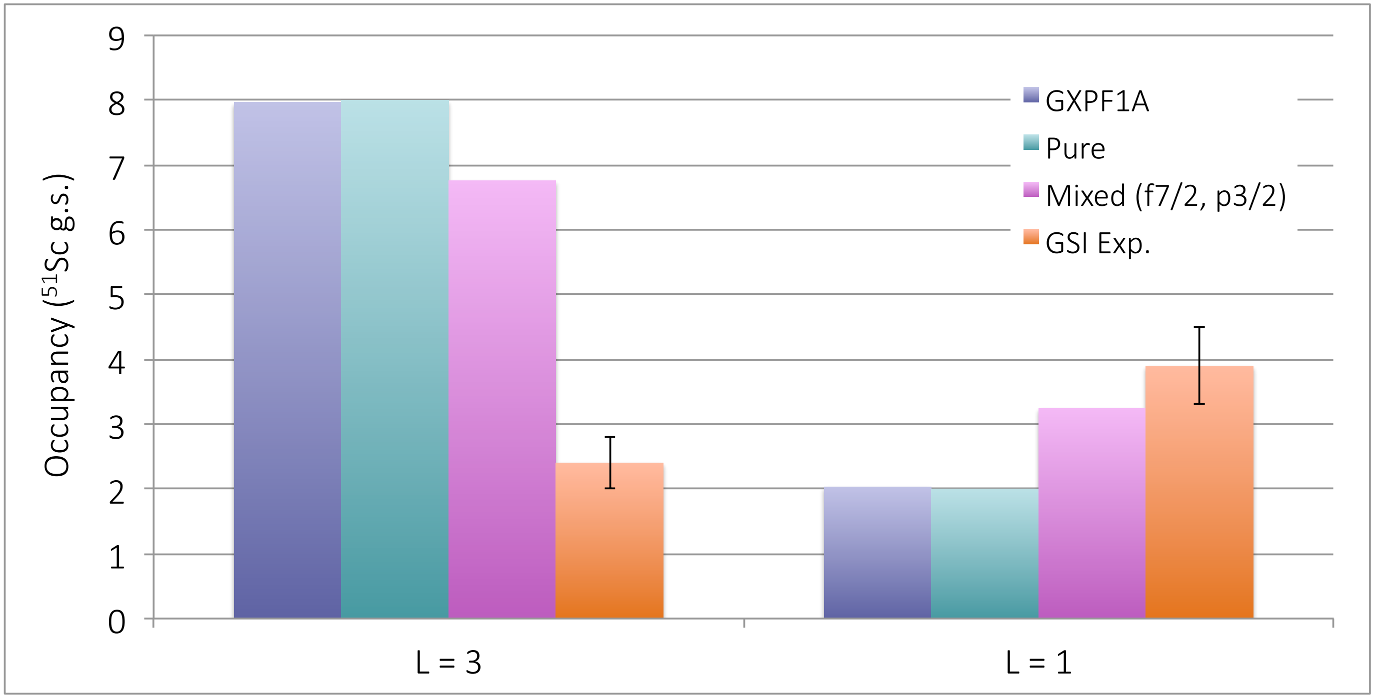




Reaction	SF_{exp}		SF_{th}			
	$L=1$	$L=3$	$\nu p_{3/2}$	$\nu p_{1/2}$	$\nu f_{7/2}$	$\nu f_{5/2}$
^{51}Sc → ^{50}Sc	3.9(6)	2.4(4)	1.78	0.16	7.32	0.10
^{52}Sc → ^{51}Sc	4.5(7)	3.5(5)	2.71	0.15	7.17	0.08
^{53}Sc → ^{52}Sc	4.4(6)	3.5(5)	3.46	0.32	7.13	0.12
^{54}Sc → ^{53}Sc	6.7(10)	3.1(7)	3.67	1.00	2.87	0.07
^{55}Sc → ^{54}Sc	4.1(9)	0.3(9)	3.62	1.86	0.44	0.13

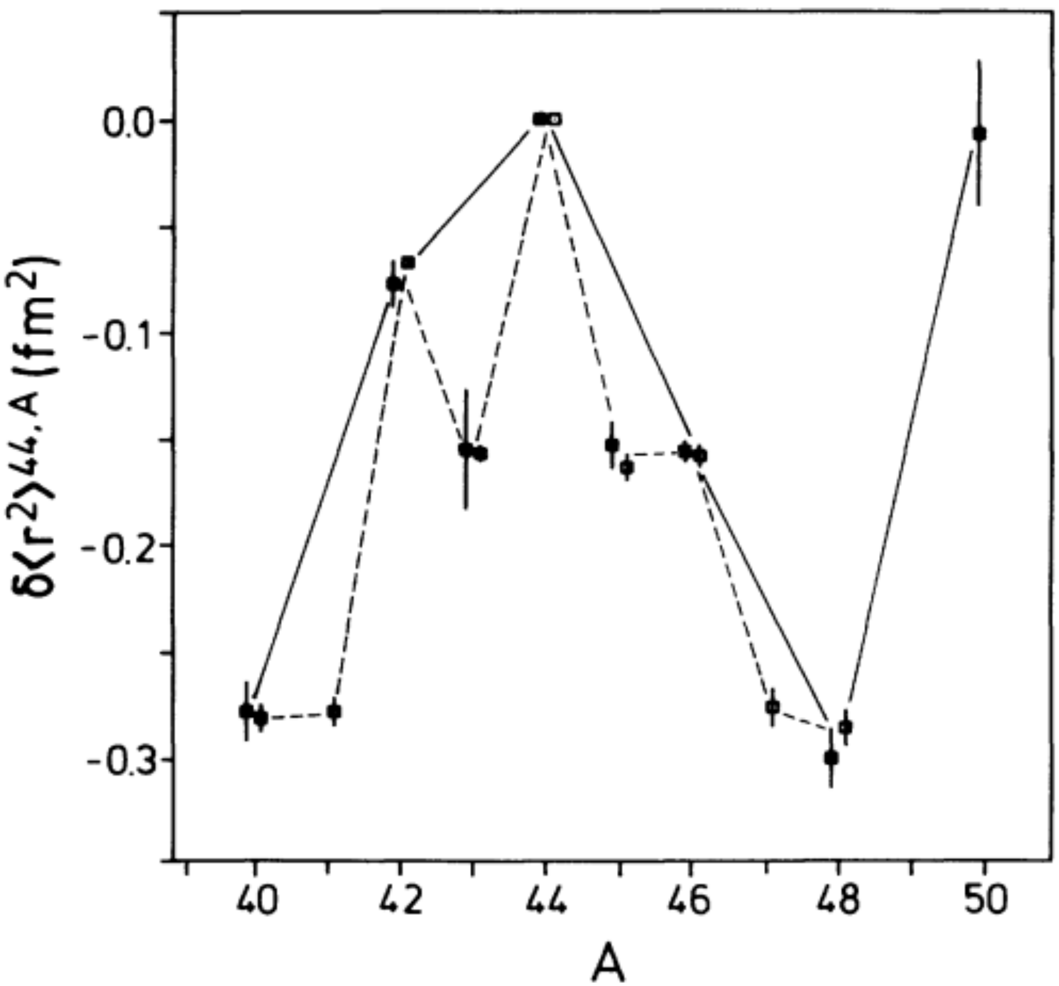
S. Schwertel *et al.*, Eur. Phys. J. A 48, 191 (2012)

Understand the GSI Data – ^{51}Sc?



- Narrowing of *N*=28 gets you part way toward agreement with the data in terms of enhancing the $p_{3/2}$ strength
- To understand the net depletion (total in L=(1 + 3) is 6.3(0.7)), require fragmentation of strength to high energies (unbound) – as captured in NN + 3N?

Radii?

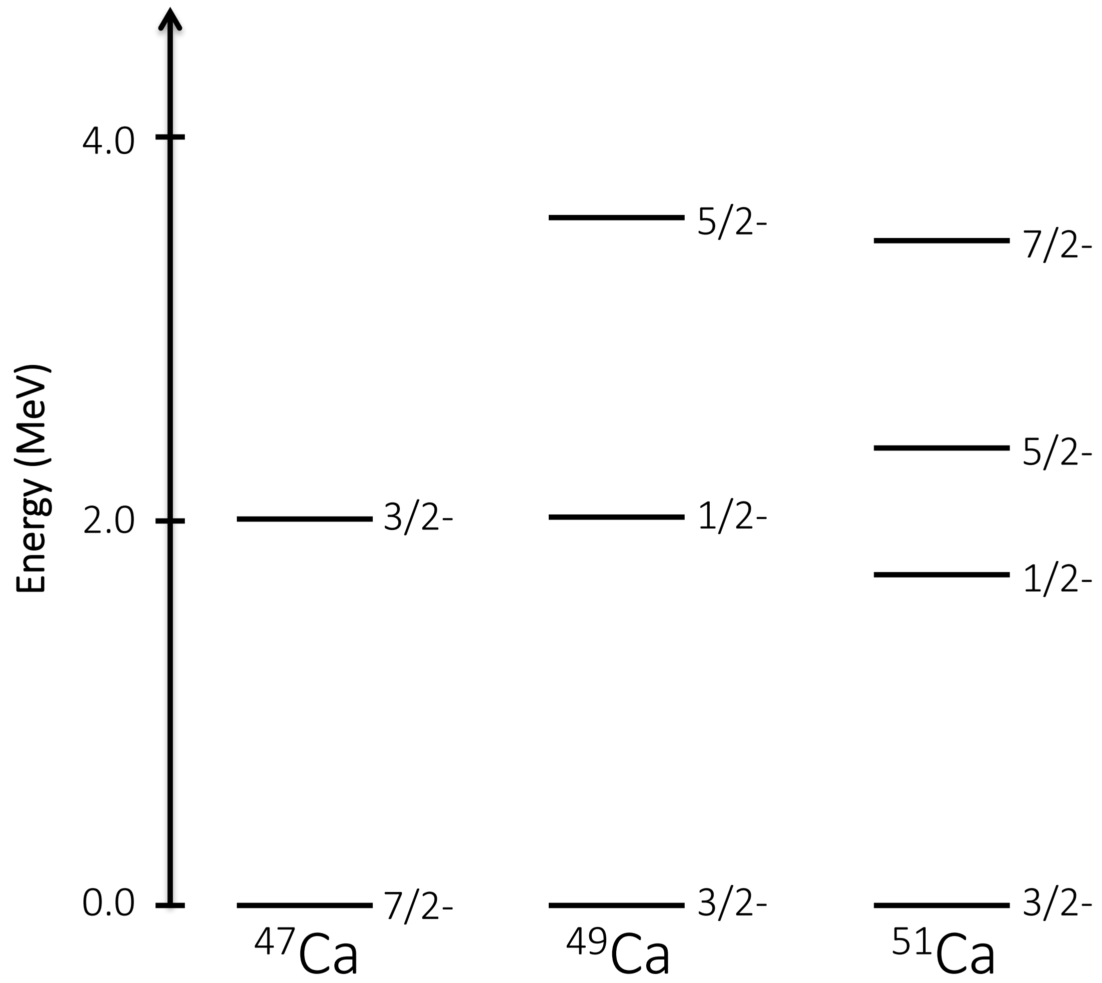


"strong coupling between the $p_{3/2}$ neutrons and the core protons" – PRL **68**, 1679 (1992)

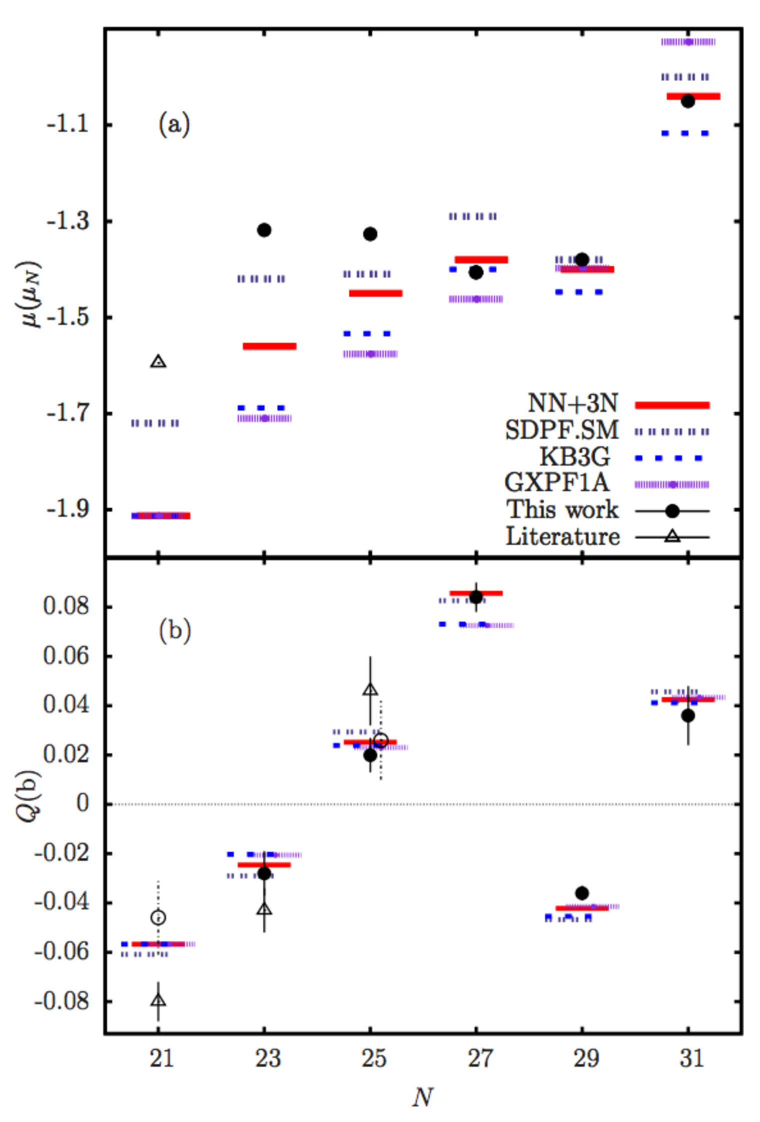
In very simple calculation, with occupancies consistent with reduced $f_{7/2} - p_{3/2}$ gap, would expect radius approximately 0.1fm larger… enough?

L. Vermeeren *et al.*, Phys. Rev. Lett. **68**, 1679 (1992).

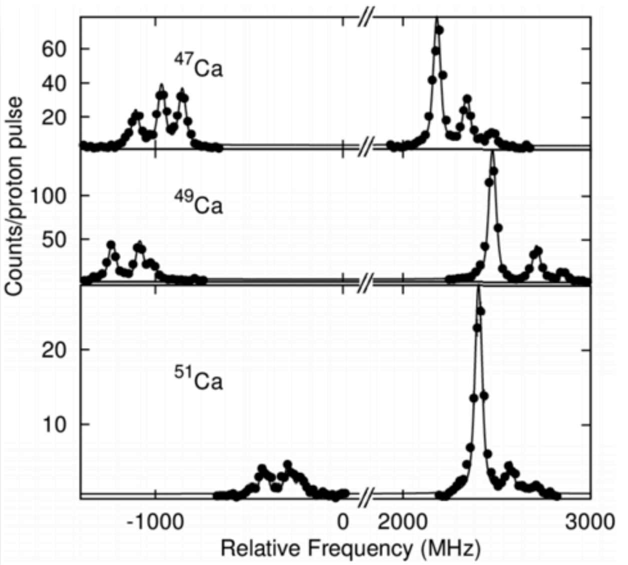
However… level schemes do not agree



And Wait! Magnetic Moment in ^{51}Ca



- Collinear laser spectroscopy measuring the optical hyperfine spectra confirms an I = 3/2 $(\nu p_{3/2})^3$ ground state in ^{51}Ca



- Magnetic moment is well reproduced by NN+3N interaction and appears very sensitive to neutron excitations across $N = 32$

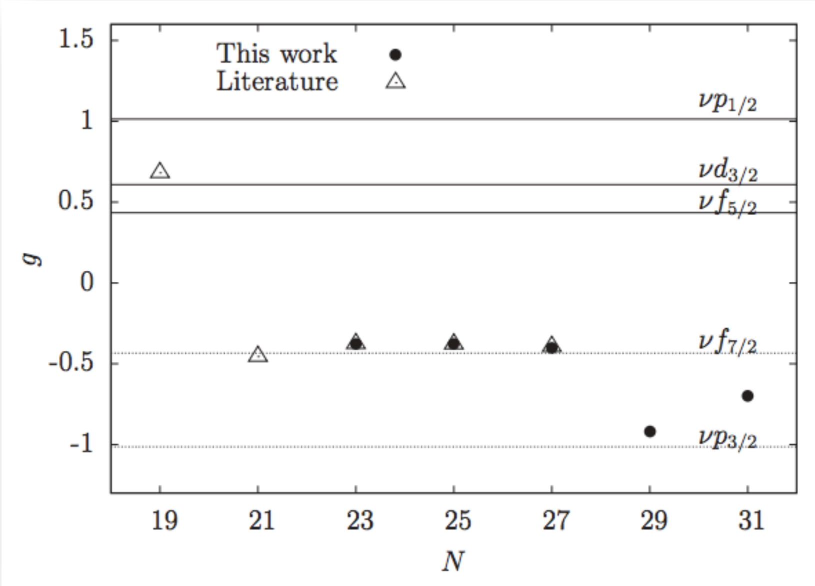
R. F. Garcia Ruiz *et al.*, Phys. Rev. C **91**, 041304(R) (2015).

Magnetic Moment in ^{51}Ca

(a) Ground state magnetic moment

- g is off of $p_{3/2}$ single-particle limit
- Interpreted as result of contribution from $(p_{3/2})^2(p_{1/2})^1$ configuration in ground state

  --> of order 3.5-4%

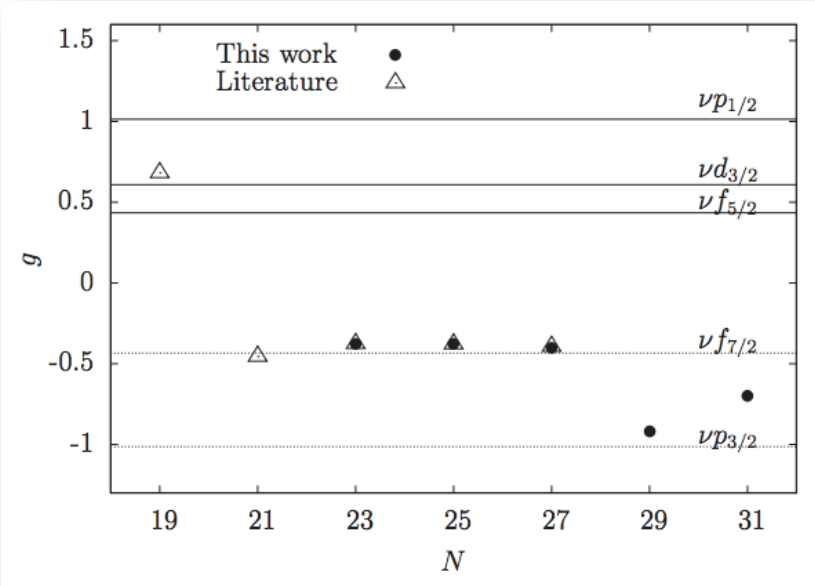


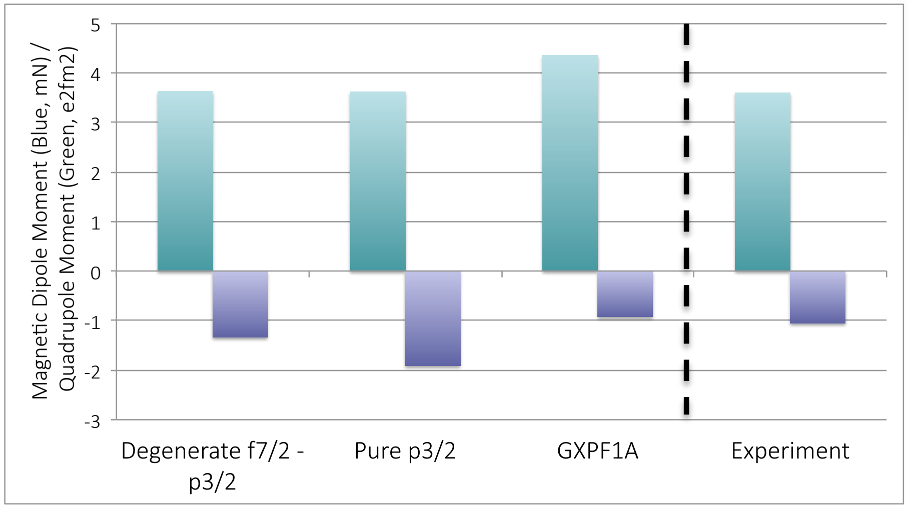
R. F. Garcia Ruiz *et al.*, Phys. Rev. C **91**, 041304(R) (2015).

Magnetic Moment in ^{51}Ca

(a) Ground state magnetic moment

- g is off of $p_{3/2}$ single-particle limit
- Interpreted as result of contribution from $(p_{3/2})^2(p_{1/2})^1$ configuration in ground state --> of order 3.5-4%





R. F. Garcia Ruiz *et al.*, Phys. Rev. C **91**, 041304(R) (2015).

Magnetic Moment in ^{51}Ca

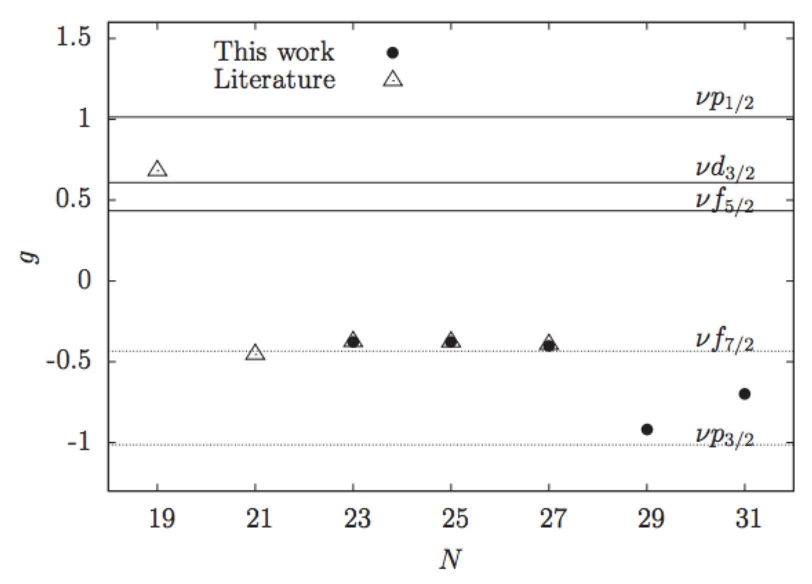
(a) Ground state magnetic moment

- g is off of $p_{3/2}$ single-particle limit
- Interpreted as result of contribution from $(p_{3/2})^2(p_{1/2})^1$ configuration in ground state

  --> of order 3.5-4%

(b) J = 3/2

- No way to get a 3/2 ground state out of a $f_{7/2}$ configuration…



R. F. Garcia Ruiz *et al.*, Phys. Rev. C **91**, 041304(R) (2015).

A Consistent Description?

No, not really.

- Knockout results in Ca and Sc isotopes at N=30 both suggest enhanced L=1 ($p_{3/2}$) occupancy in the ground state --> significant mixing across N=28 gap
- Overall reduction of L=3 strength suggests fragmentation of $1f_{7/2}$ strength above the separation energy

A Consistent Description?

No, not really.

- Knockout results in Ca and Sc isotopes at *N*=30 both suggest enhanced L=1 ($p_{3/2}$) occupancy in the ground state --> significant mixing across *N*=28 gap
- Overall reduction of L=3 strength suggests fragmentation of $1f_{7/2}$ strength above the separation energy

---

- Level schemes on either side of *N*=30 INCONSISTENT with vanishing gap between $f_{7/2}$ and $p_{3/2}$
- ^{51}Ca ground state looks like $(p_{3/2})^{-1}$; magnetic moment consistent with only minimal mixing across *N*=32

A Consistent Description?

No, not really.

- Knockout results in Ca and Sc isotopes at N=30 both suggest enhanced L=1 ($p_{3/2}$) occupancy in the ground state --> significant mixing across N=28 gap
- Overall reduction of L=3 strength suggests fragmentation of $1f_{7/2}$ strength above the separation energy

---

- Level schemes on either side of N=30 INCONSISTENT with vanishing gap between $f_{7/2}$ and $p_{3/2}$
- ^{51}Ca ground state looks like $(p_{3/2})^{-1}$; magnetic moment consistent with only minimal mixing across N=32

- Is there any explanation feasible as a result of rapid changes with N?

A Consistent Description?

No, not really.

- Knockout results in Ca and Sc isotopes at N=30 both suggest enhanced L=1 ($p_{3/2}$) occupancy in the ground state --> significant mixing across N=28 gap
- Overall reduction of L=3 strength suggests fragmentation of $1f_{7/2}$ strength above the separation energy

---

- Level schemes on either side of N=30 INCONSISTENT with vanishing gap between $f_{7/2}$ and $p_{3/2}$
- ^{51}Ca ground state looks like $(p_{3/2})^{-1}$; magnetic moment consistent with only minimal mixing across N=32

- Is there any explanation feasible as a result of rapid changes with N?
  - Phase change from normal to BCS to normal configurations?

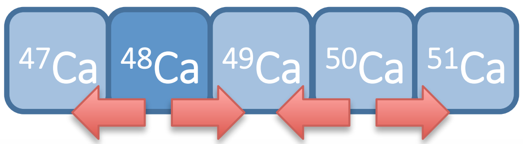
What's Next?
(for experimentalists…)

Transfer in the Ca Isotopes

Proposal I:

(p,d) and (d,p) on ^{48,50}Ca

- Degraded beam energies of 30MeV/A
- Complete data set: CD, CH and C targets



Energy [keV]	J^π	Configuration	Expected C^2S	σ_{sp} [mb]	Particle Rate [1/hour]	E_γ [keV]	ϵ_γ	γ Rate [1/hour]
^{48}Ca(p,d)^{47}Ca								
0	7/2-	$1f_{7/2}^{-1}$	8	4.2	2580k	–	–	–
2014	3/2-	$[1f_{7/2}^{-2}2p_{3/2}^{1}]$	0	14.3	– ($C^2S = 1$) 1111k	2014	0.062	– 69k
2578	3/2+	$1d_{3/2}^{-1}$	4	2.6	671k	564	0.117	77k
2599	1/2+	$2s_{1/2}^{-1}$	2	4.3	808k	585	0.115	95k
^{48}Ca(d,p)^{49}Ca								
0	3/2-	$2p_{3/2}^{1}$	1	7.4	498k	–	–	–
2023.2	1/2-	$2p_{1/2}^{1}$	1	3.5	238k	2023.2	0.062	15k
3357	7/2-	$[1f_{7/2}^{-1}2p_{3/2}^{2}]$	0	8.1	– ($C^2S = 0.125$) 69k	3357	0.044	– 3k
3991	5/2-	$1f_{5/2}^{1}$	1	9.5	647k	3991	0.038	25k

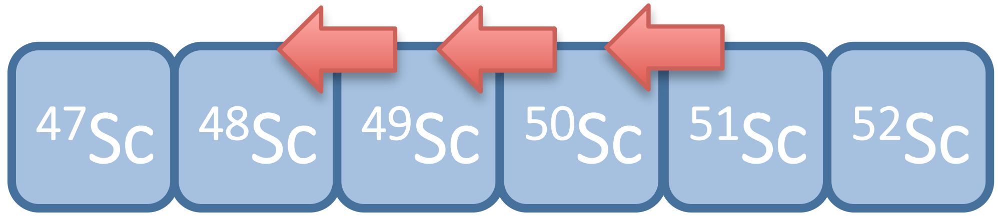
Energy [keV]	J^π	Configuration	Expected C^2S	σ_{sp} [mb]	Particle Rate [1/shift]	E_γ [keV]	ϵ_γ	γ Rate [1/shift]
^{50}Ca(p,d)^{49}Ca								
0	$3/2^-$	$2p_{3/2}^{1}$	2	11.9	86k	–	–	–
2023.2	$1/2^-$	$2p_{1/2}^{1}$	0	13.3	– ($C^2S = 1$) 48k	2023.2	0.062	– 2976
3357	$7/2^-$	$[1f_{7/2}^{-1}2p_{3/2}^{2}]$	8	4.4	126k	3357	0.043	5418
3991	$5/2^-$	$1f_{5/2}^{1}$	0	5.7	– ($C^2S = 1$) 21k	3991	0.041	– 843
^{50}Ca(d,p)^{51}Ca								
0	3/2-	$2p_{3/2}^{3}$	0.5	3.5	2730	–	–	–
2378	1/2-	$[2p_{3/2}^{2}2p_{1/2}^{1}]$	1	1.4	2238	2378	0.053	125
3462	7/2-	$[1f_{7/2}^{-1}2p_{3/2}^{4}]$	0	4.9	– ($C^2S = 0.05$) 388	3462	0.041	– 17
4320	5/2-	$[2p_{3/2}^{2}1f_{5/2}^{1}]$	1	5.6	8837	1942	0.060	562

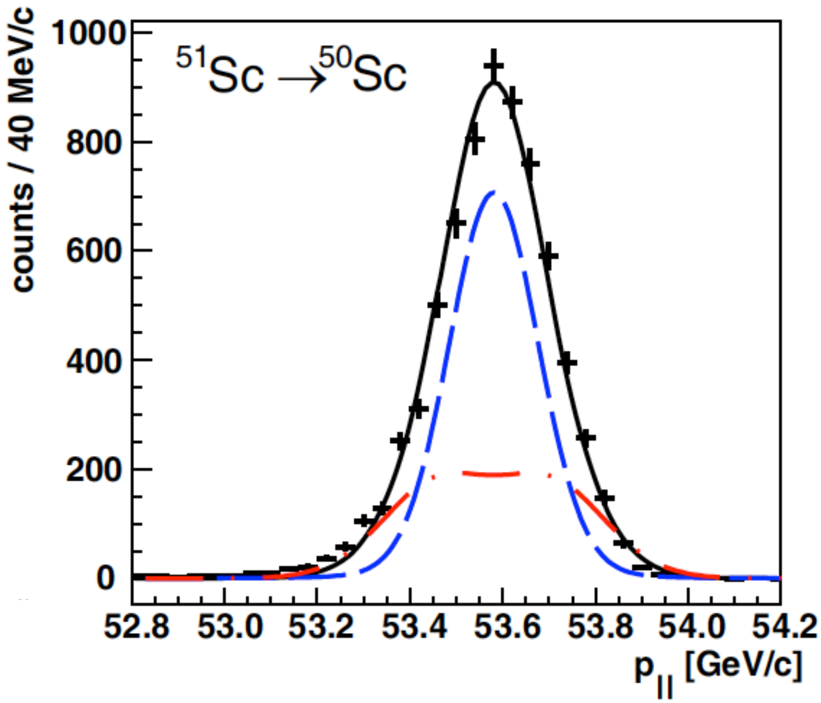
Neutron Knockout in the Sc Isotopes

Proposal II:

Neutron knockout in $_{21}Sc$

- Identical to last GRETINA campaign Ca measurement
- 1n removal from ^{51}Sc to ^{49}Sc

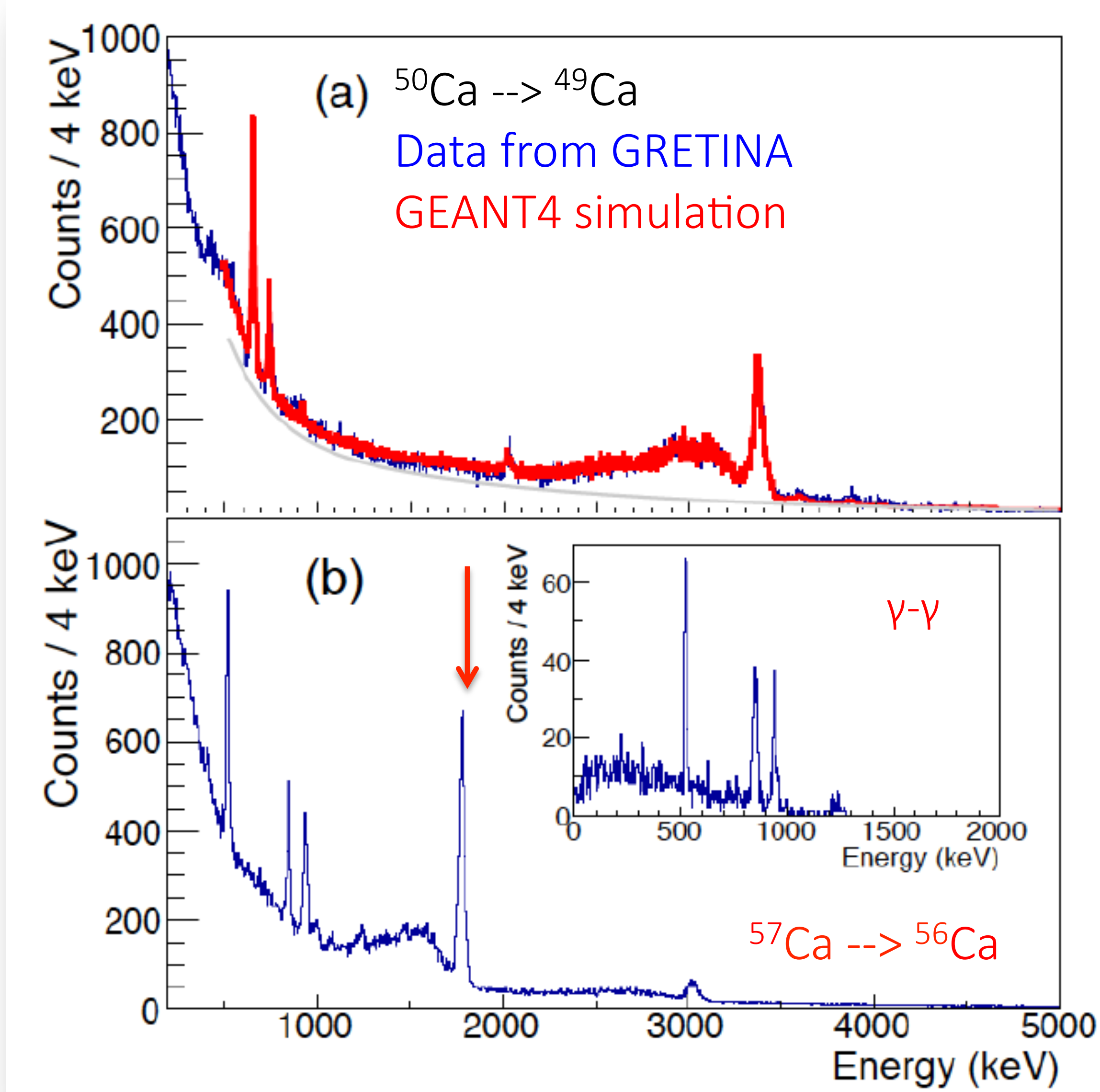




What’s Next: Can We Shed More Light?

Ultimately:

GRETA @ FRIB will allow detailed spectroscopy at least to ^{57}Ca



Acknowledgements

LAWRENCE BERKELEY NATIONAL LABORATORY

A.O. Macchiavelli, C.M. Campbell, R.M. Clark, M. Cromaz, P. Fallon, I.Y. Lee, J. Rissanen and A. Wiens

MICHIGAN STATE UNIVERSITY & NSCL

V. Bader, D. Bazin, A. Gade, C. Langer, S. Noji, M. Scott, F. Recchia, R. Stroberg and D. Weisshaar

ARGONNE NATIONAL LABORATORY

M. Albers, R.V.F. Janssens, T. Lauritsen and S. Zhu

UNIVERSITY OF BRITISH COLUMBIA & TRIUMF

J. Dilling, A. Gallant and R. Kruecken

T.U. DARMSTADT

A. Schwenk, J. Holt, J. Menendez, S. Paschalis and C. Walz

CENTRAL MICHIGAN UNIVERSITY

K. Wimmer

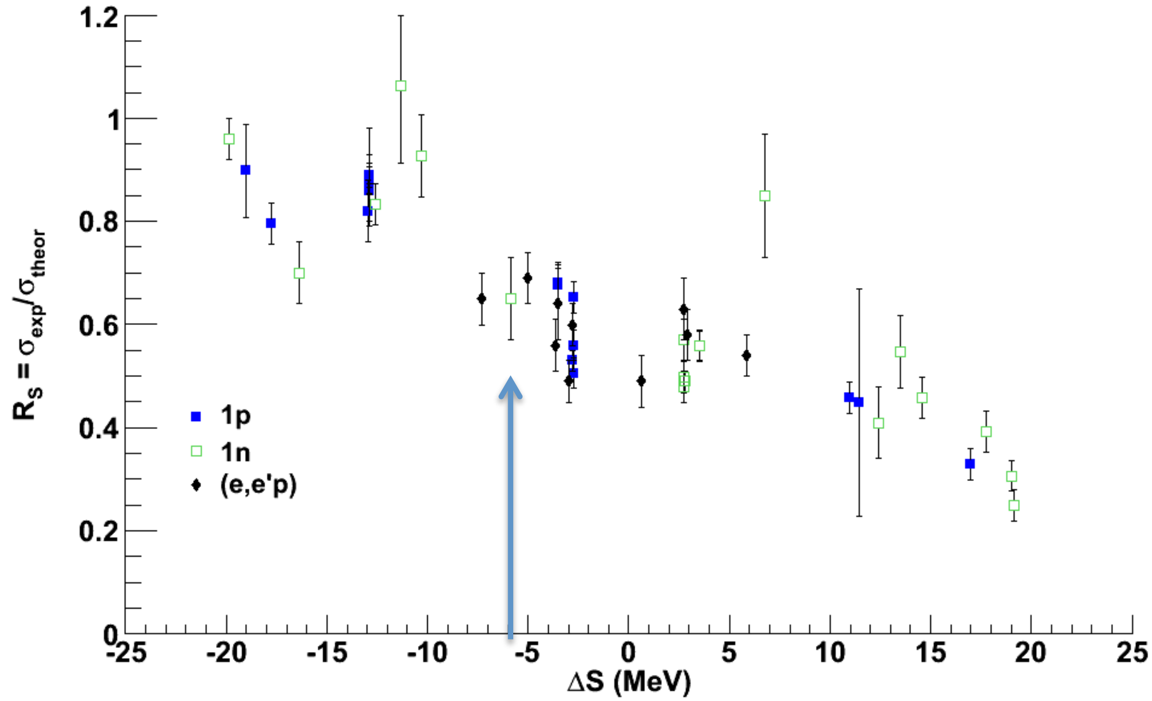
UNIVERSITY OF SURREY

J. Tostevin

Thank you!

Back-Up

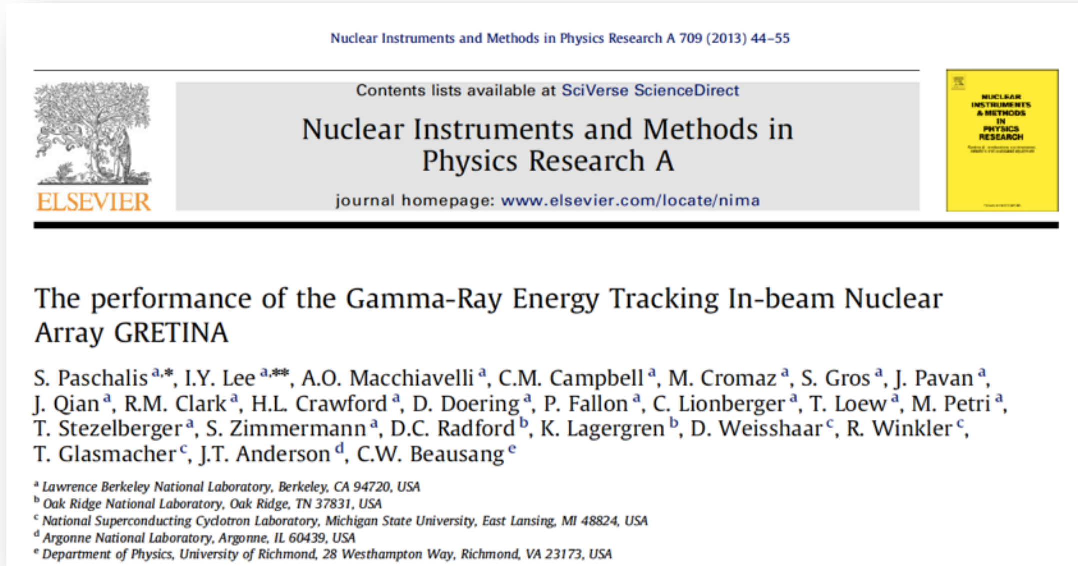
Neutron SFs and 'Quenching'



- Based on separation-energy differences, we empirically expect a suppression factor of order 0.6 in ^{48}Ca(-1n), so for a full $1f_{7/2}$ orbital we would expect to measure a spectroscopic factor of approx. 5
- Experimentally, this amount to population of states for which de-excitation is unresolved of order 14mb, which corresponds to 85000 events
  - If all of these events populate high-energy states which decay direct to the ground state, we need 7000-9000 MORE counts in the region above 2.5 MeV

Gamma-Ray Spectroscopy with GRETINA

- Covers approx. ¼ of 4π solid angle
- 28 x 36 fold segmented crystals housed in 7 (quad) modules
- Pulse shape analysis provides information to achieve sub-segment interaction point position resolution on the order of 2mm
- Gamma-ray tracking provides means to eliminate Compton scattered events and reduce background



Nuclear Instruments and Methods in Physics Research A 709 (2013) 44–55

Contents lists available at SciVerse ScienceDirect

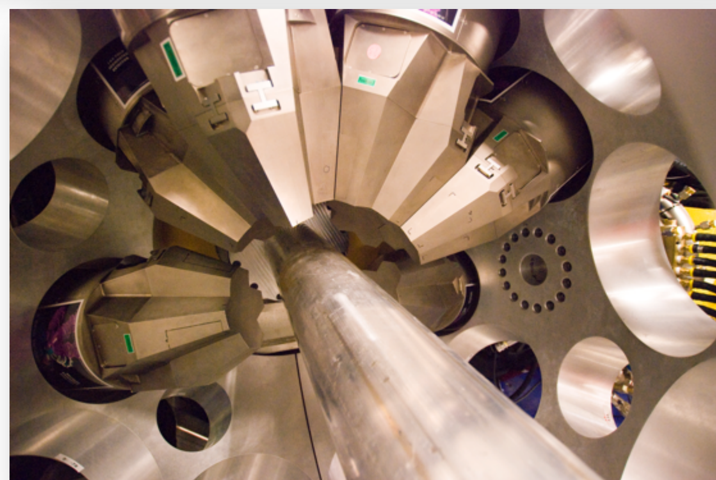
Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

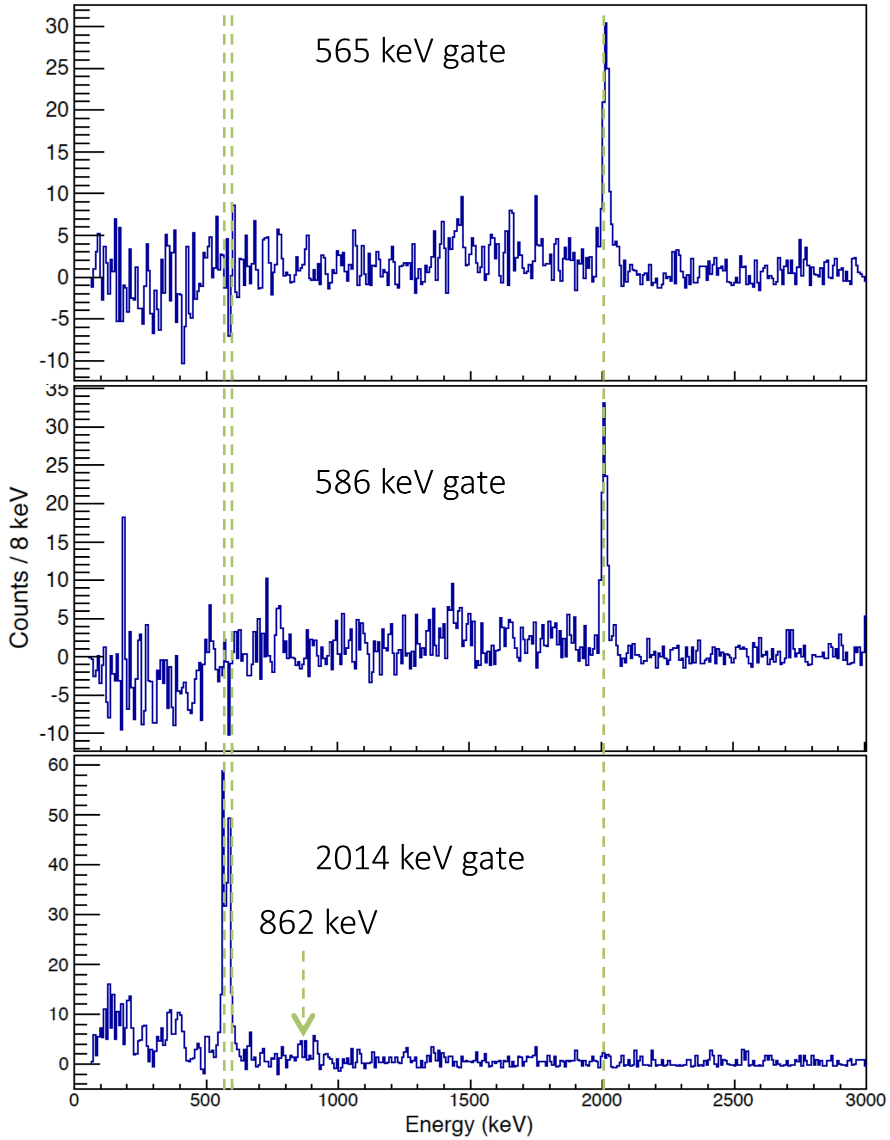
The performance of the Gamma-Ray Energy Tracking In-beam Nuclear Array GRETINA

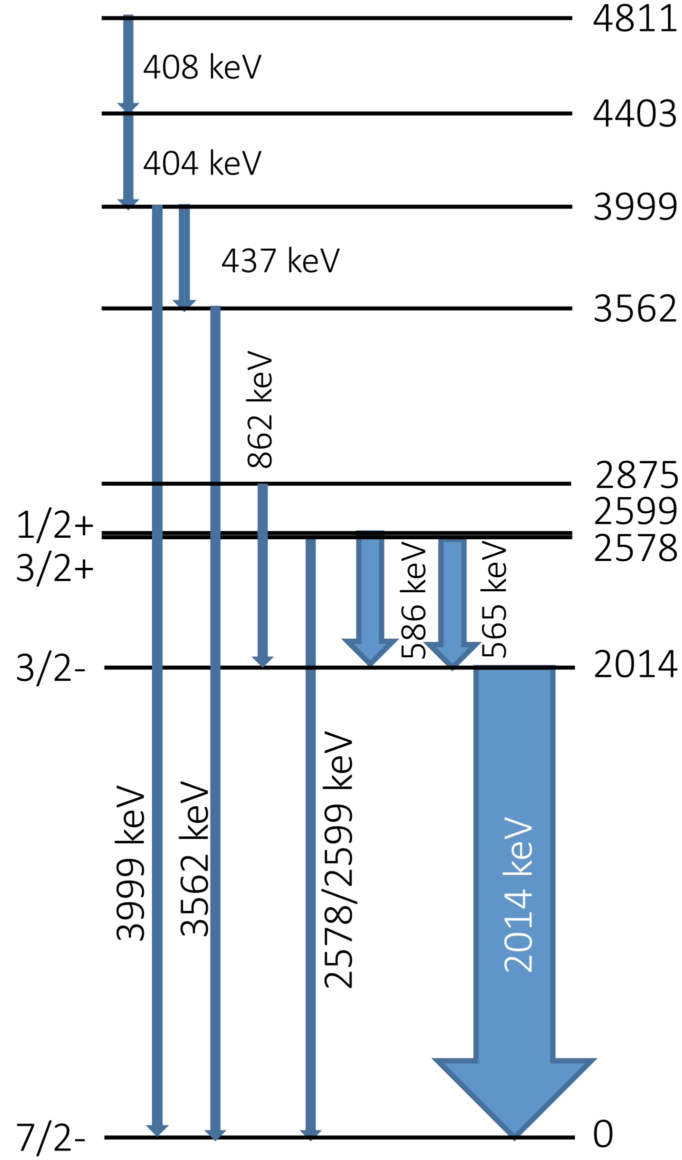
S. Paschalis[a,*], I.Y. Lee[a,**], A.O. Macchiavelli[a], C.M. Campbell[a], M. Cromaz[a], S. Gros[a], J. Pavan[a], J. Qian[a], R.M. Clark[a], H.L. Crawford[a], D. Doering[a], P. Fallon[a], C. Lionberger[a], T. Loew[a], M. Petri[a], T. Stezelberger[a], S. Zimmermann[a], D.C. Radford[b], K. Lagergren[b], D. Weisshaar[c], R. Winkler[c], T. Glasmacher[c], J.T. Anderson[d], C.W. Beausang[e]

[a] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[b] Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[c] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
[d] Argonne National Laboratory, Argonne, IL 60439, USA
[e] Department of Physics, University of Richmond, 28 Westhampton Way, Richmond, VA 23173, USA

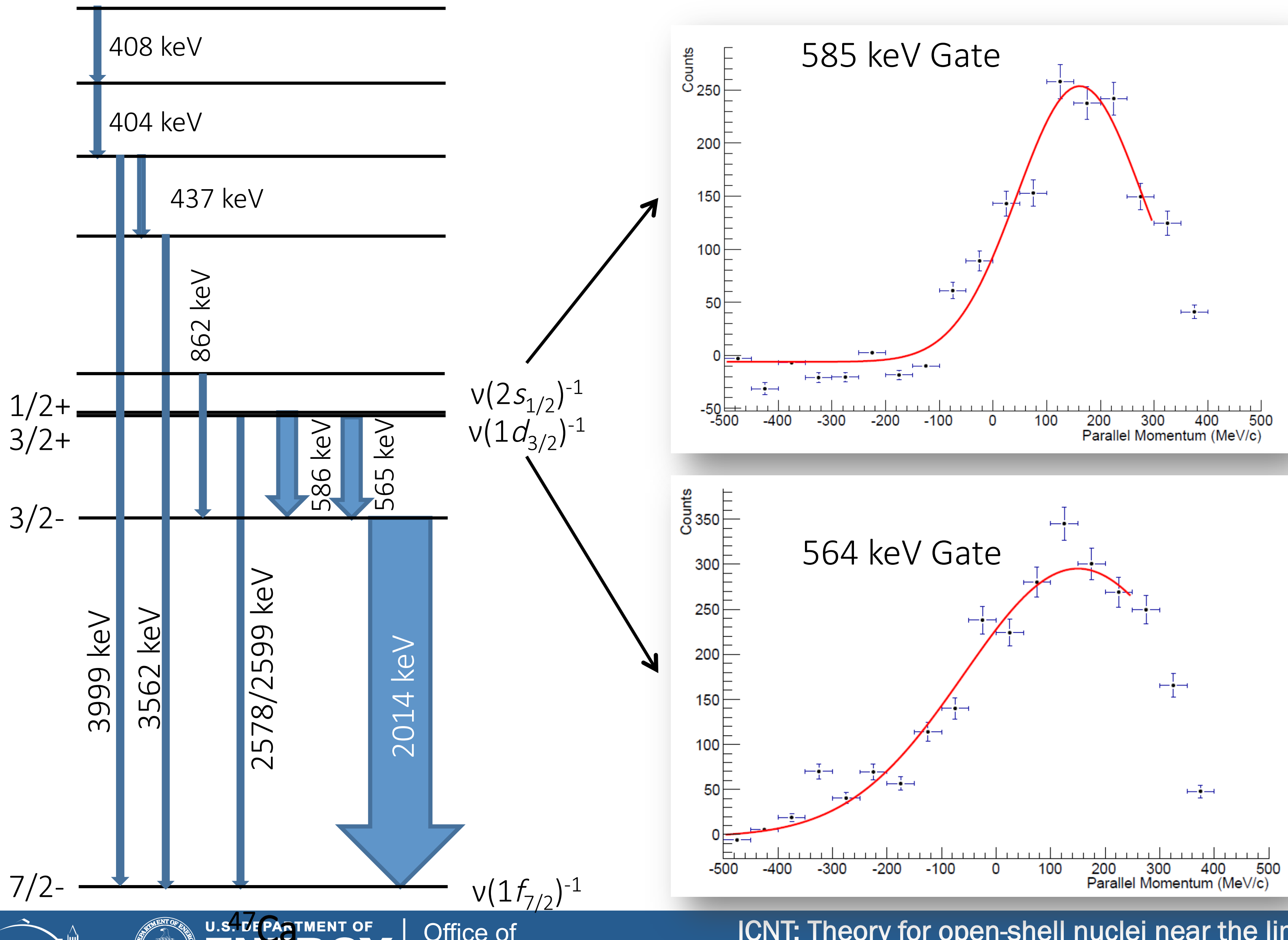


^{47}Ca: Gamma-Gamma and Level Scheme

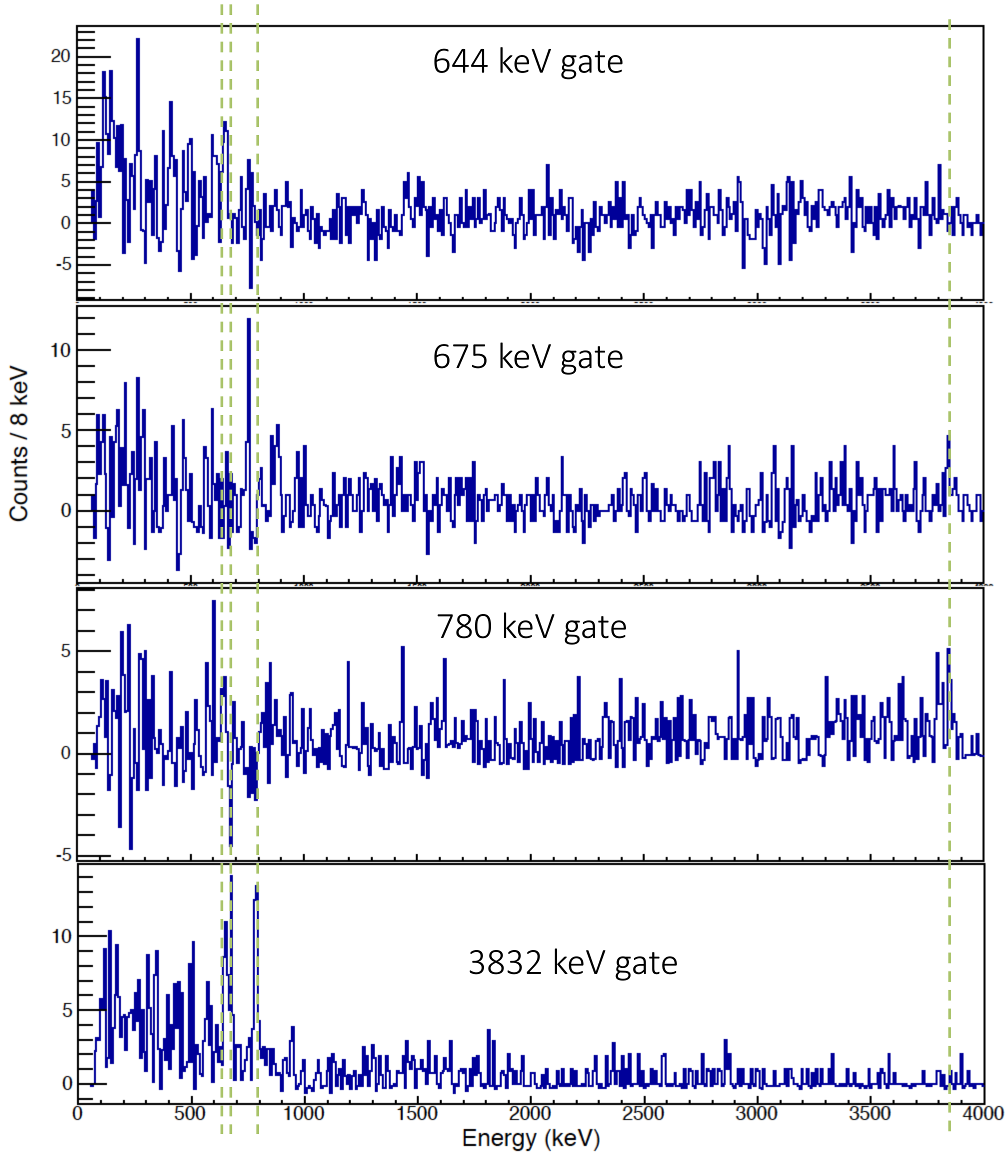


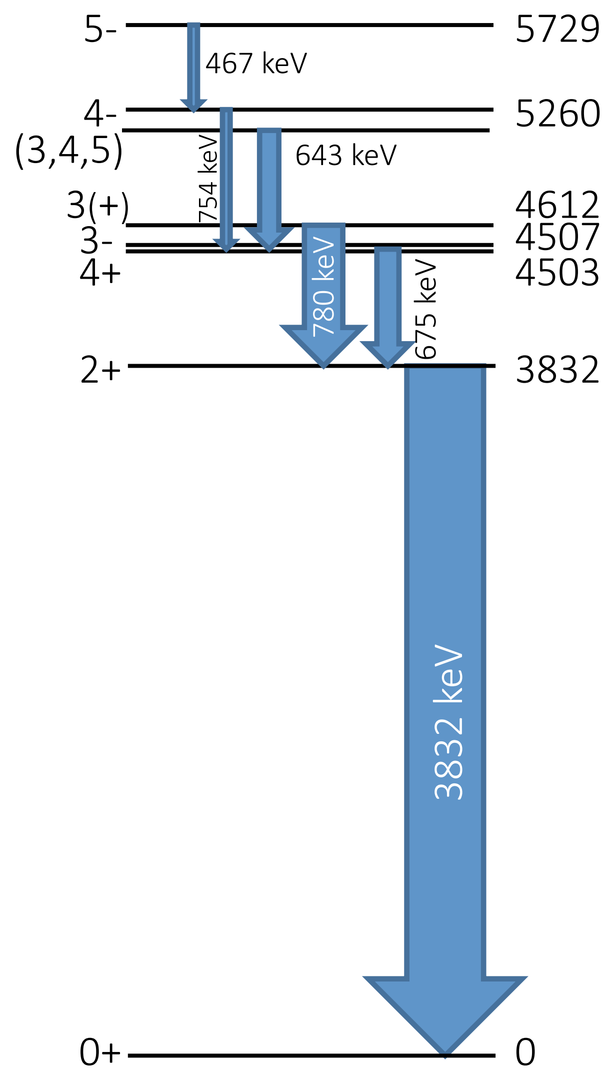


Exclusive Momentum Distributions in ^{47}Ca



^{48}Ca: Gamma-Gamma and Level Scheme





^{47}Ca Acceptance & Momentum Distributions

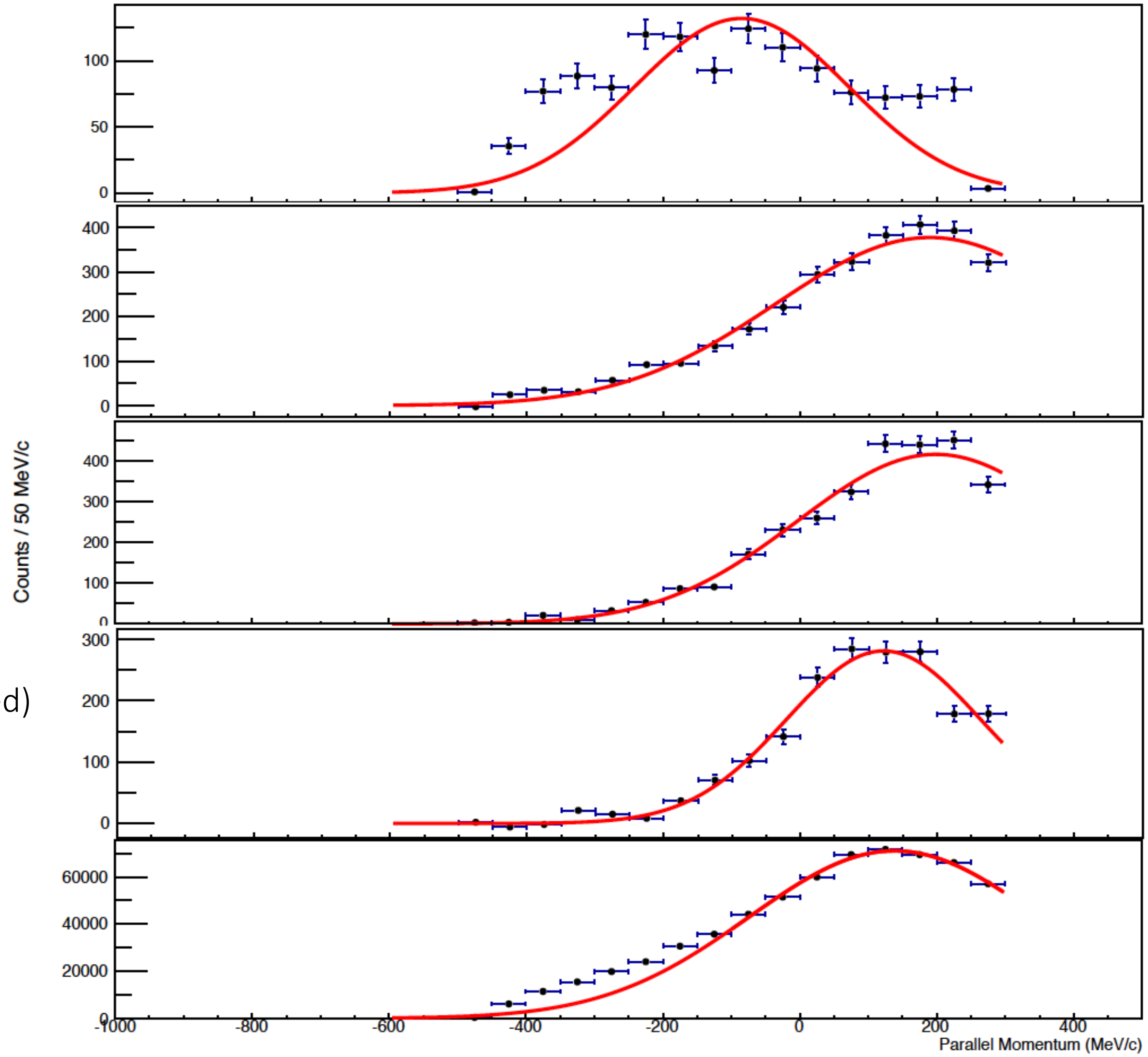
403 keV
Mean: -85, σ: 157
Correction: 1.01 ± 0.19

565 keV
Mean: 189, σ: 225
Correction: 1.45 ± 0.16

586 keV
Mean: 198, σ: 202
Correction: 1.44 ± 0.16

2013 keV (565, 586 subtracted)
Mean: 121, σ: 141
Correction: 1.11 ± 0.15

All ^{47}Ca
Mean: 138, σ: 212
Correction: 1.27 ± 0.02



^{49}Ca Acceptance & Momentum Distributions

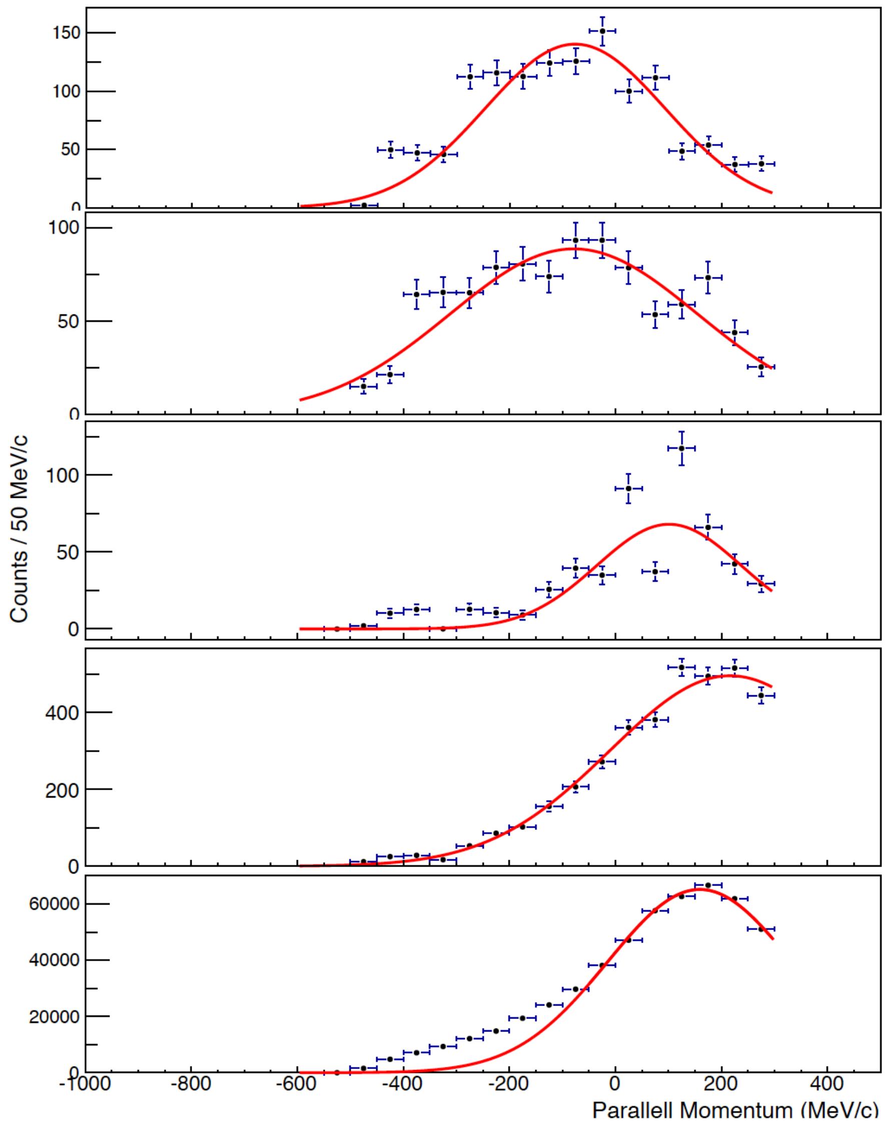
660 keV (743 subtracted)
Mean: -72, σ: 156
Correction: 1.01 ± 0.23

743 keV
Mean: -78, σ: 233
Correction: 1.06 ± 0.21

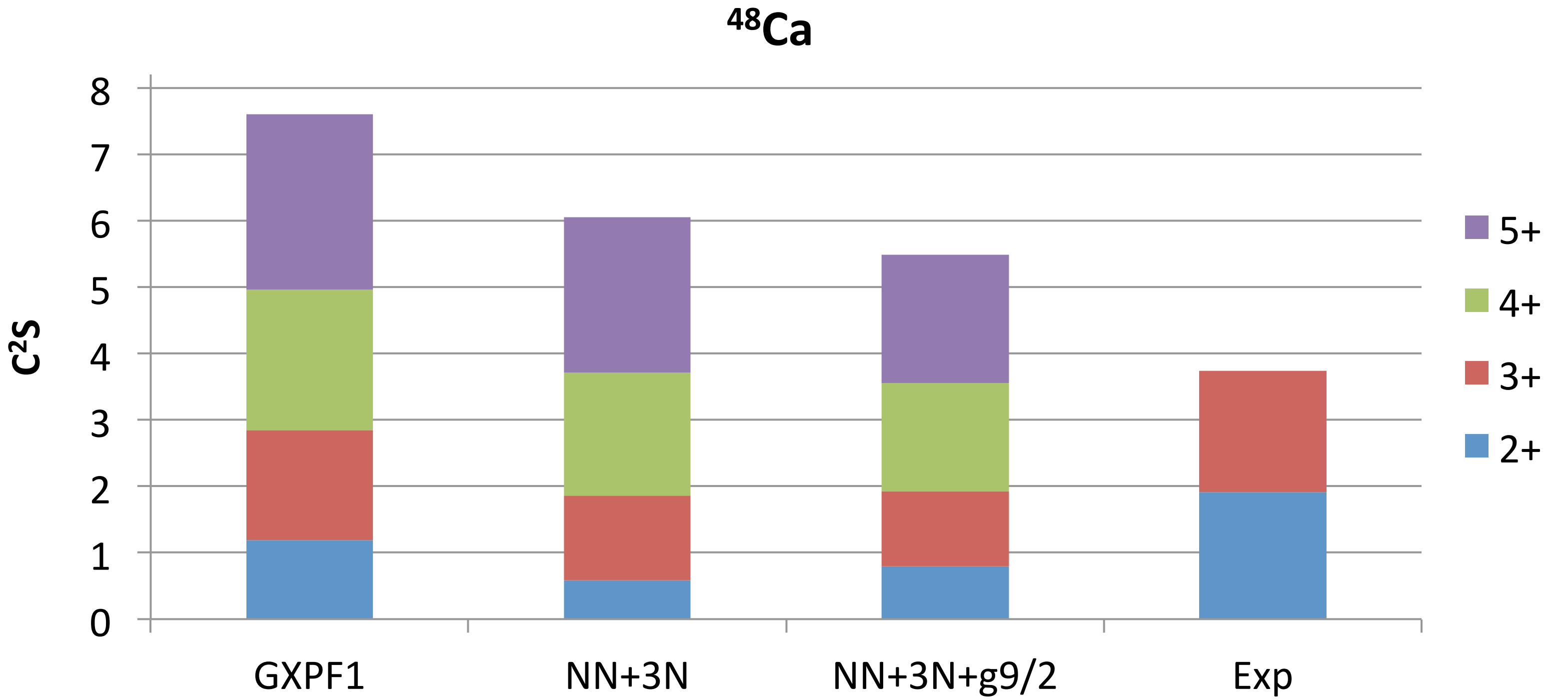
2023 keV
Mean: 82, σ: 134
Correction: 1.06 ± 0.24

3357 keV (660 subtracted)
Mean: 180, σ: 206
Correction: 1.39 ± 0.13

All ^{49}Ca
Mean: 155, σ: 167
Correction: 1.21 ± 0.02



^{48}Ca – Reduced $f_{7/2}$?



- Only confirmed feedings to +ve parity states feed 2+ and 3+ in ^{48}Ca
- There are a few unplaced transitions remaining in ^{48}Ca which may come from population of the 4+ and 5+ states – *work to try and place those is continuing*
- However, even if **all** gamma-rays were coming though $f_{7/2}$ states, the total $1f_{7/2}$ strength will not reach much more than $C^2S \approx 5$