TRIUMF

Study of cross-shell excitations near the 'island of inversion' using fusion-evaporation and Doppler shift methods

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For TIP and TIGRESS

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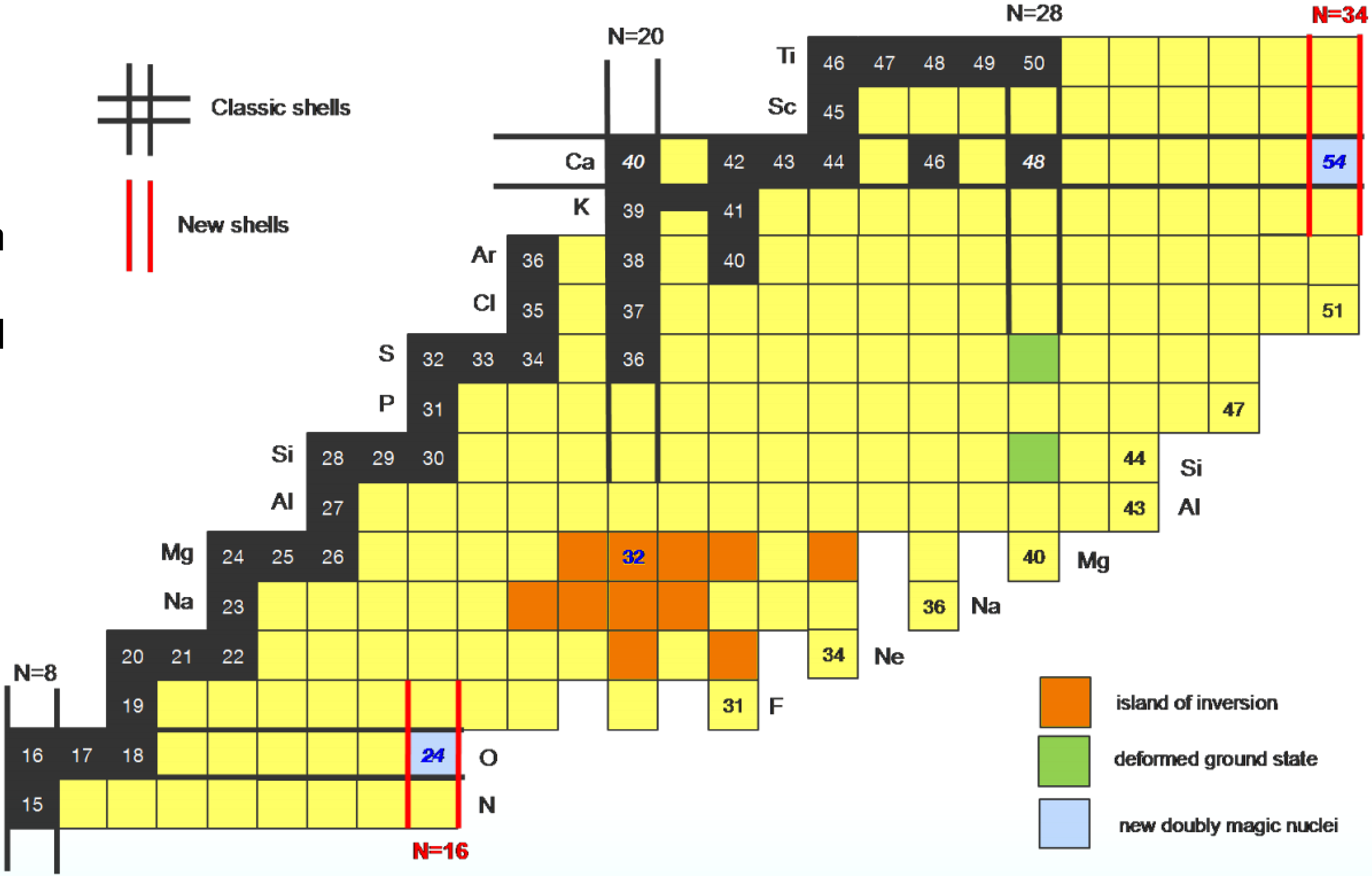
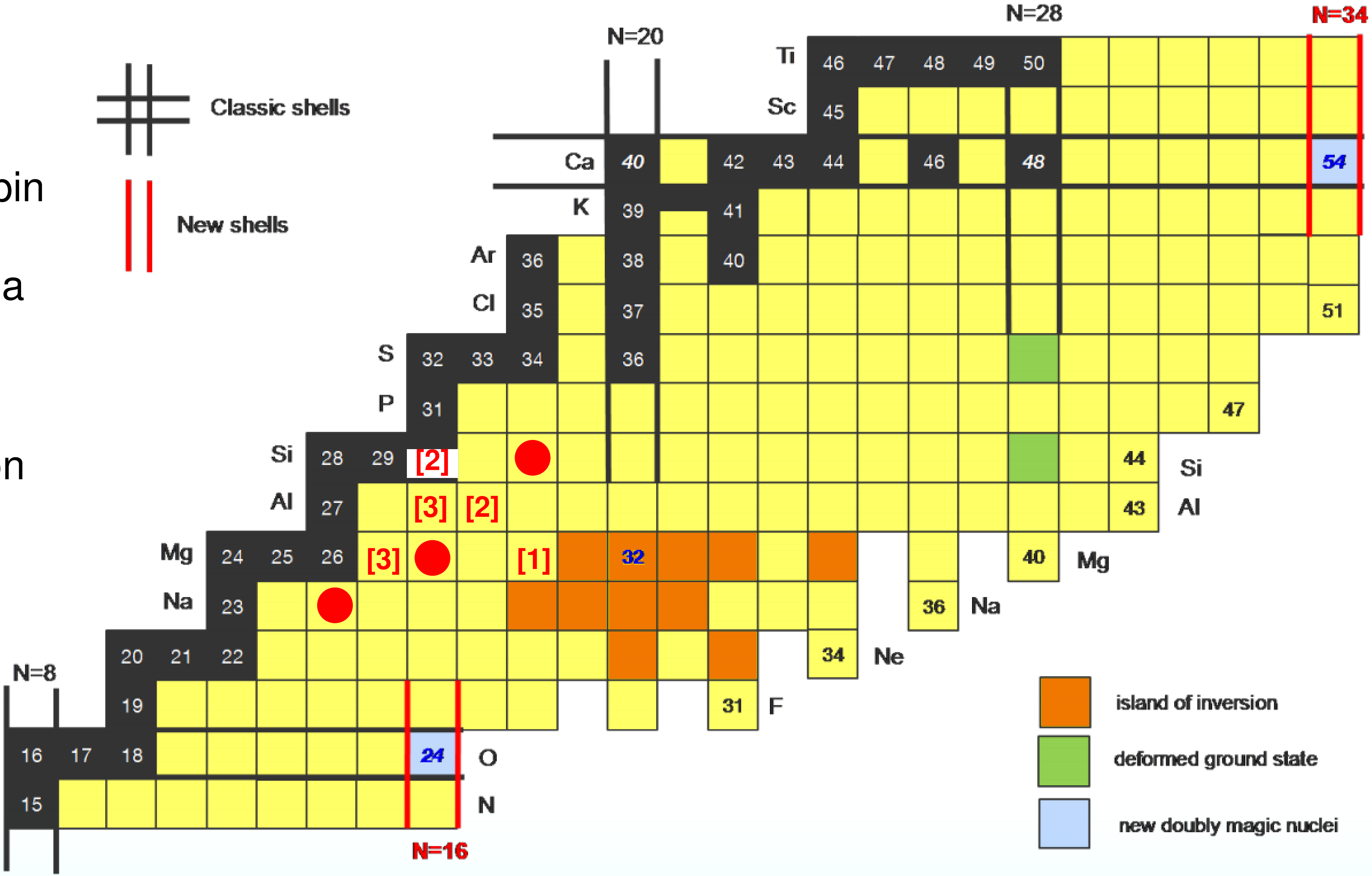
Background

- At the N=20 ‘island of inversion’ around ^{32}Mg, residual nucleon-nucleon interactions and shell evolution result in ground states with neutrons in the *pf* shell.
- For less neutron-rich species in the *sd* shell, similar configurations occur at high energy.
- Data on these ‘cross-shell’ excited states gives insight into shell evolution, but is limited for many nuclides.



Background

- Recent studies have investigated the higher-spin regime (likely to contain cross-shell excitations) via fusion-evaporation reactions.
- Needs channel separation via particle or recoil identification, and/or γ coincidence gating.
- Lifetime information is also useful for identifying intruder states.



Some recent studies of high-spin states:

[1] *A. N. Deacon et al., PRC 82 034305 (2010).*

[2] *D. Steppenbeck et al., Nucl Phys A 847 149-167 (2010).*

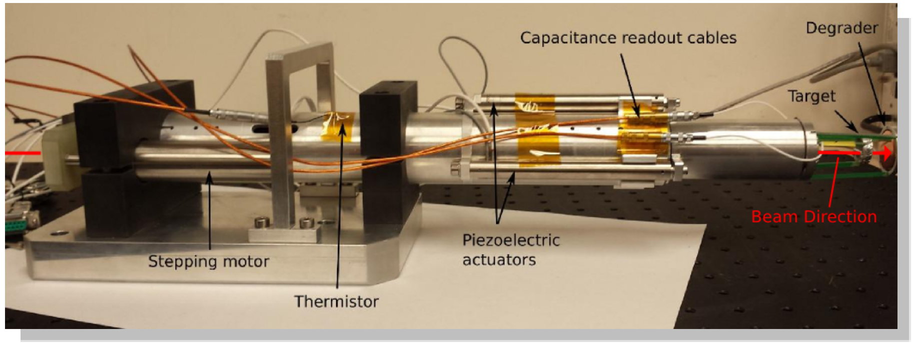
[3] *R. Dungan et al., PRC 94 064305 (2016).*

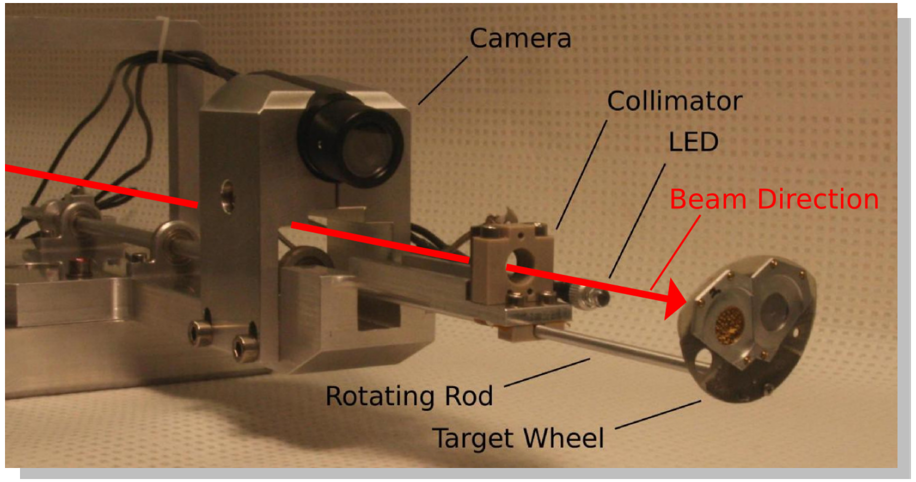
● ***Nuclides covered in this talk***

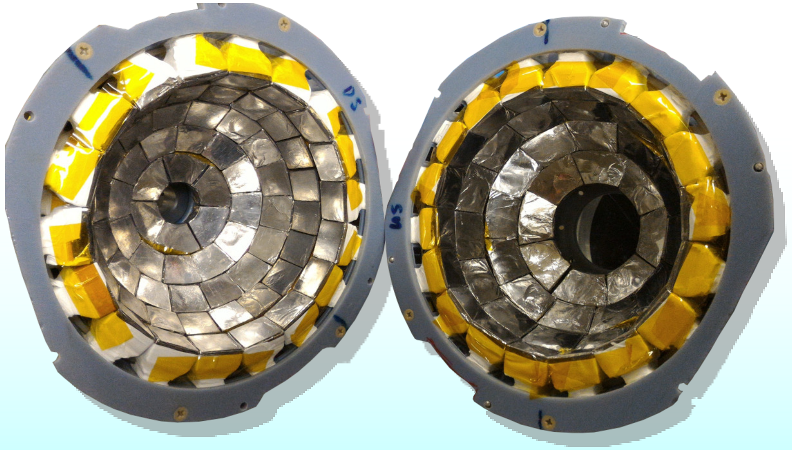
TIP Overview

Program developed at Simon Fraser University, focused on lifetime measurements using Doppler shift methods.

- Lifetimes > 1 ps measured via the Recoil Distance Method (RDM) using a plunger device.
- Lifetimes < 1 ps measured via the Doppler Shift Attenuation Method (DSAM) using a backed target.
- CsI(Tl) “ball” array for charged particle detection/identification.
- Target chamber which can be integrated with TIGRESS (γ-ray spectrometer) and/or EMMA (recoil separator).

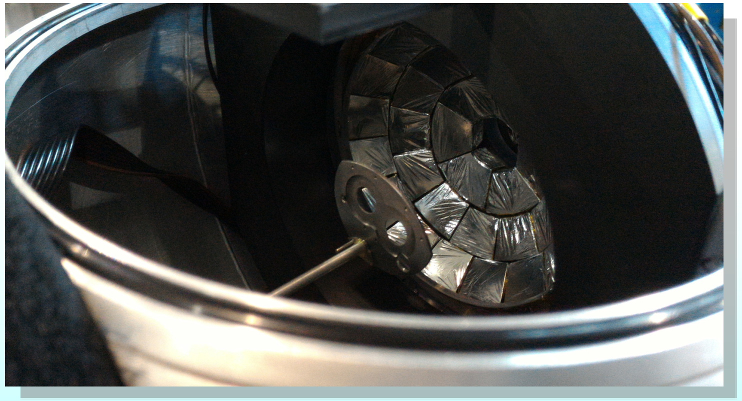


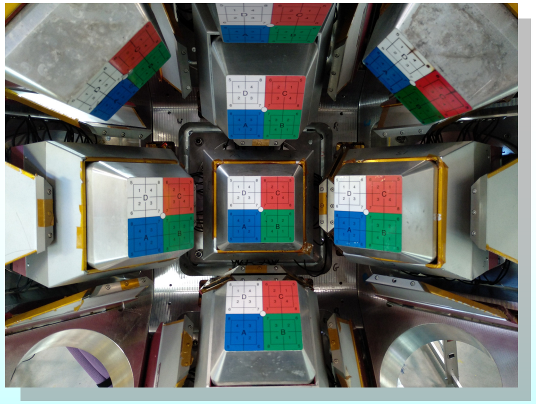


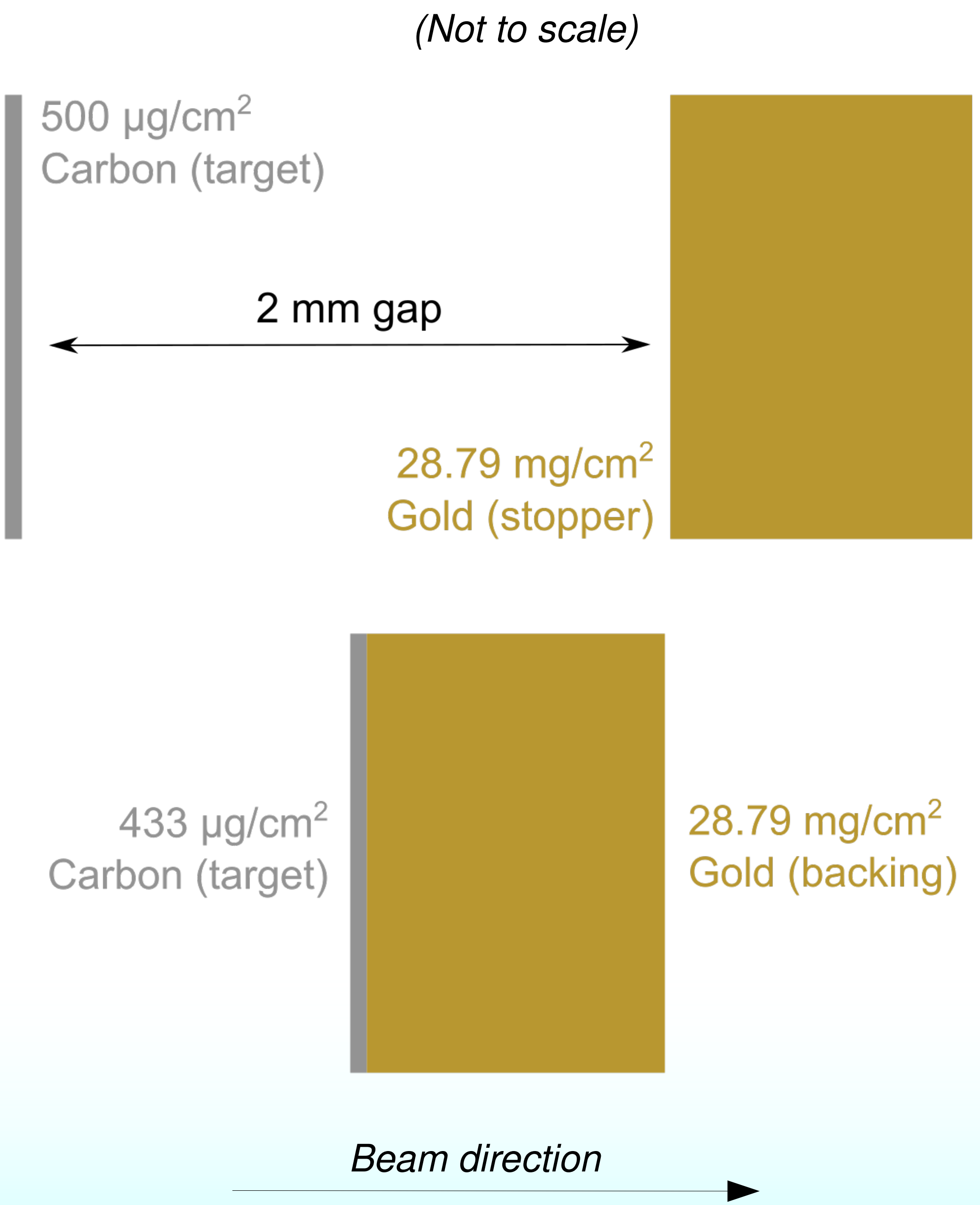


Configuration for this experiment

- ^{18}O beam @ ~10^{10} pps, 48 MeV, $^{nat.}$C targets.
  - Channels of interest: ^{25}**Na** (αp), ^{28}**Mg** (2p)
- Run time split between a thin target (~21 hours) for coincidence spectroscopy and a DSAM target (~40.5 hours) for lifetime measurements.
- 38-element partial CsI ball.
- 13 TIGRESS clovers in 4/5/4 configuration.

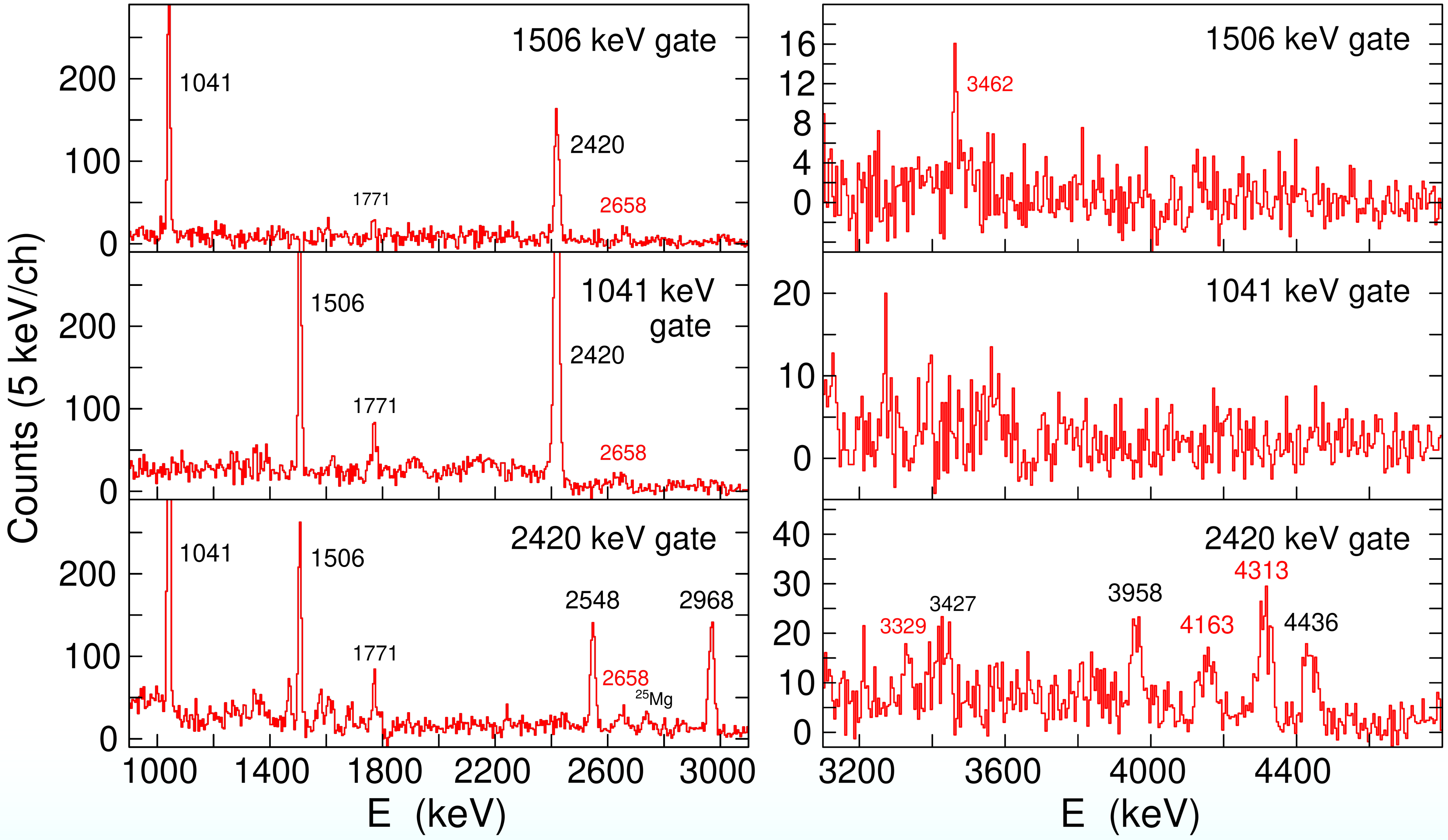






^{25}Na thin target results

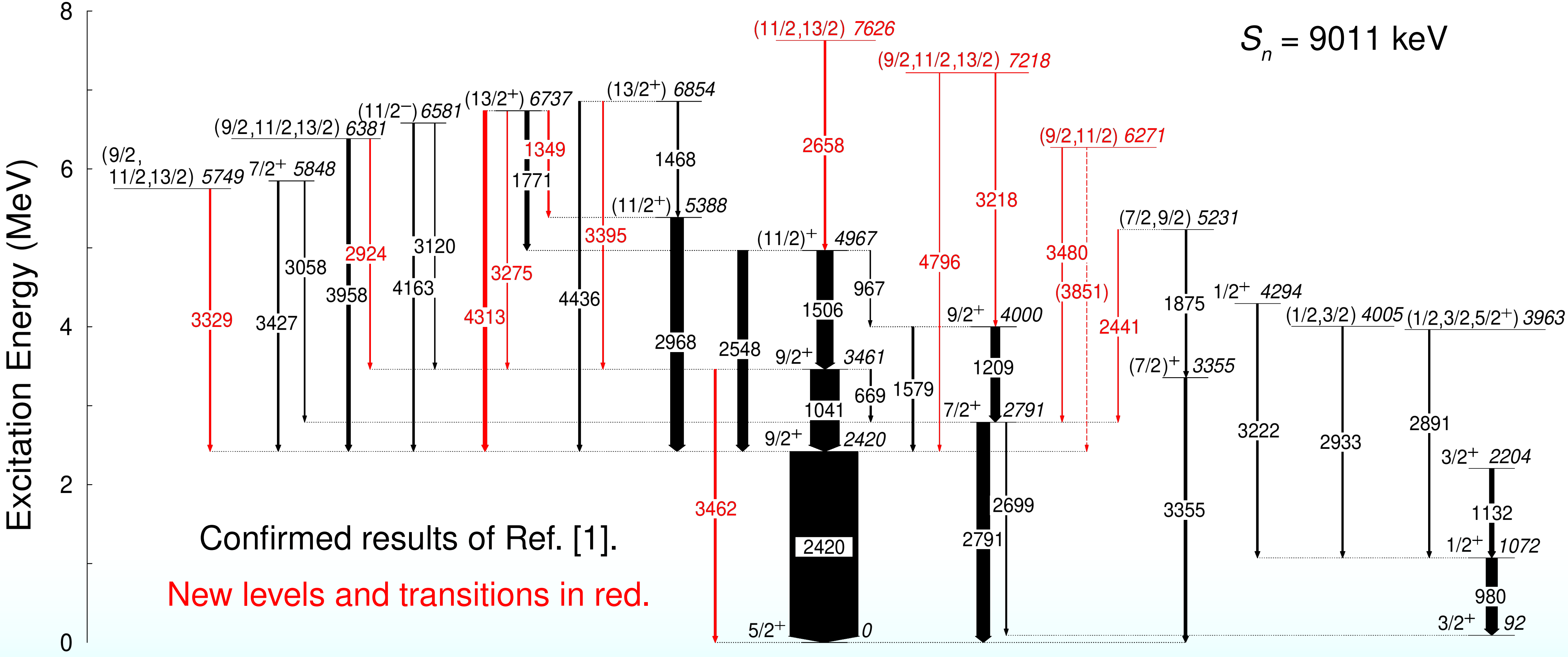
- ^{25}Na was populated using the $^{12}C(^{18}O,\alpha p)$ reaction.
- Strong population of a “main band” of 2420, 1041, and 1506 keV transitions.
- Some previously unobserved transitions (labels in red) at high energies.



^{25}Na γ-gated spectra (thin target, Doppler corrected).

J. Williams et al., PRC 102 064302 (2020)

^{25}Na full level scheme

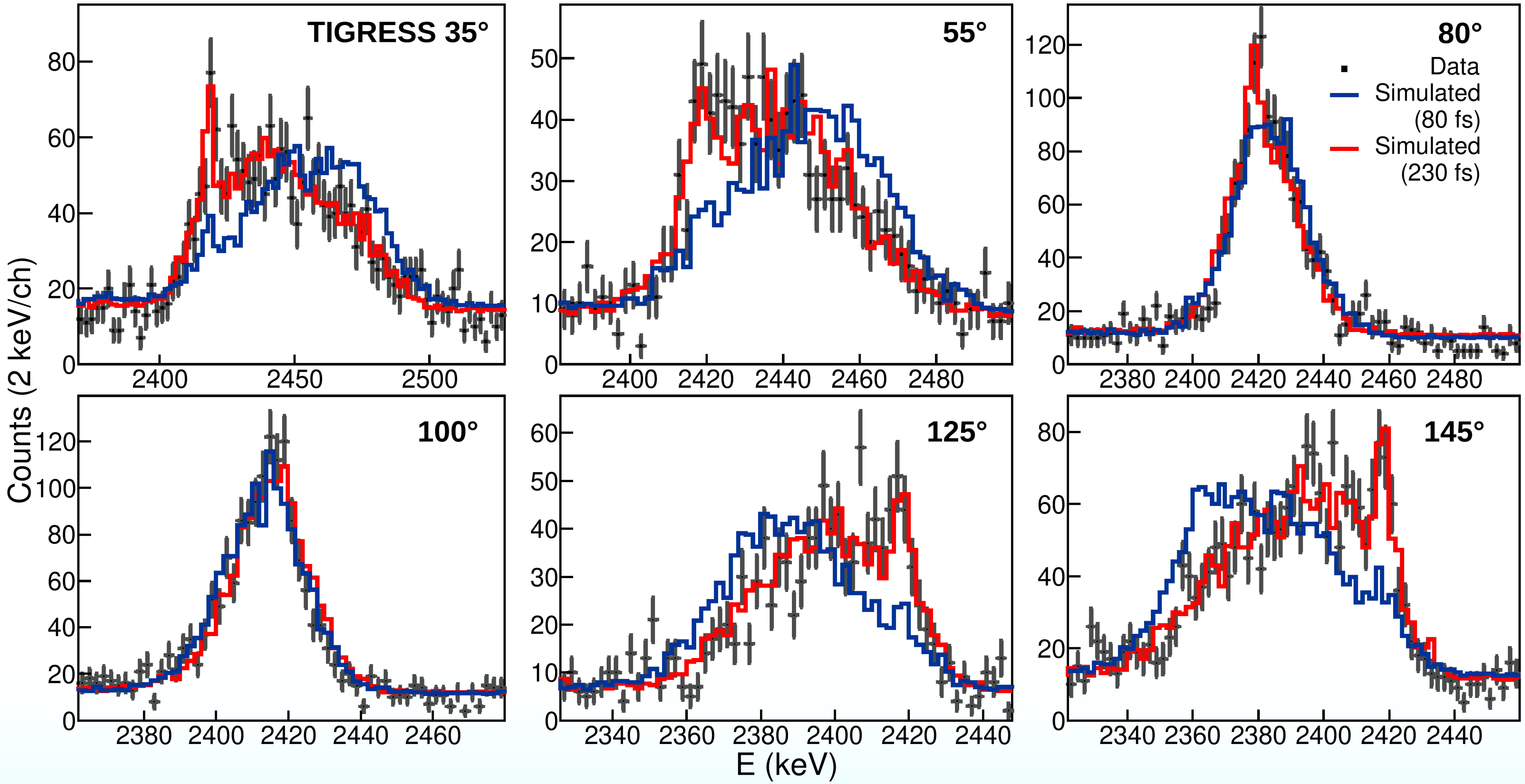


Confirmed results of Ref. [1].

New levels and transitions in red.

[1] *J. M. VonMoss et al., PRC 92 034301 (2015)*

^{25}Na DSAM results

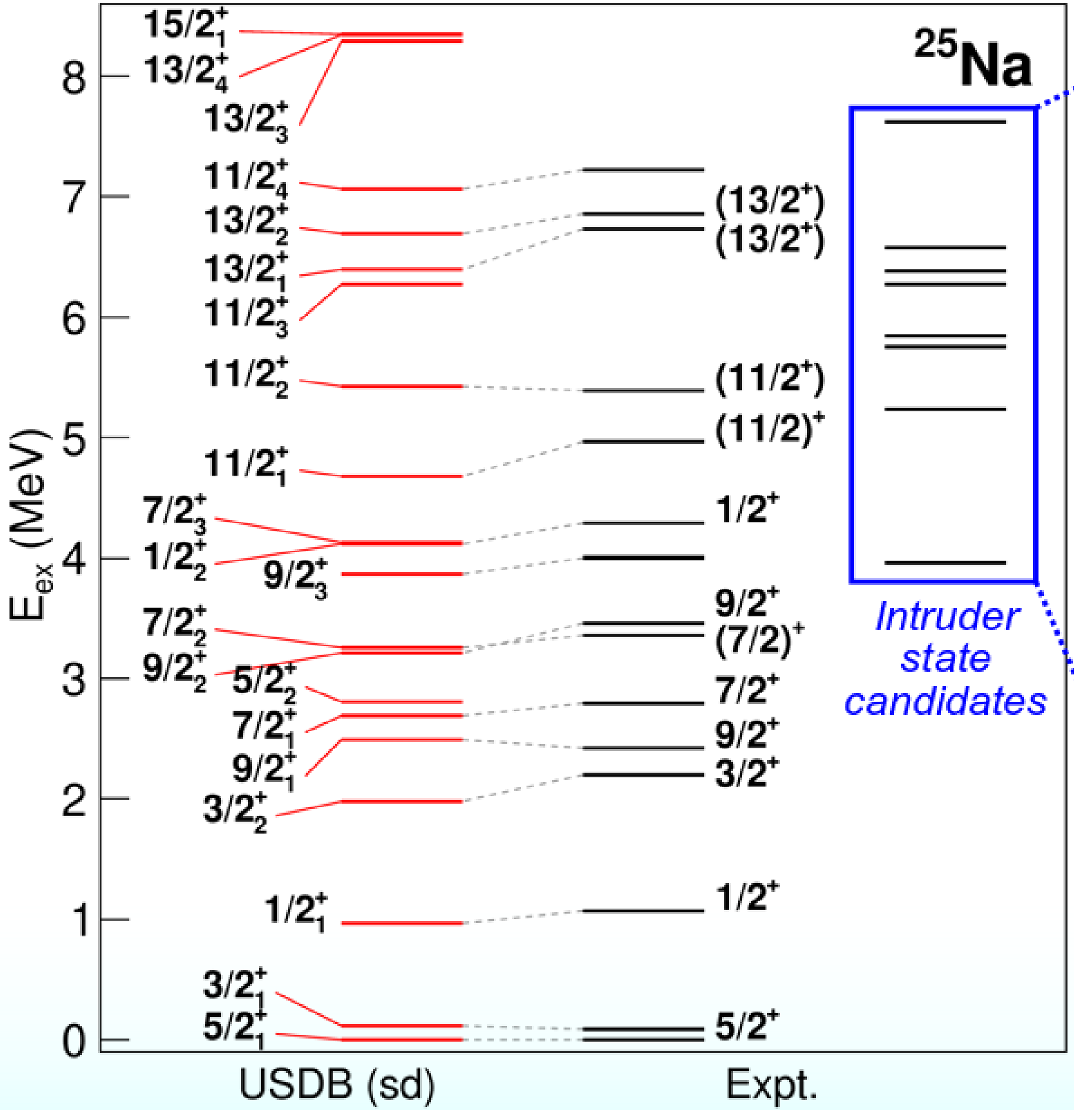


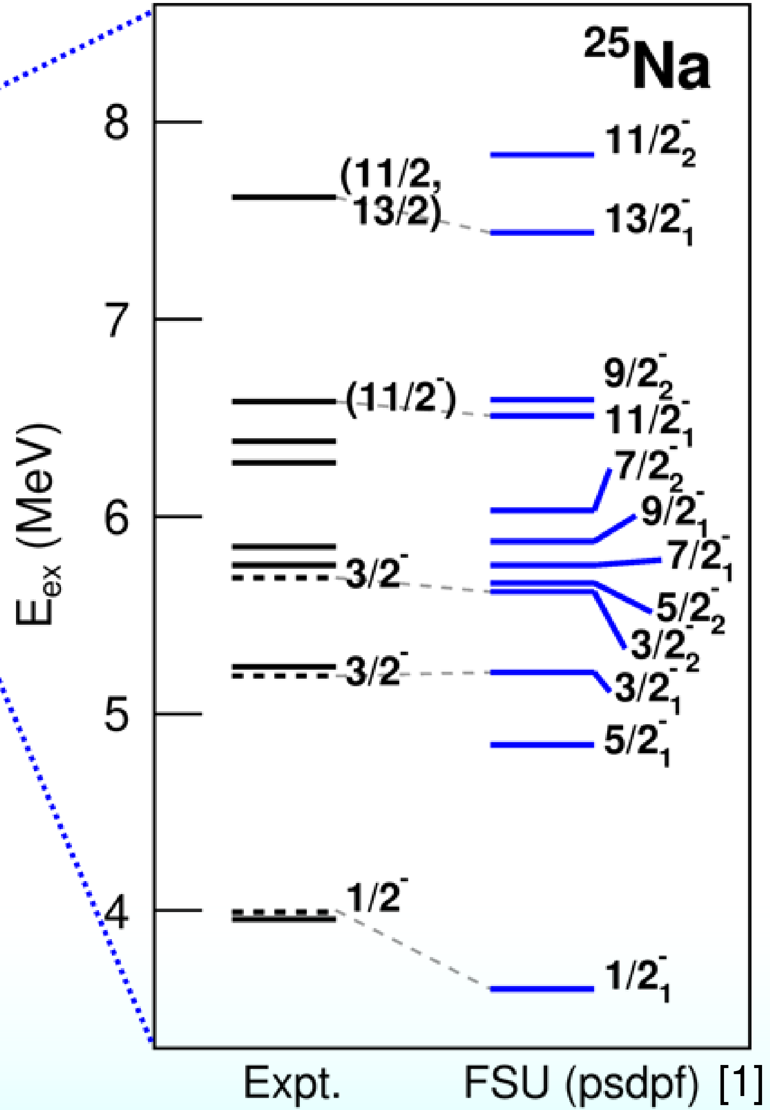
- Comparison to GEANT4 simulations, using maximum-likelihood χ^2 method.
- Feeding corrected by gating from above and simulating the effect of the feeding transition.

^{25}Na 2420 keV transition, simulation @ τ_{mean} = 230(40) fs

^{25}Na calculations (sd shell)

- Low-lying states are well reproduced in USDB calculations in the *sd* shell.
- Some high-lying states don't fit in well and are intruder state candidates.
- Highest energy state @ 7626(4) keV most likely negative parity.



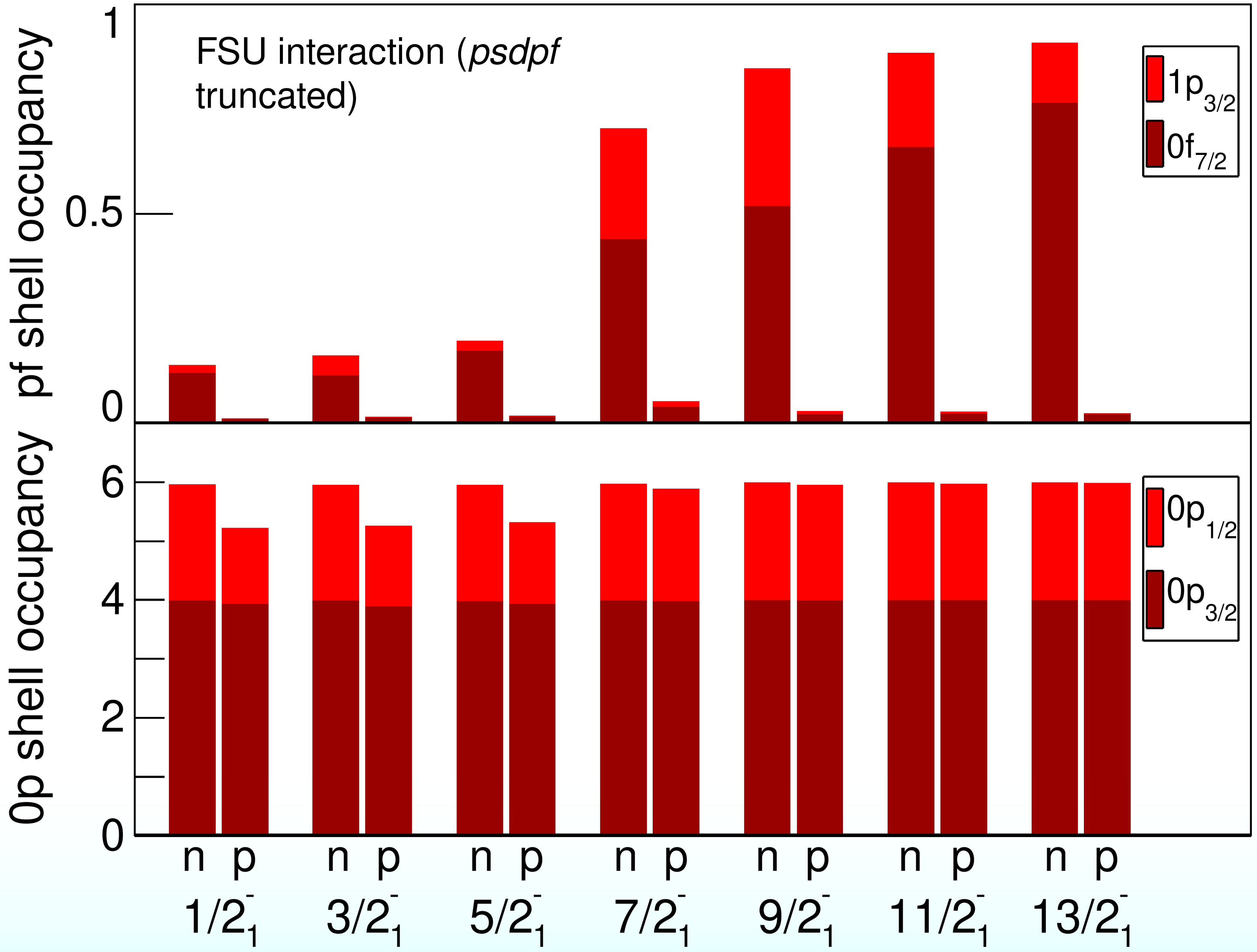


[1] *R. S. Lubna, et al., Phys. Rev. Research 2 043342 (2020)*

^{25}Na calculations (cross-shell occupancies)

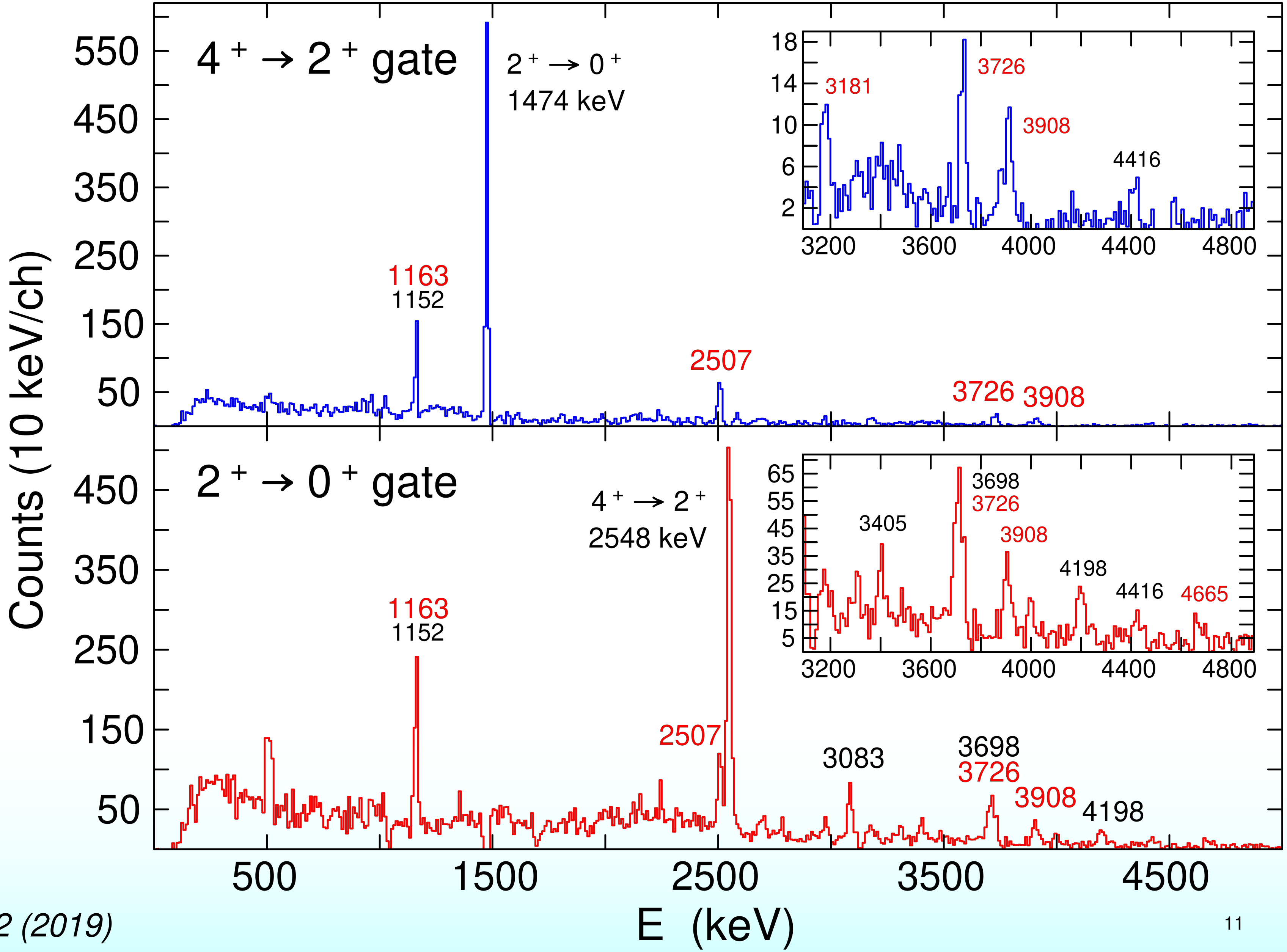
Calculated *pf* orbital occupanices of *1p1h* intruder states in ^{25}Na show differing excitation modes:

- Low spin: proton excitation from the *0p* shell.
- High spin: neutron excitation to the upper *pf* shell.



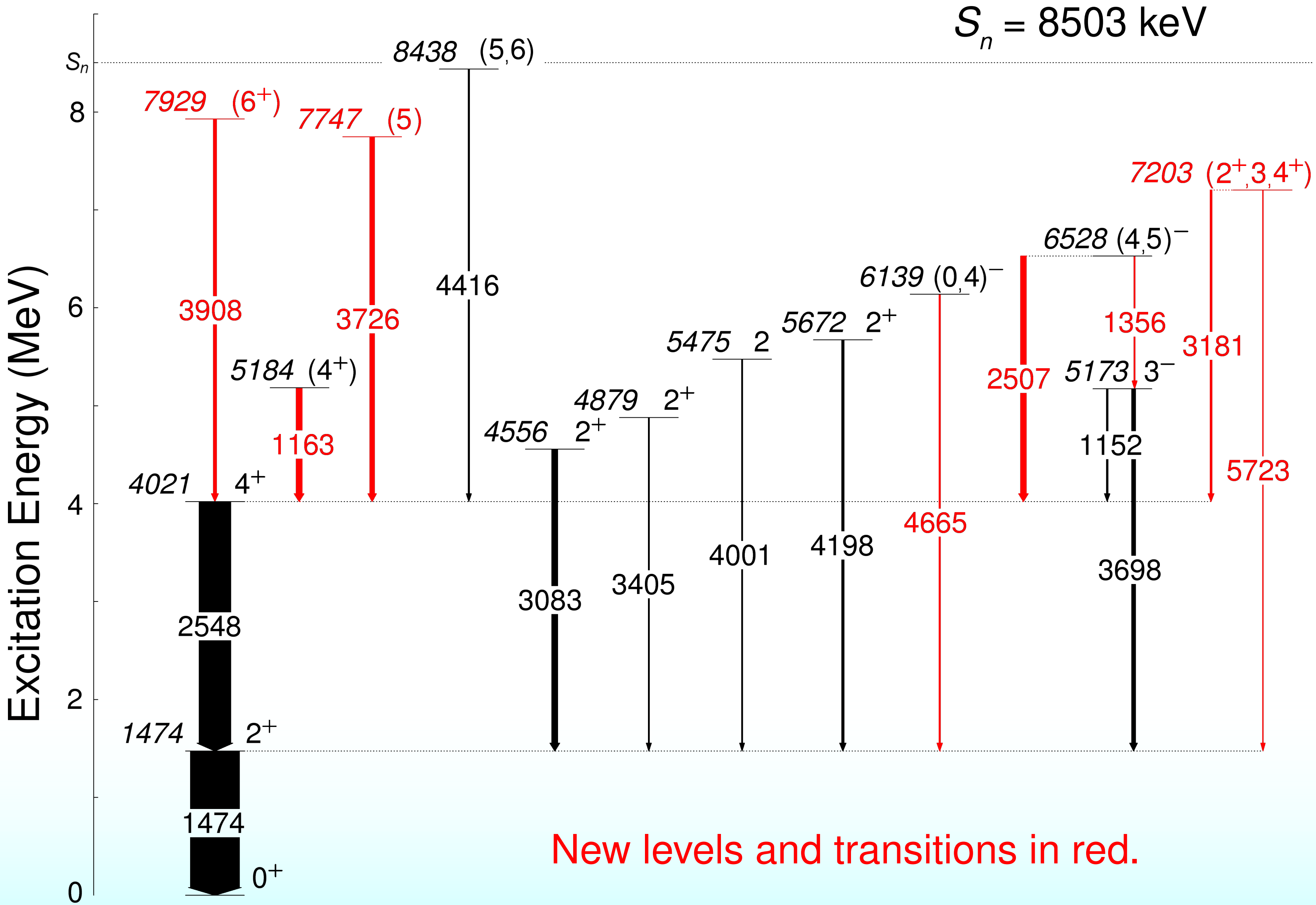
^{28}Mg thin target results

- ^{28}Mg was populated using the $^{12}C(^{18}O,2p)$ reaction.
- A large fraction of transitions are newly observed (labels in red), including some of the most intense.



J. Williams et al., PRC 100 014322 (2019)

^{28}Mg level scheme

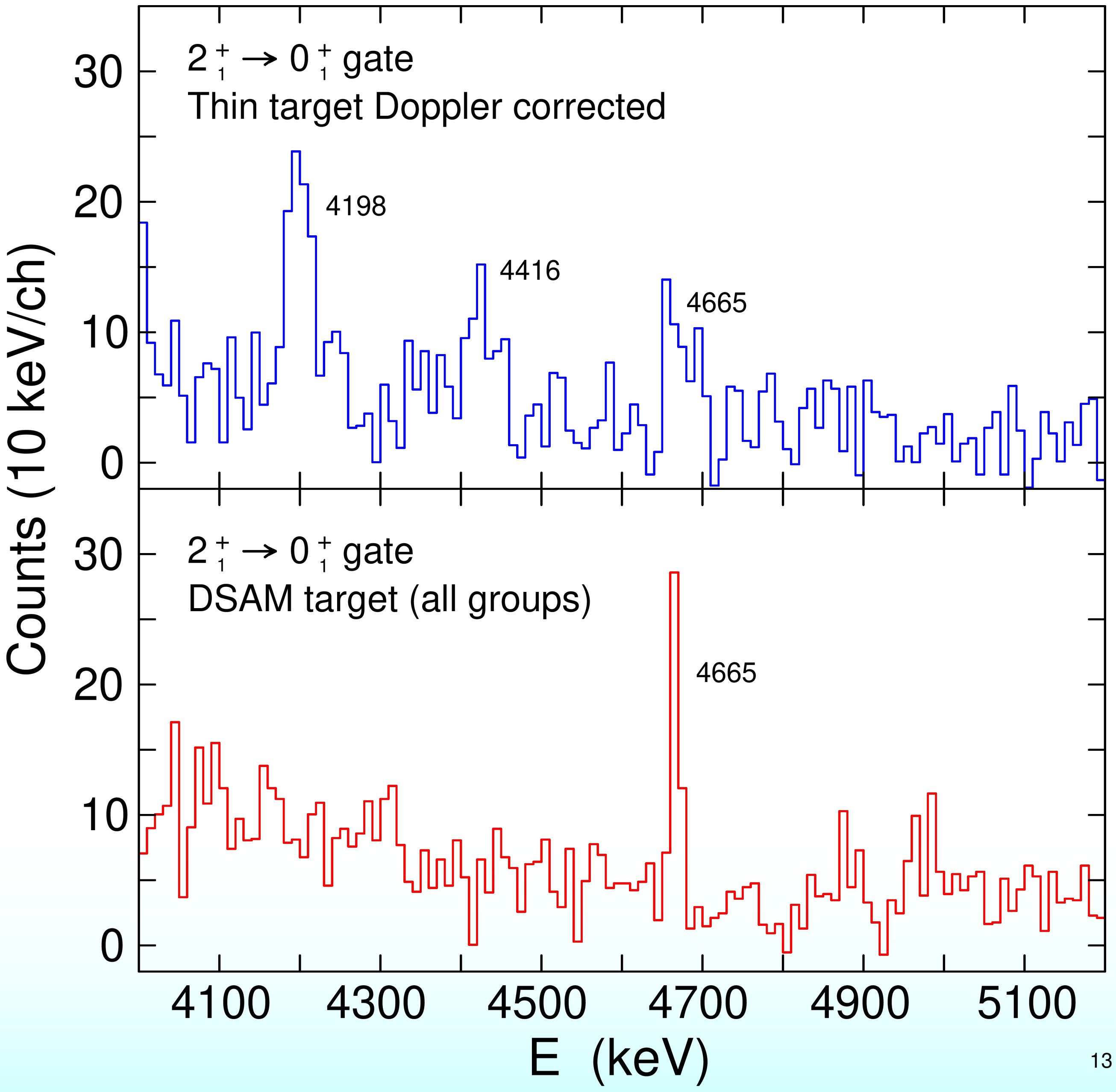


New levels and transitions in red.

^{28}Mg long-lived level

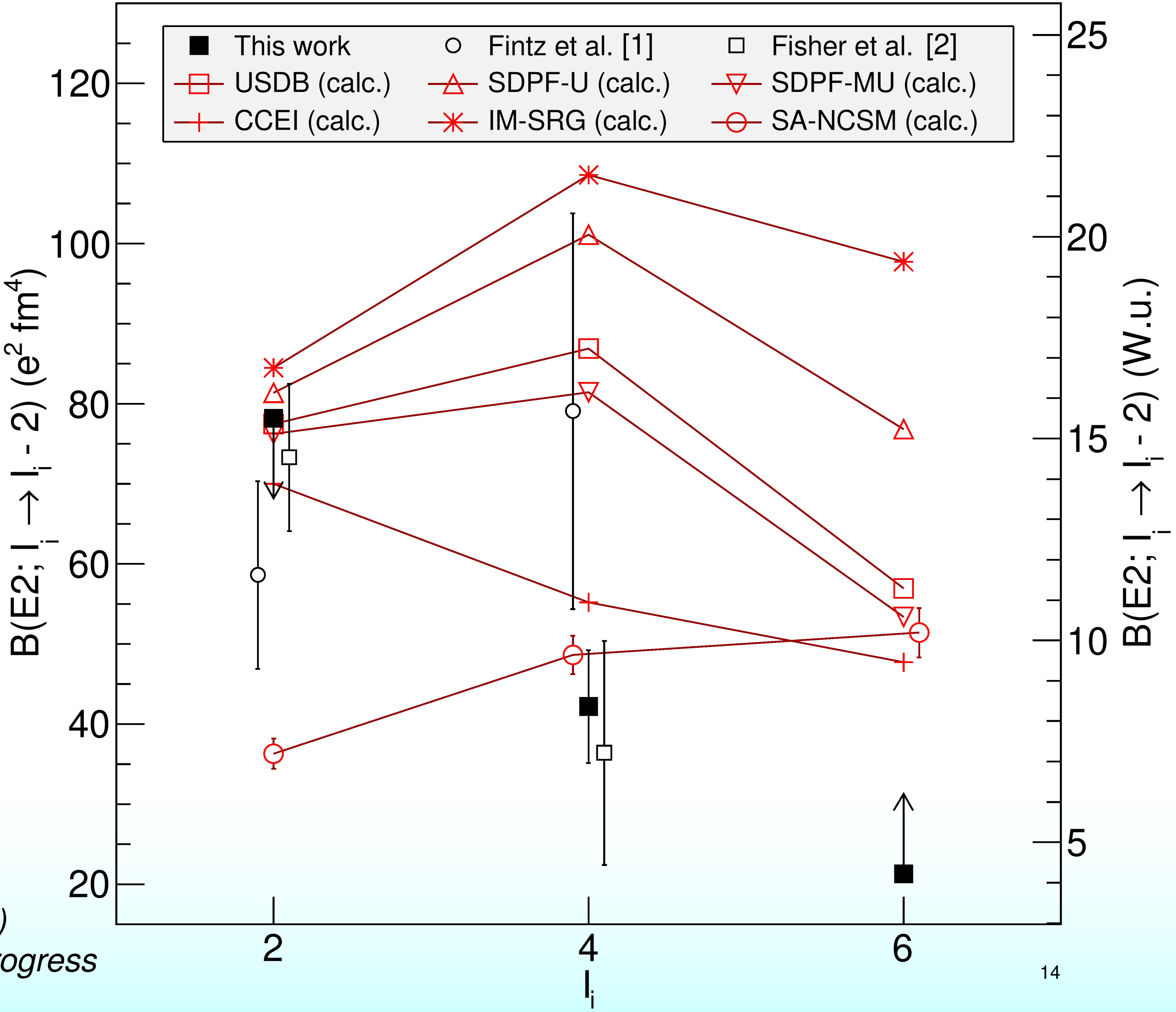
- Long lived level at 6139 keV:
  - 4664.9(12) keV transition stopped in DSAM target data.
  - Doppler shifted in thin target data.

- Inferred level lifetime: > 1 ps, < 250 ps.
- Suggests transition of M2 or higher multipolarity, level I^{π} = 0^- or 4^-
- Similar isomer in nearby ^{32}Si, also negative parity.



^{28}Mg yrast band B(E2) values

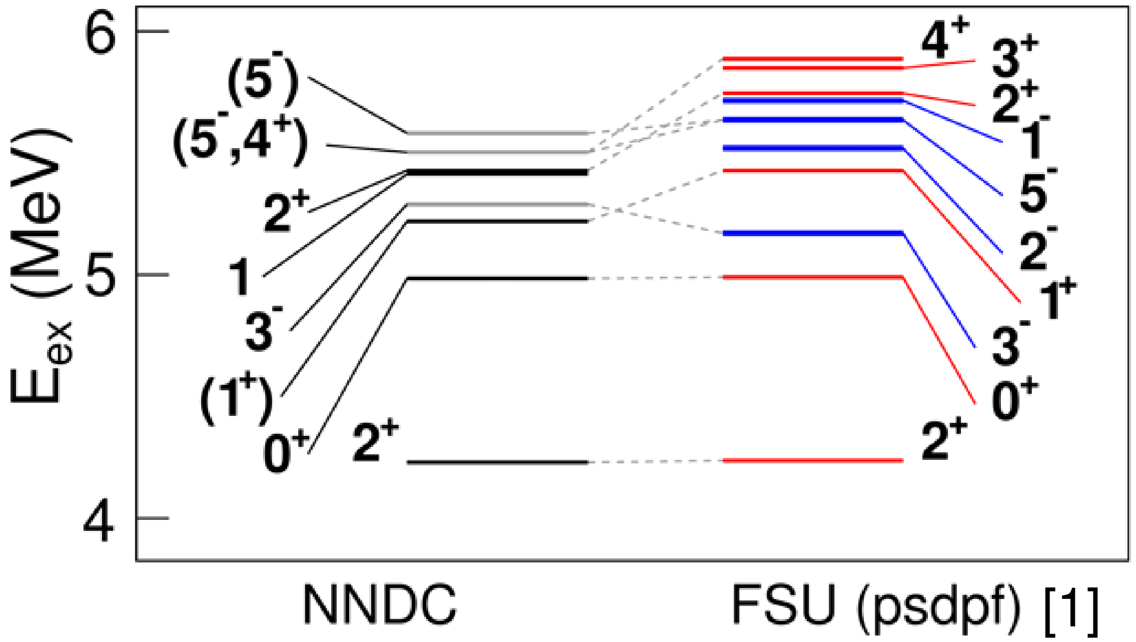
- B(E2) values along yrast band trend lower than most model calculations.
- Ab-initio SA-NCSM [3] calculations agree well with B(E2; $4^+ \rightarrow 2^+$) from this data, but disagree with previous data.
  - Plunger data taken to measure B(E2; $2^+ \rightarrow 0^+$) populated using the same reaction (M. S. Martin, SFU).



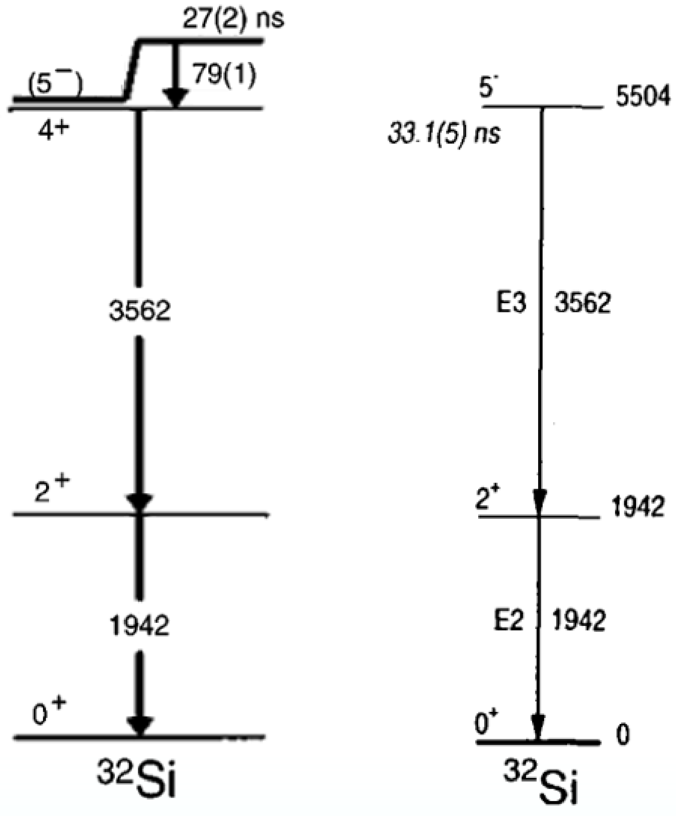
[1] P. Fintz et al., Nucl. Phys. A 197, 423 (1972)
[2] T. R. Fisher et al., Phys. Rev. C 7, 1878 (1973)
[3] K. D. Launey, T. Dytrych, and J. P. Draayer, Progress in Particle and Nuclear Physics 89, 101 (2016)

Future plans - ^{32}Si

Cross-shell excitations in ^{32}Si will be investigated with the ^{22}Ne(^{12}C,2p) reaction. Goals are to obtain improved lifetime measurements, measure angular distributions, and determine the placement of the $I^{\pi} = (5^{-})$ *nanosecond isomer*.



Calculated levels at intermediate energies in ^{32}Si.



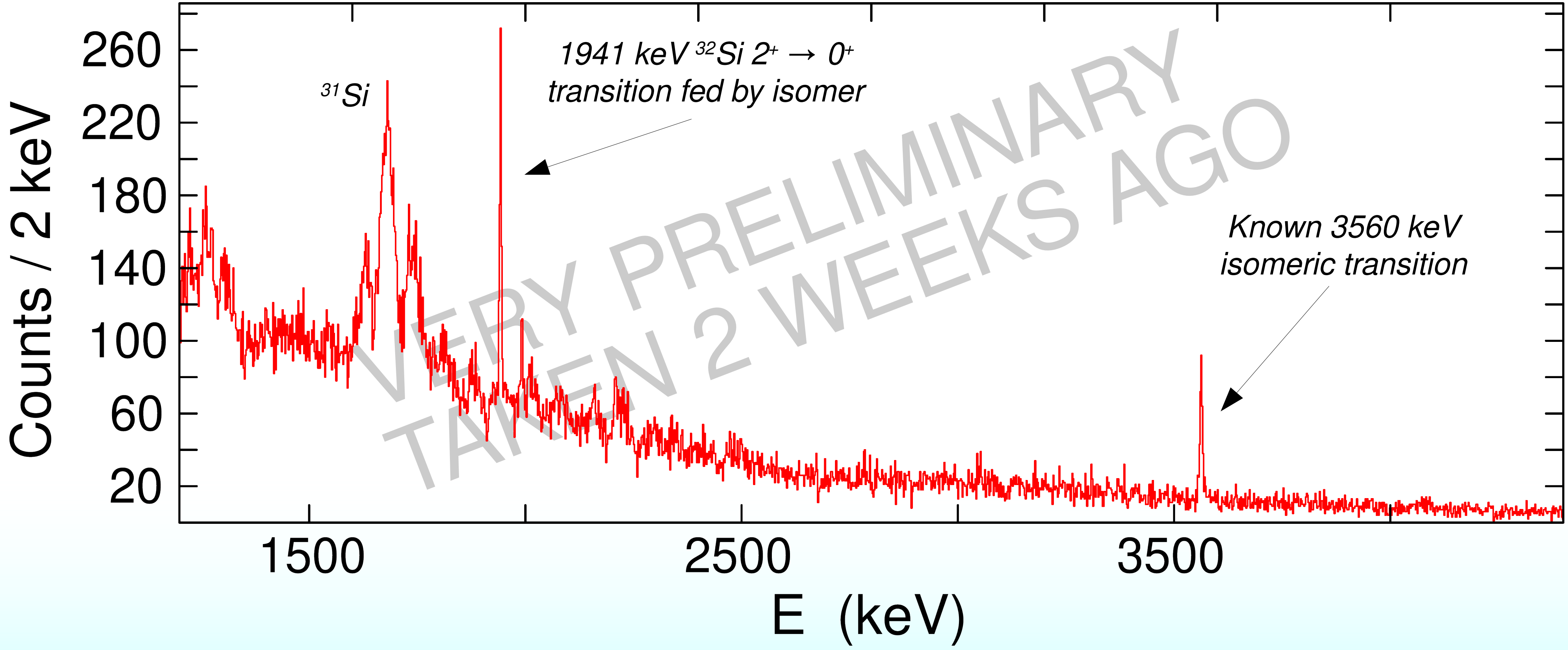
Fornal et al. [2] *Asai et al. [3]*

Proposed decay schemes of the nanosecond isomer.

[1] R. S. Lubna, et al., Phys. Rev. Research 2 043342 (2020)
[2] B. Fornal et al., Phys. Rev. C 55 762 (1997)
[3] M. Asai et al., JAERI Tandem Annual Report 2001, 23 (2002)

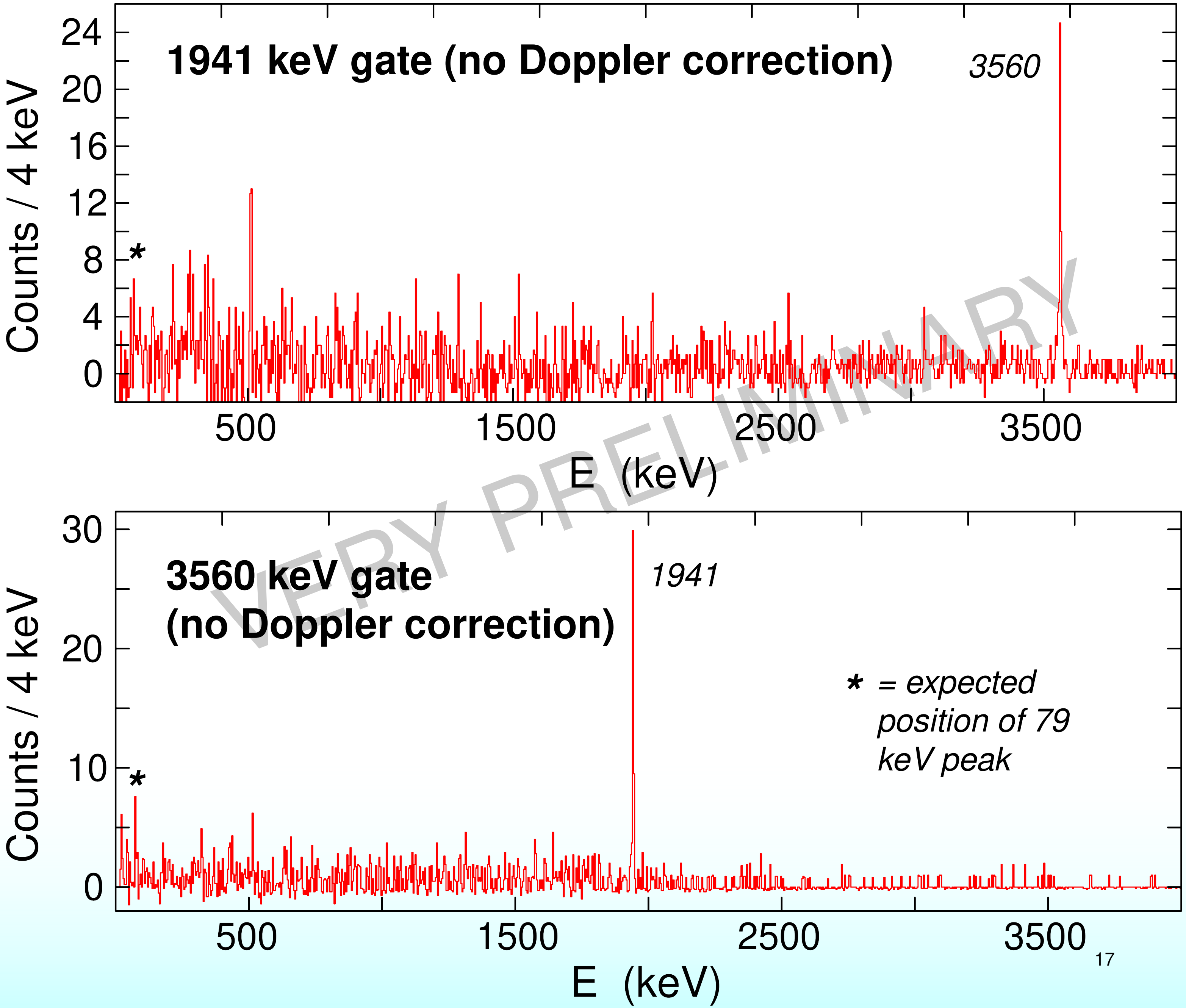
^{32}Si test data – singles

Initial test data taken with a ^{12}C thin target + downstream ^{197}Au stopper shows population of the isomer. Analysis of this data will inform plans to run the full experiment in the coming year.



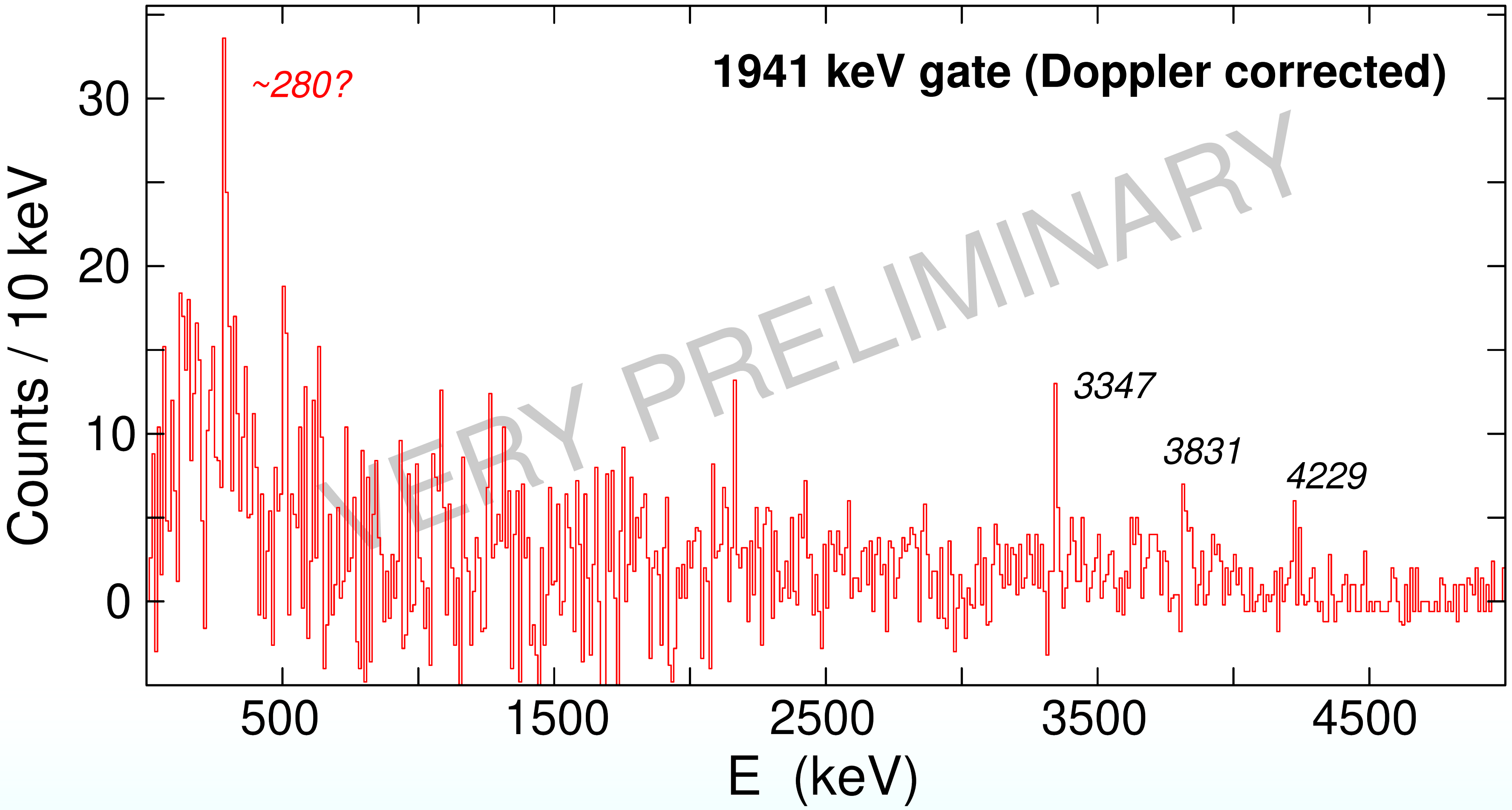
^{32}Si test data – the isomer

- No evidence yet of the 79 keV isomeric transition assumed in NNDC (expect >1/2 the counts of the 1941 keV line).
  - Suggests a $5^- \rightarrow 2^+_1$ E3 transition.
  - B(E3)↓ would be ~100x lower than values in nearby ^{36}Cl and ^{39}K.
- If true, then the 4^+_1 state in ^{32}Si is not yet assigned (maybe we can do it).



^{32}Si test data – prompt transitions

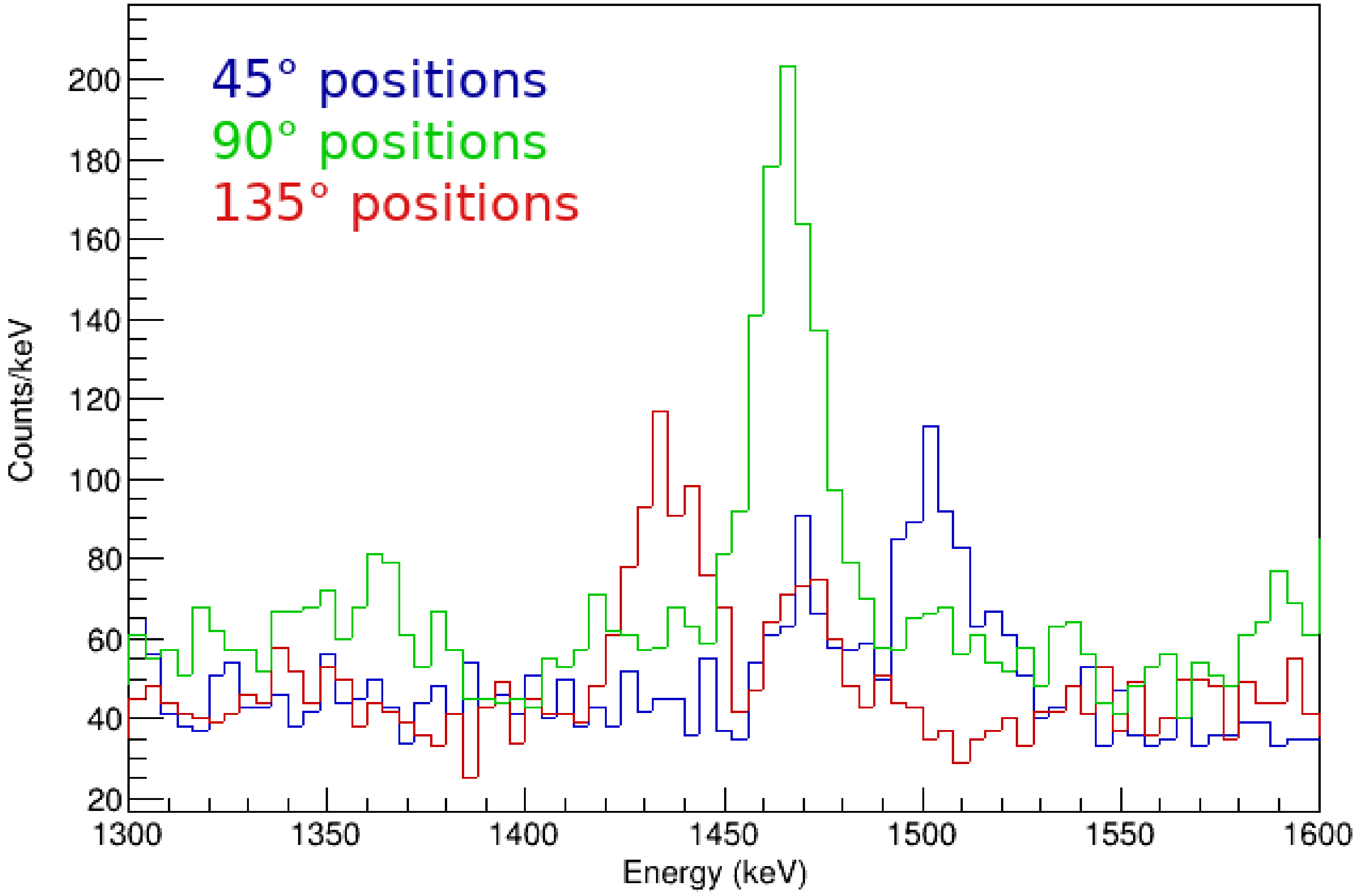
- Doppler corrected data shows that the 2^+_1 level is also populated by prompt transitions.
  - Includes known $3^-_1 \rightarrow 2^+_1$ transition.
  - No immediately obvious indication of a 4^+_1 level.
- More data coming soon™.



Recent TIP experiments: ^{28}Mg RDM

Follow-up to the earlier DSAM measurements in ^{28}Mg.

- Aims to measure $B(E2; 2^+_1 \rightarrow 0^+_1)$ and investigate the discrepancy with ab-initio SA-NCSM calculations.
- May also measure the lifetime of the long-lived state at 6139 keV.
- Beamtime in 2021, data under early analysis.



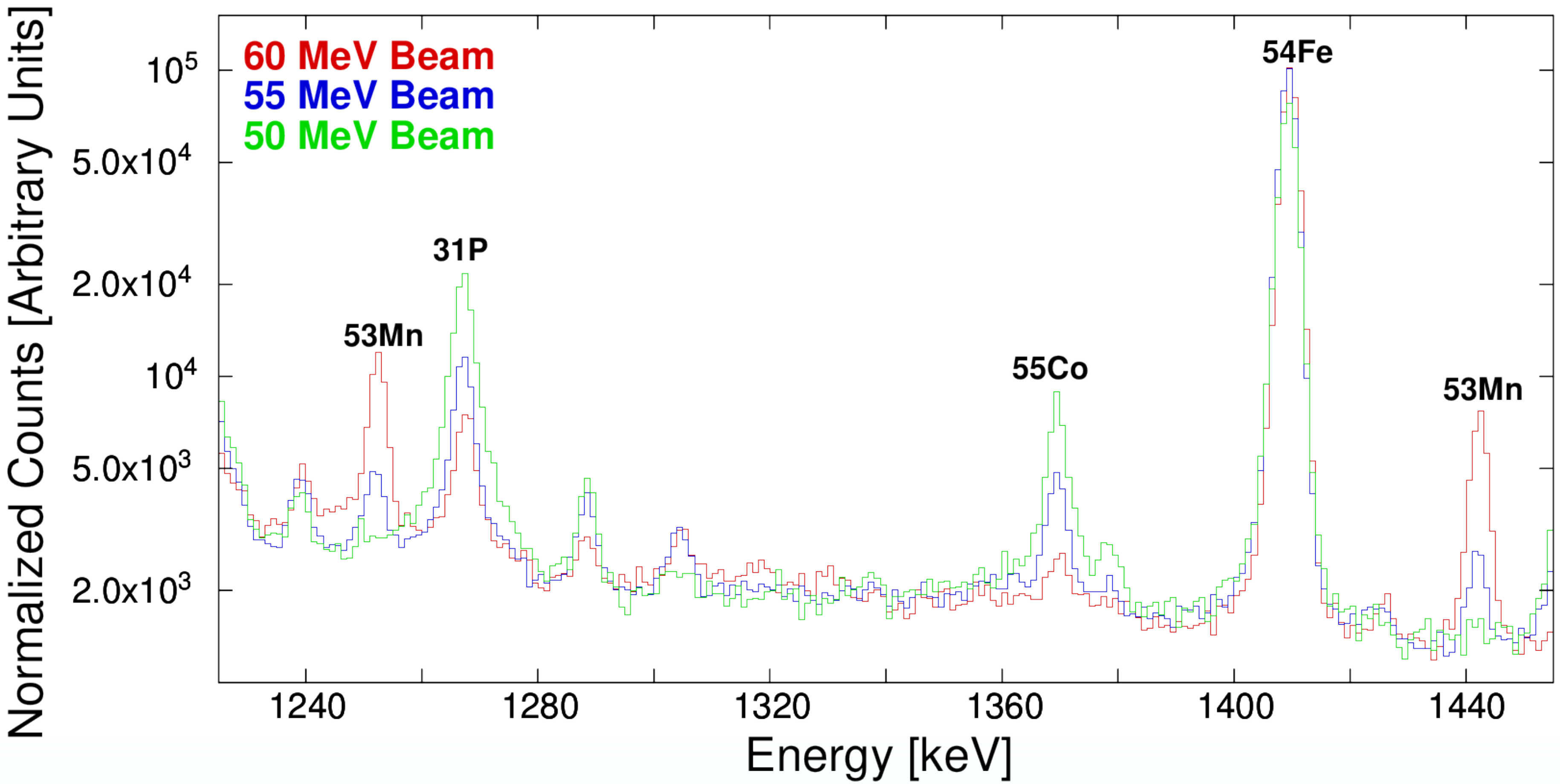
Plunger spectra of the $2^+_1 \rightarrow 0^+_1$ transition in ^{28}Mg (51.5µm separation).

Poster: Electromagnetic Transition Rate Studies in ^{28}Mg (M. S. Martin, SFU)

Recent TIP experiments: *A=55* mirror symmetry

Study of mirror symmetry in *A=55* nuclei (^{55}Co, ^{55}Ni) populated using fusion-evaporation.

- ^{55}Co via stable beam: ^{40}Ca(^{20}Ne, αp)^{55}Co.
- ^{55}Ni via radioactive beam: ^{40}Ca(^{20}**Na**, αp)^{55}Ni.
- Stable beam portion completed June 2022.



Poster: Mirror Symmetry in the $f_{7/2}$ Shell Below ^{56}Ni, Excited States and Electromagnetic Transition Rates in ^{55}Ni and ^{55}Co (H. Asch, SFU)

Summary

Experimental results:

- Extension of level schemes in ^{25}Na and ^{28}Mg in the high energy/spin regime.
  - Higher energy states in ^{25}Na not well reproduced by USDB, are probable intruder states.
  - Long-lived intruder state in ^{28}Mg.
- Also studied ^{22}Ne (2α channel) and found several new transitions/levels.
- Initial ^{32}Si data shows nanosecond isomer population.

Ongoing and future work:

- Analysis of plunger data on ^{28}Mg (M. S. Martin, SFU).
- Study of *A=55* mirror nuclei (^{55}Co/^{55}Ni) using fusion-evaporation with a radioactive ^{20}Na beam (H. Asch, SFU).
- Follow up study of cross-shell excitations in ^{32}Si.

Acknowledgments

Simon Fraser University – H. Asch, A. Chester, T. Domingo, M. S. Martin, P. Spagnoletti, K. Starosta, K. Whitmore

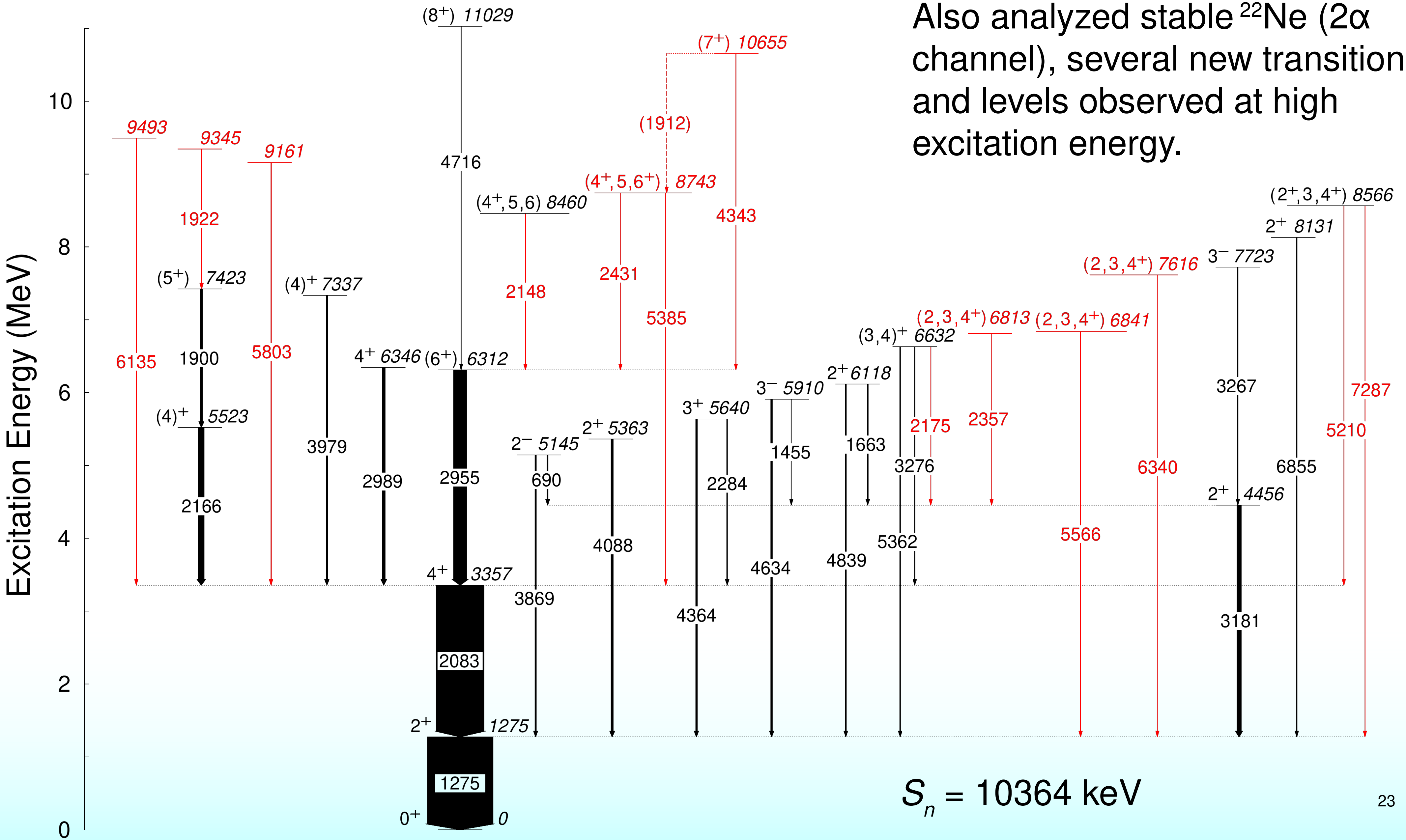
TRIUMF - G. C. Ball, A. B. Garnsworthy, G. Hackman, J. Henderson, R. Henderson, V. Karayonchev, R. Krücken, R. S. Lubna, J. Measures, O. Paetkau, J. Park, D. Rhodes, J. Smallcombe, M. Williams

University of Guleph - C. E. Svensson

Louisiana State University – K. D. Launey, G. H. Sargsyan

IIT Roorkee – A. Kumar, P. C. Srivastava, P. Choudhary

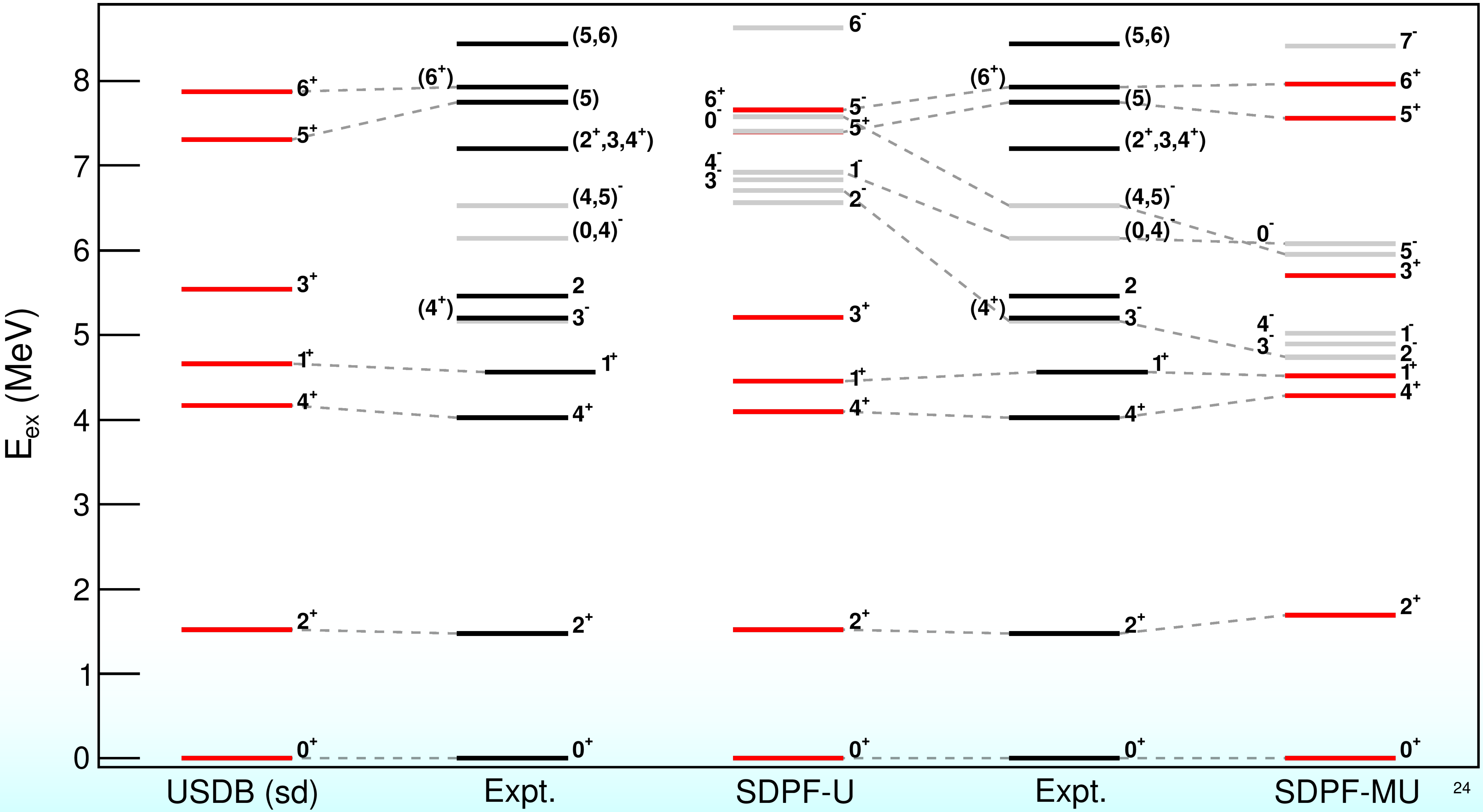
Backup – ^{22}Ne level scheme



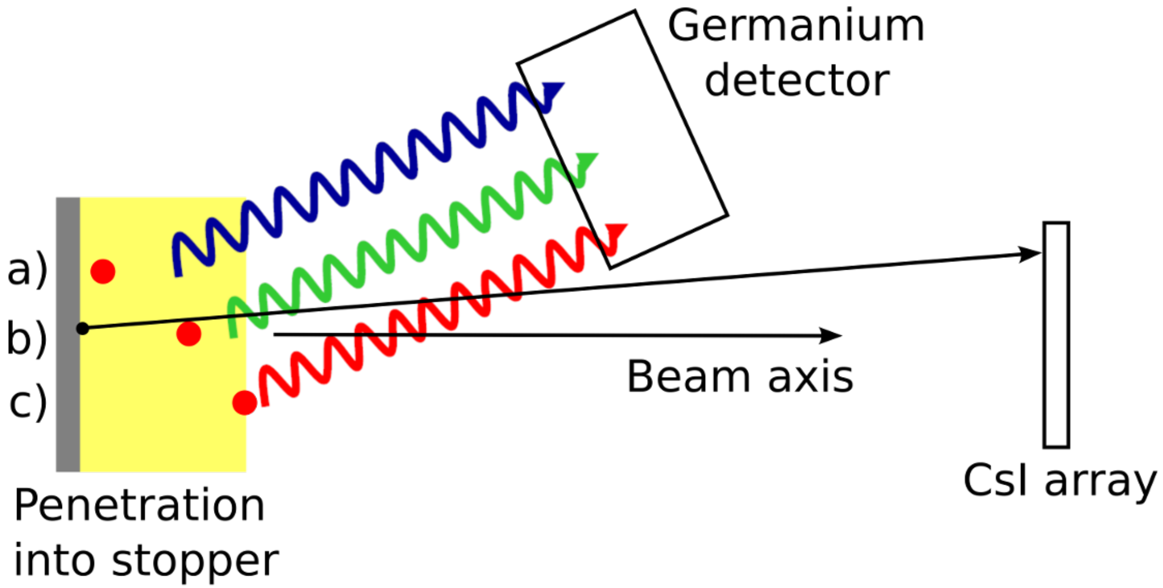
Also analyzed stable ^{22}Ne (2α channel), several new transitions and levels observed at high excitation energy.

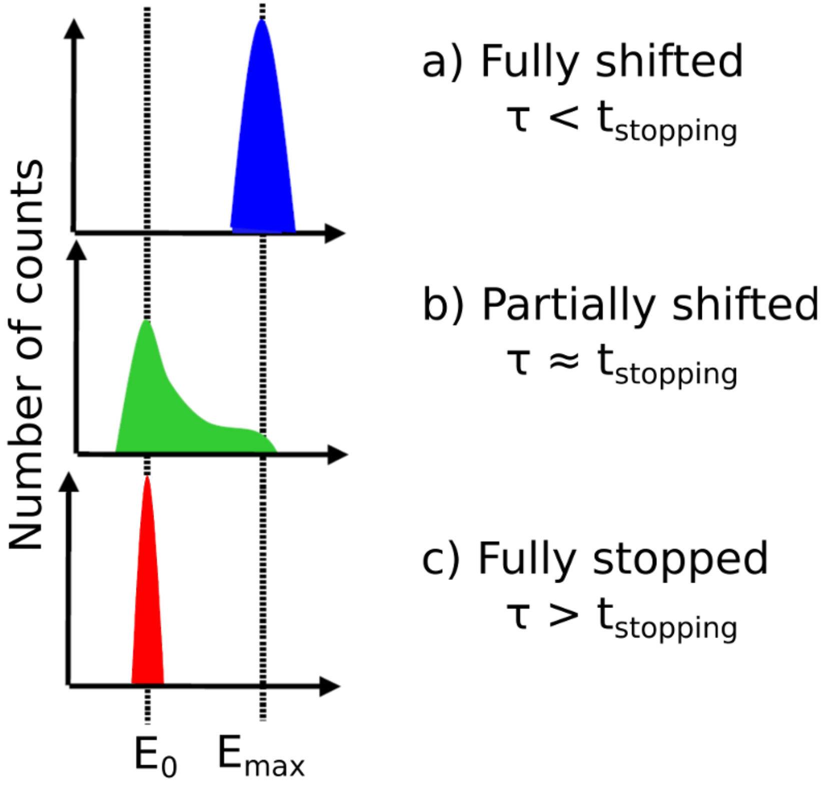
S_n = 10364 keV

Backup - ^{28}Mg shell model calculations

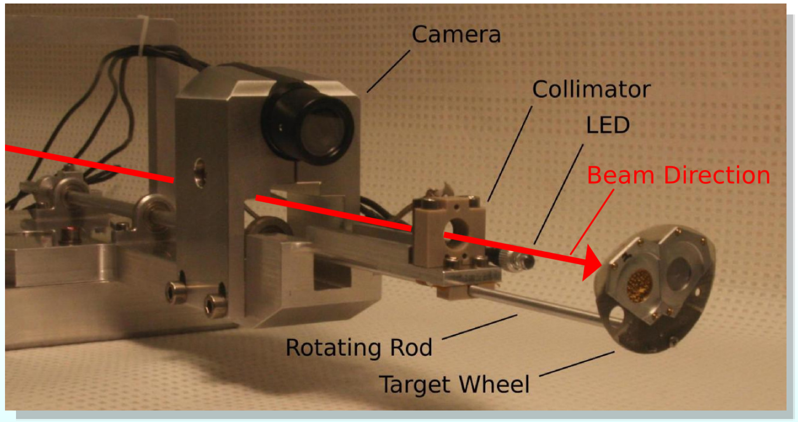


Backup - DSAM Primer

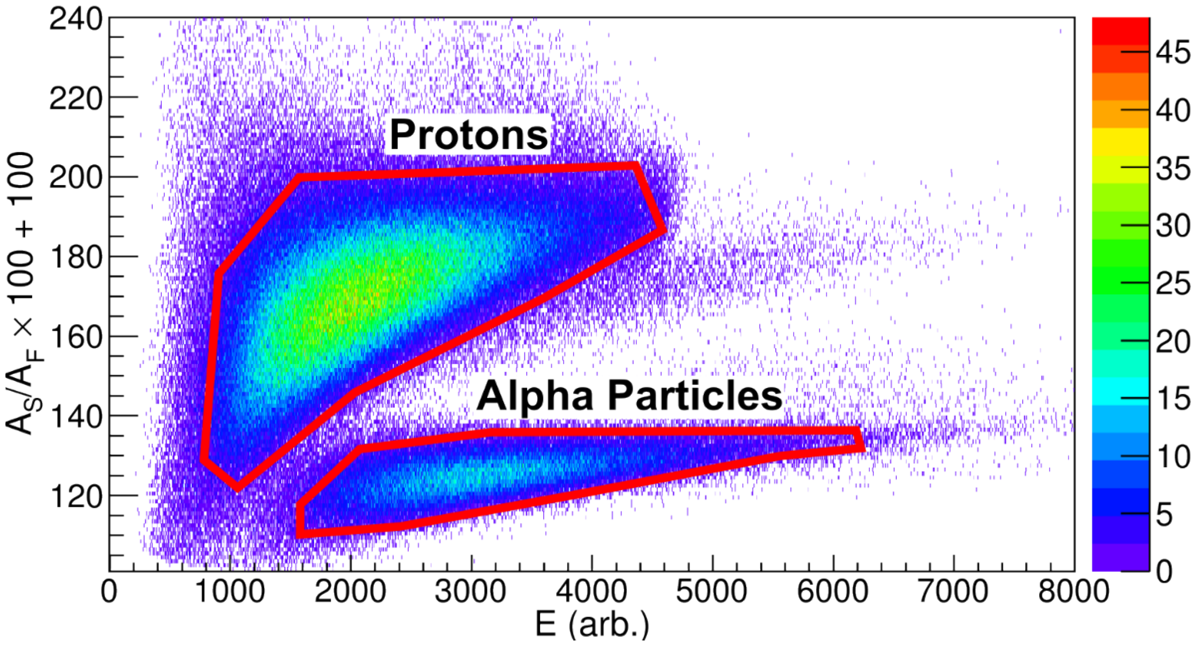


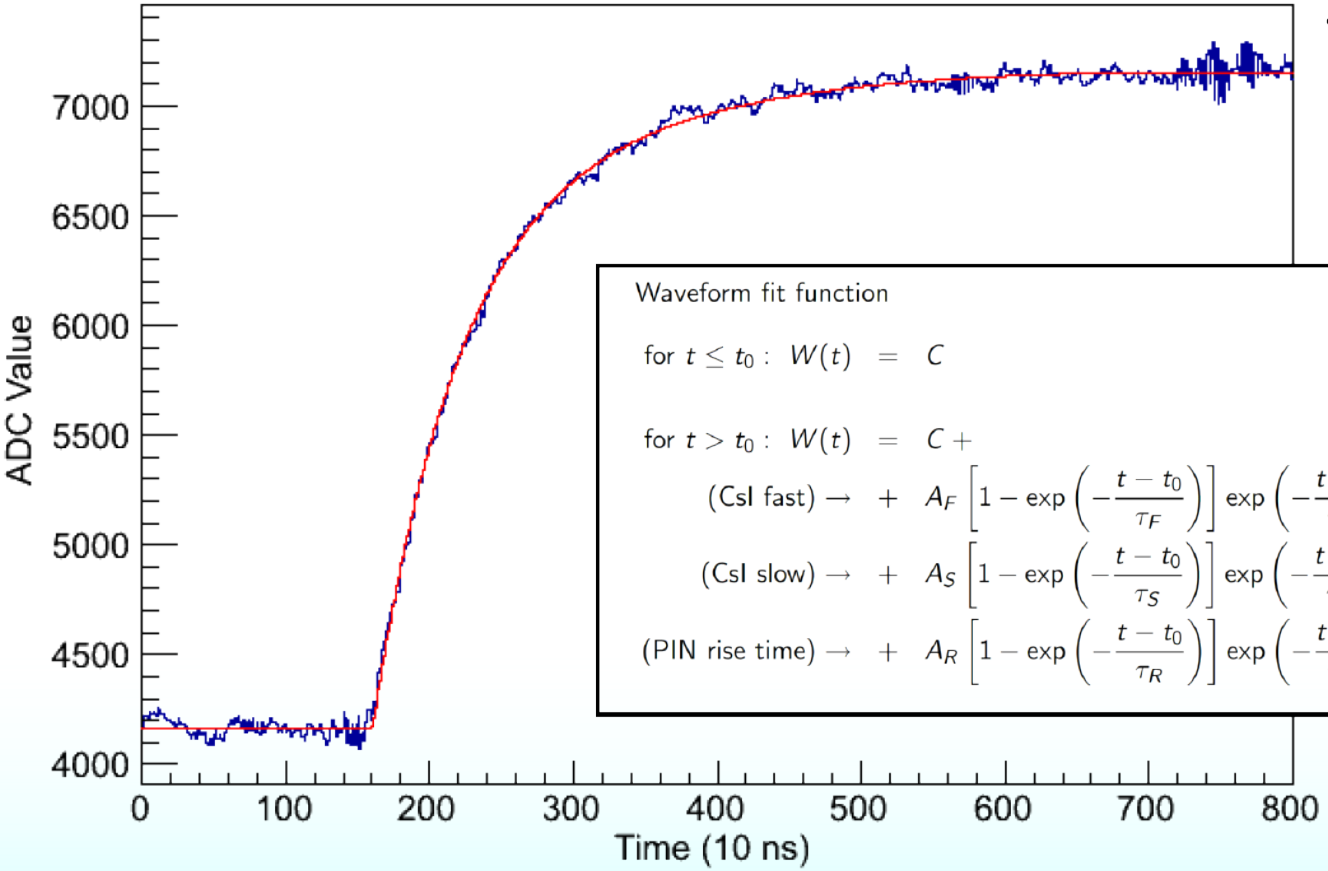


- The species of interest is produced in the target and recoils into a backing, which slows it over time.
- The distribution of Doppler shifted gamma-ray energies observed depends on the mean lifetime of the transition.



Backup – CsI Particle Identification





Waveform fit function

$$\text{for } t \le t_0: \quad W(t) = C$$

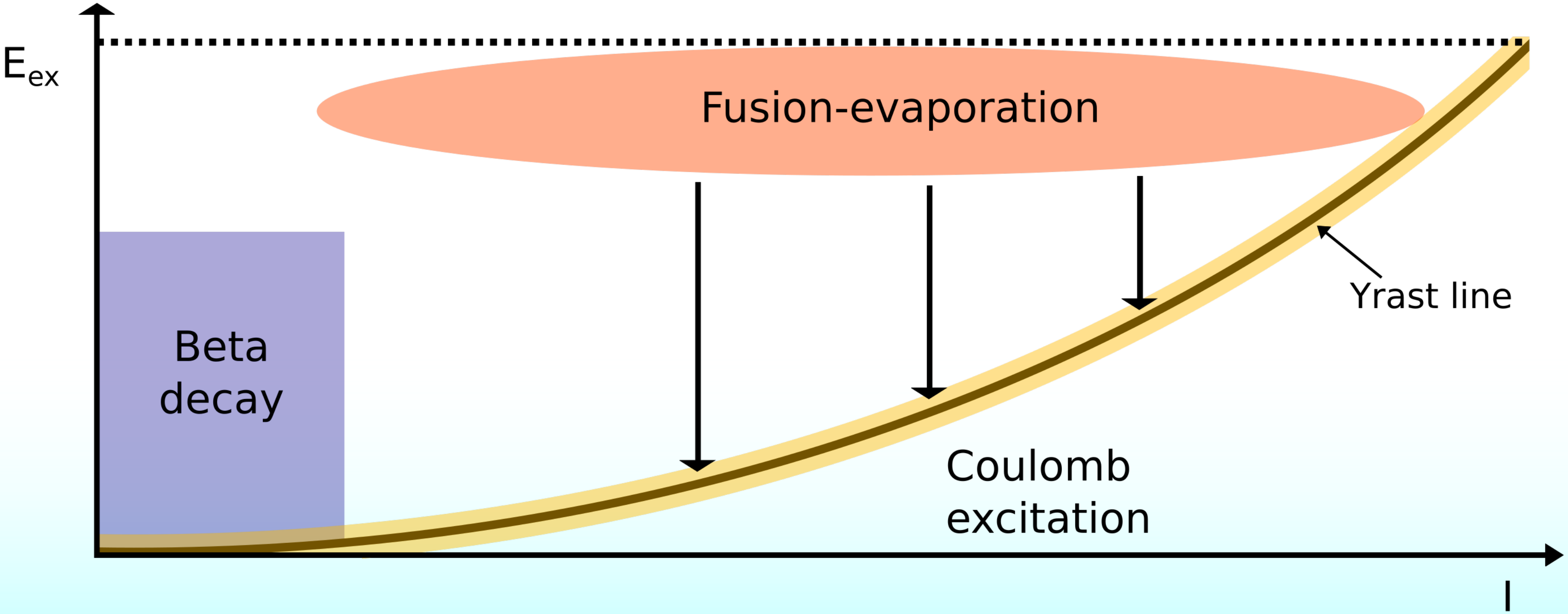
$$\begin{aligned}
\text{for } t > t_0: \quad W(t) &= C + \\
(\text{CsI fast}) \rightarrow \quad &+ A_F\left[1-\exp\left(-\frac{t-t_0}{\tau_F}\right)\right]\exp\left(-\frac{t-t_0}{\tau_{RC}}\right) + \\
(\text{CsI slow}) \rightarrow \quad &+ A_S\left[1-\exp\left(-\frac{t-t_0}{\tau_S}\right)\right]\exp\left(-\frac{t-t_0}{\tau_{RC}}\right) + \\
(\text{PIN rise time}) \rightarrow \quad &+ A_R\left[1-\exp\left(-\frac{t-t_0}{\tau_R}\right)\right]\exp\left(-\frac{t-t_0}{\tau_{RC}}\right)
\end{aligned}$$

- Particle ID from waveform fit parameters (amplitude ratio of fast and slow components).

Backup – Reaction mechanisms

Fusion-evaporation reactions give access to states in the regime where cross-shell excitations play a role.

- Complementary to existing beta decay studies in the region.
- Multiple channels can be analyzed from a single dataset.
- Identification of charged particles and/or the residual nucleus is needed to separate reaction channels.



Backup – ^{22}Ne data table

This work						Ref. [29]	
E_{level} (keV)	E_γ (keV)	$I_{\gamma,\mathrm{rel}}$	a_2	I^π	τ_{mean} (fs)	I^π	τ_{mean} (fs)
1274.59(3)	1274.55(3)	1.000(15)	0.25(3)	(2^+)	>3500[b]	2^+	5190(70)
3357.2(4)	2082.5(4)	0.747(13)	0.30(2)	(4^+)	290(50)[a]	4^+	325(6)
4455.7(10)	3180.9(10)	0.066(3)	0.16(8)	–	<14[b]	2^+	5(4)
5145.3(10)	690.4(3)	0.0161(15)	−0.31(17)	–	1170(140)	2^-	1200(300)
	3869.1(14)	0.0162(16)	−0.78(16)				
5363.4(18)	4088.4(18)	0.032(2)	0.02(9)	–	<4[b]	2^+	100(17)
5523.0(6)	2165.7(5)	0.084(2)	0.56(3)	–	20(5)[a]	$(4)^+$	30(4)
5639.9(13)	2283.5(16)	0.013(2)	−0.1(4)	–	20(8)	3^+	<4
	4364(2)	0.023(2)	−0.09(10)				
5910.3(10)	1454.9(7)	0.0040(8)	−0.1(3)	–	71(16)	3^-	46(16)
	4634.4(19)	0.024(2)	−0.50(9)				
6117.8(15)	1662.6(9)	0.0091(19)	−0.7(4)	–	24(16)	2^+	20(10)
	4839(3)	0.0111(13)	−0.09(15)				
6312.0(10)	2954.6(9)	0.206(5)	0.24(3)	(6^+)	57(6)	(6^+)	71(6)
6345.9(13)	2988.5(12)	0.044(2)	0.21(13)	–	16(5)	4^+	19(4)
6632.4(19)	2175(2)	0.0028(7)	−0.3(7)	–	<240[a]	$(3, 4)^+$	70(30)
	3276(3)	0.0055(10)	−0.3(4)				
	5362(5)	0.0083(14)	−0.31(17)				
6812.8(17)	2356.9(13)	0.0019(6)	−0.3(6)	$(2, 3, 4^+)$	160^{+130}_{-90}		
6841(7)	5566(7)	0.0050(12)	−0.2(2)	$(2, 3, 4^+)$	<380[b]	–	–
7337(2)	3979(2)	0.025(2)	0.17(10)	–	<26[b]	$(4)^+$	50(30)
7423.0(9)	1899.9(6)	0.033(2)	−0.47(19)	–	<40[b]	(5^+)	<4
7616(7)	6340(7)	0.0052(10)	−0.4(2)	$(2, 3, 4^+)$	<32[b]	–	–
7723(2)	3266.9(18)	0.0056(11)	−0.5(6)		<22[b]	3^-	
8131(7)	6855(7)	0.0071(11)	−0.6(2)	–	<31[b]	2^+	–
8460(3)	2148(3)	0.0056(12)	−0.7(16)	$(4^+, 5, 6)$	<110[b]	–	–
8566(5)	5210(6)	0.0038(8)	0.0(4)	$(2^+, 3, 4^+)$	<360[b]	–	–
	7287(9)	0.0020(7)	0.7(5)				
8743(4)	2431(4)	0.0040(10)	−0.1(3)	$(4^+, 5, 6^+)$	<40[b]	–	–
	5385(7)	0.0030(7)	−0.5(5)				
9161(5)	5803(4)	0.0069(12)	−0.02(18)	–	70(30)	–	–
9344.6(18)	1921.5(15)	0.0084(17)	0.0(4)	–	<90[b]	–	–
9493(7)	6135(7)	0.0050(10)	0.0(3)	–	<270[b]	–	–
10655(5)	*1912(7)*	<0.0037	–	(7^+)	<120[b]	–	–
	4343(5)	0.0022(7)	0.9(5)				
11029(4)	4716(3)	0.0017(9)	0.5(6)	(8^+)	<64[b]	$(6^+, 8^+)$	–

[a]Corrected for feeding from an observed transition.
[b]Limit reported to a 90% confidence level.

Backup – ^{25}Na data table

This work						Previous results (see footnotes)	
E_{level} (keV)	E_γ (keV)	$I_{\gamma,rel}$	a_2	I^π	τ_{mean} (fs)	I^π	τ_{mean} (fs)
92(3)	–	–	–	–	–	$3/2^+$[f]	$7.4(4) \times 10^{6}$[f]
1072(4)	980.4(5)	0.170(14)	−0.7(3)	–	>800[b]	$1/2^+$[f]	1900(200)[f]
2204(4)	1131.8(4)	0.069(12)	−0.1(3)	–	26(11)	$3/2^+$[f]	36(6)[f]
2419.8(11)	2419.6(11)	1.00(3)	0.30(3)	$(9/2^+)$	230(40)[a]	$9/2^+$[e]	240(40)[c]
2791.0(12)	2699(3)	0.018(4)	0.9(3)	–	150(20)[a]	$7/2^+$[e]	190(35)[c] / 250(50)[d]
	2790.8(13)	0.192(15)	0.39(14)	–			
3355(3)	3355(3)	0.045(16)	−0.2(3)	–	<49[b]	$(7/2)^+$[c]	23(7)[f]
3460.9(9)	669.1(7)	0.022(3)	−0.4(2)	$(9/2^+)$	190(30)[a]	$9/2^+$[e]	210(25)[f] / 130(40)[c]
	1041.3(4)	0.427(11)	0.12(3)				
	3462(3)	0.032(11)	−0.1(7)				
3963(4)	2891(3)	0.026(9)	0.0(5)	$(1/2, 3/2, 5/2^+)$	<250[b]	$(1/2^+, 3/2, 5/2^+)$[f]	< 140[f]
3999.6(11)	1209.0(4)	0.135(10)	−0.31(9)	–	90(7)	$9/2^+$[e]	100(20)[c]
	1579.1(13)	0.028(4)	0.0(3)				
4005(5)	2933(3)	0.026(9)	−0.8(6)	(1/2, 3/2)	90(50)	–	45(10)[f]
4294(5)	3222(3)	0.030(10)	−0.4(7)	–	<29[b]	$1/2^+$[f]	–
4967.3(8)	967.3(9)	0.011(3)	−0.2(5)	–	72(6)[a]	$(11/2)^+$[c]	
	1506.2(6)	0.244(10)	−0.70(8)				80(20)[c]
	2548.0(12)	0.140(9)	−0.03(13)				120(30)[c]
5231(2)	1875.0(12)	0.04(2)	0.3(2)	(7/2, 9/2)	<15[b]	–	–
	2441(3)	0.009(3)	−0.9(9)				
5388.4(18)	2968.4(15)	0.170(10)	−0.15(13)	$(11/2^+)$	<4[b]	$(9/2, 11/2)^+$[c]	–
5749(4)	3329(4)	0.016(3)	0.1(4)	(9/2, 11/2, 13/2)	<280[b]	–	–
5848(3)	3058(3)	0.014(3)	0.9(5)	–	<75[b]	$7/2^+$[e]	–
	3427(4)	0.017(3)	0.1(4)				
6271(5)	3480(4)	0.010(2)	−0.3(7)	(9/2, 11/2)	<37[b]	–	–
	3851(5)	<0.004	–				
6381(3)	2924(5)	0.018(5)	−0.6(8)	(9/2, 11/2, 13/2)	<9[b]	–	–
	3958(4)	0.037(4)	−0.1(2)				
6581(2)	3120(4)	0.020(4)	−0.2(7)	–	<40[b]	$(11/2^-)$[e]	–
	4163(4)	0.027(3)	−0.1(3)				
6736.6(19)	1348.9(13)	0.021(5)	0.3(3)	$(13/2^+)$	<4[b]	–	–
	1770.7(16)	0.064(8)	−0.3(2)				
	3275(6)	0.012(4)	−0.1(10)				
	4313(3)	0.053(4)	0.3(2)				
6854(2)	1467.9(10)	0.026(4)	−0.6(3)	$(13/2^+)$	60(40)	$(11/2, 13/2)^+$[c]	–
	3395(5)	0.015(4)	−0.7(7)				
	4436(3)	0.031(3)	0.5(4)				
7218(4)	3218(4)	0.012(3)	0.6(4)	(9/2, 11/2, 13/2)	<140[b]	–	–
	4796(9)	0.006(2)	−1.4(13)				
7626(4)	2658(4)	0.027(5)	−0.6(4)	(11/2, 13/2)	<75[b]	–	–

[a]Corrected for feeding from an observed transition.
[b]Limit reported to a 90% confidence level.
[c]Previous result from Ref. [8].
[d][26].
[e][27].
[f][28].

Backup – ^{28}Mg data table

This work					Ref. [19]	
Level energy (keV)	Gamma rays (keV)	$I_{\gamma,\mathrm{rel}}$	I^{π}	τ_{mean} (fs)	I^{π}_{eval}	$\tau_{\mathrm{mean,eval}}$ (fs)
1473.63(9)	1473.59(9)	1.000(15)		$>1.5 \times 10^3$ [a]	2^+	$1.73(14) \times 10^3$
4021.4(3)	2547.6(3)	0.65(2)	4^+	$1.8(3) \times 10^2$	4^+	$1.5(5) \times 10^2$
4556.3(12)	3082.5(12)	0.119(16)		<42[a]	2^+	<43
4879(2)	3405(2)	0.023(7)		<26[a]	2^+	$<1.2 \times 10^2$
5172.9(7)	3698(3), 1151.5(6)	0.08(2), 0.031(10)		$2.6^{+1.6}_{-1.3} \times 10^2$	3^-	$1.6(13) \times 10^2$
5184.3(5)	1163.1(4)	0.120(9)	(4^+)	21^{+15}_{-14}		
5475(3)	4001(3)	0.018(8)		$<5.0 \times 10^2$ [a]	2	
5672(3)	4198(3)	0.048(10)		$1.1(4) \times 10^2$	2^+	
6139.0(12)	4664.9(12)	0.032(9)	$(0, 4)^-$	$>1.0 \times 10^3$ [a], $<2.5 \times 10^5$ [b]		
6528.2(9)	1356.3(12), 2506.7(8)	0.021(5), 0.115(12)	$(4, 5)^-$	$1.9(6) \times 10^2$		
7203(3)	3181(3), 5723(5)	0.033(10), 0.009(4)	$(2^+, 3, 4^+)$	$<3.8 \times 10^2$ [a]		
7747(2)	3726(2)	0.033(8)	(5)	<85[a]		
7929.3(12)	3907.6(12)	0.060(11)	(6^+)	<42[a]		
8438(5)	4416(5)	0.024(10)	(5,6)	$<1.5 \times 10^3$ [b]	(6^+)	

[a]Limit reported to a 90% confidence level.
[b]Limit estimated based on lineshape (see text).