# First Identification of Resonant States in the $^{45}V(p,\gamma)^{46}Cr$ Reaction and Their Influence on the Production of $^{44}Ti$ in Core-collapse Supernovae

Chris Cousins

DREB 2026

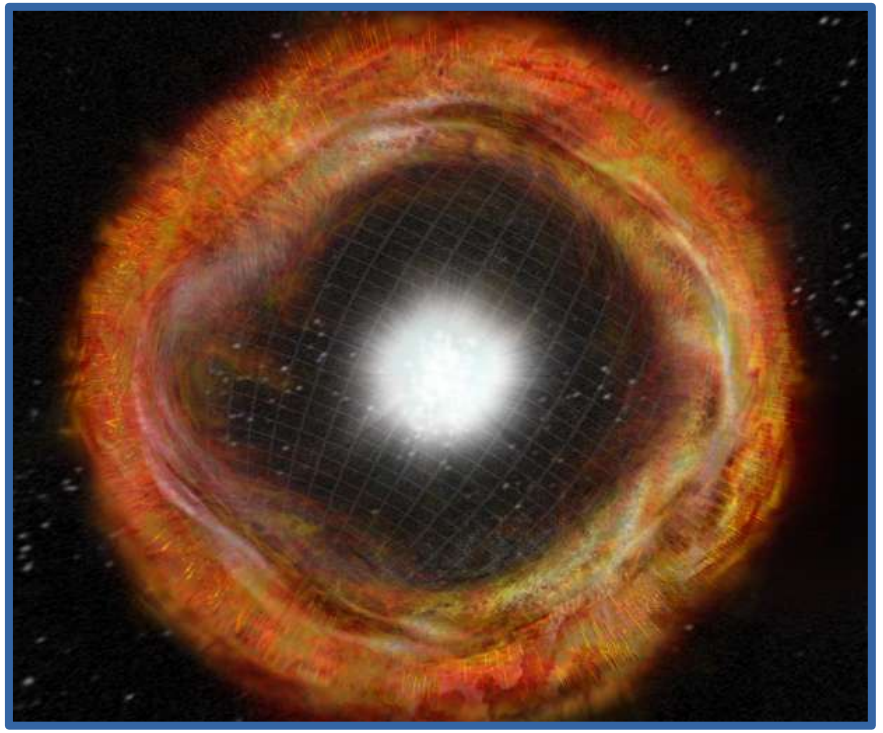
UNIVERSITY OF SURREY

# Talk Outline

- A – Why is the $^{45}V(p,\gamma)^{46}Cr$ astrophysical reaction important in CCSNe?
- B – Experiment: Identification of resonant states in the $^{45}V(p,\gamma)^{46}Cr$ via fusion-evaporation
- C – How can direct reactions further constrain astrophysical radiative proton-capture reaction rates?

# Motivation and Astrophysical Background

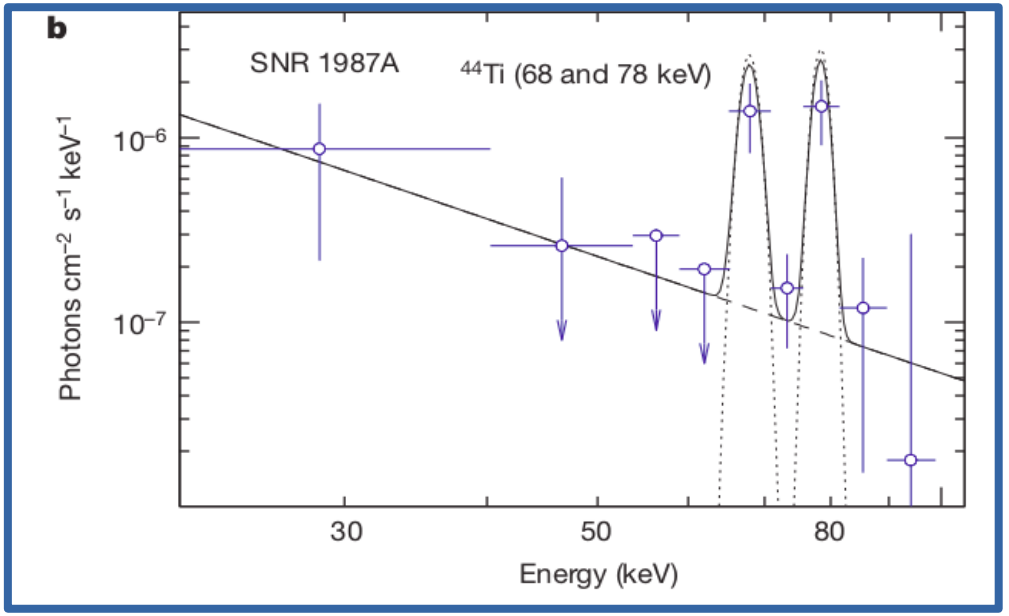
- Core-collapse supernovae (CCSNe) mechanism:
  - $M \gtrsim 8M_{\odot}$ progenitor
  - Core → Chandrasekhar mass ($1.44\ M_{\odot}$)
  - Rapid core collapse → bounce
  - Shock formation and stagnation
- After this point, **uncertainty in explosion mechanism** of CCSNe – neutrino burst from core?



Bill Saxton (NRAO/AUI/NSF)

# Motivation and Astrophysical Background

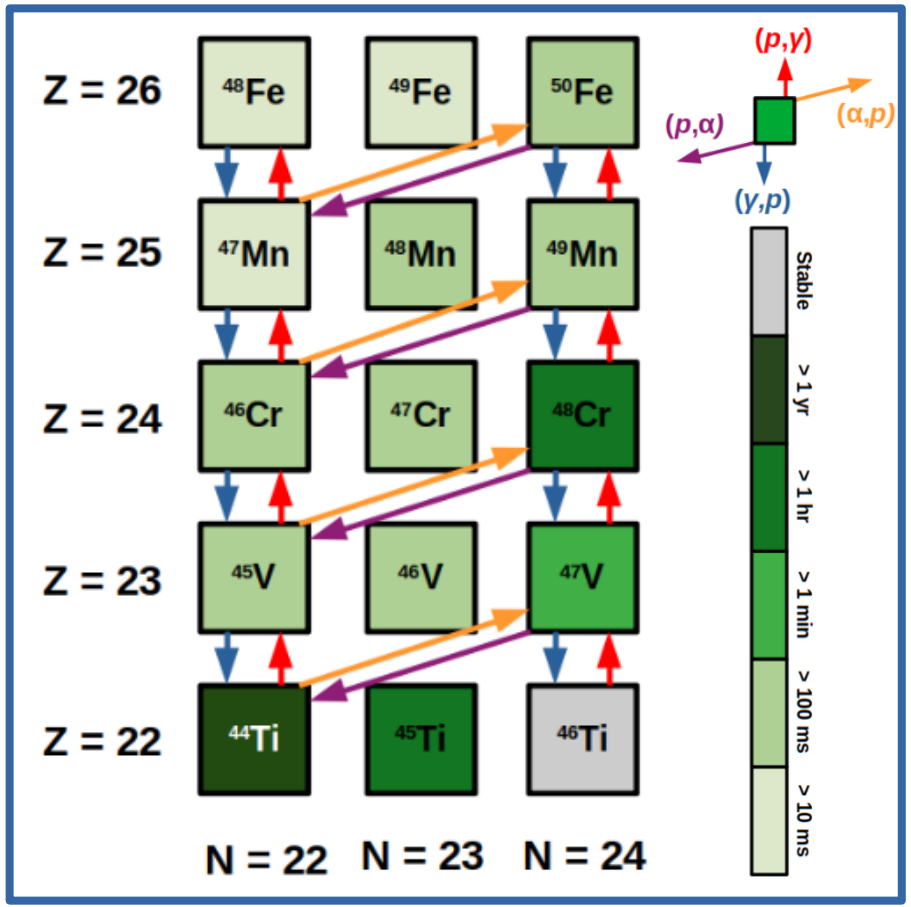
- New insight – observing **$^{44}$Ti cosmic *y* rays** ($t_{1/2} \approx 60$ yr) – INTEGRAL
- $^{44}$Ti synthesised in same region as **mass cut point**
- $^{44}$Ti abundances → mass cut location
- Road block! – **uncertainty** in nuclear reactions that **destroy $^{44}$Ti** – most notably **$^{45}$V(*p*,*y*)$^{46}$Cr**




S.A. Grebenev et al., Nature **490**, 373 (2012).

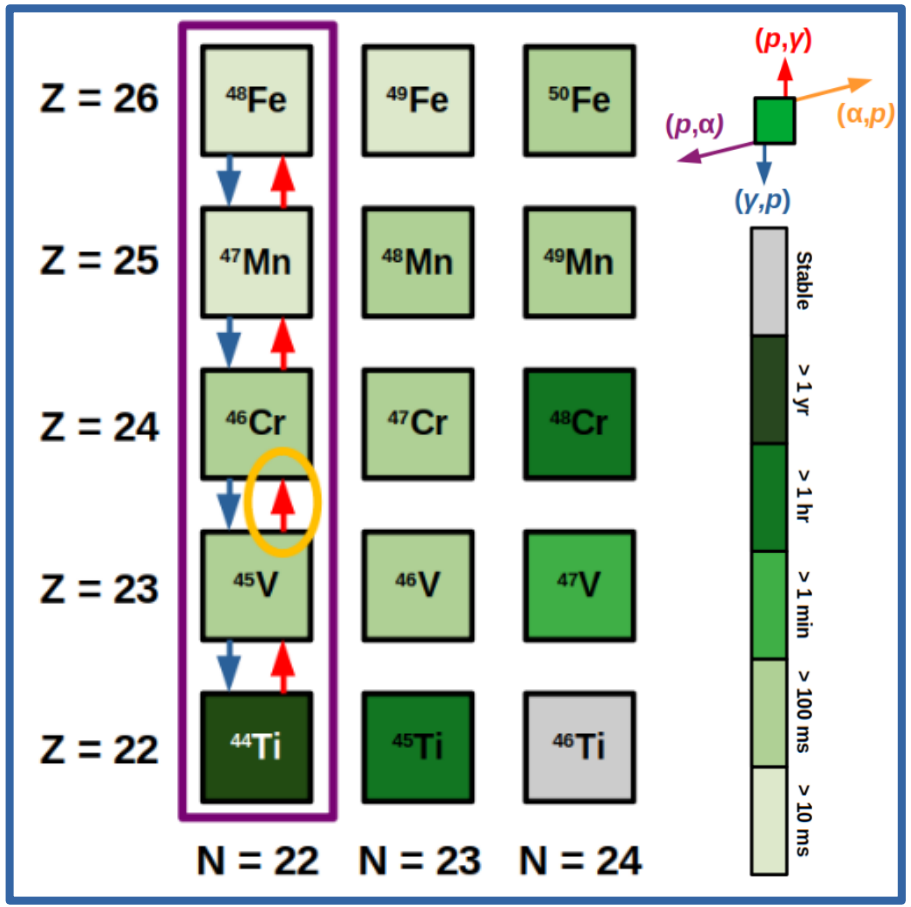
# Importance of $^{45}V(p,\gamma)^{46}Cr$ for $^{44}Ti$ Destruction – α-rich Freeze Out

- **Shock wave** breaks nuclei → Temp ↓, nuclei begin forming again → NSE/QSE formation
- **Alpha captures** on *N*=22 isotone nuclei **break down**, separating it from the equilibrium



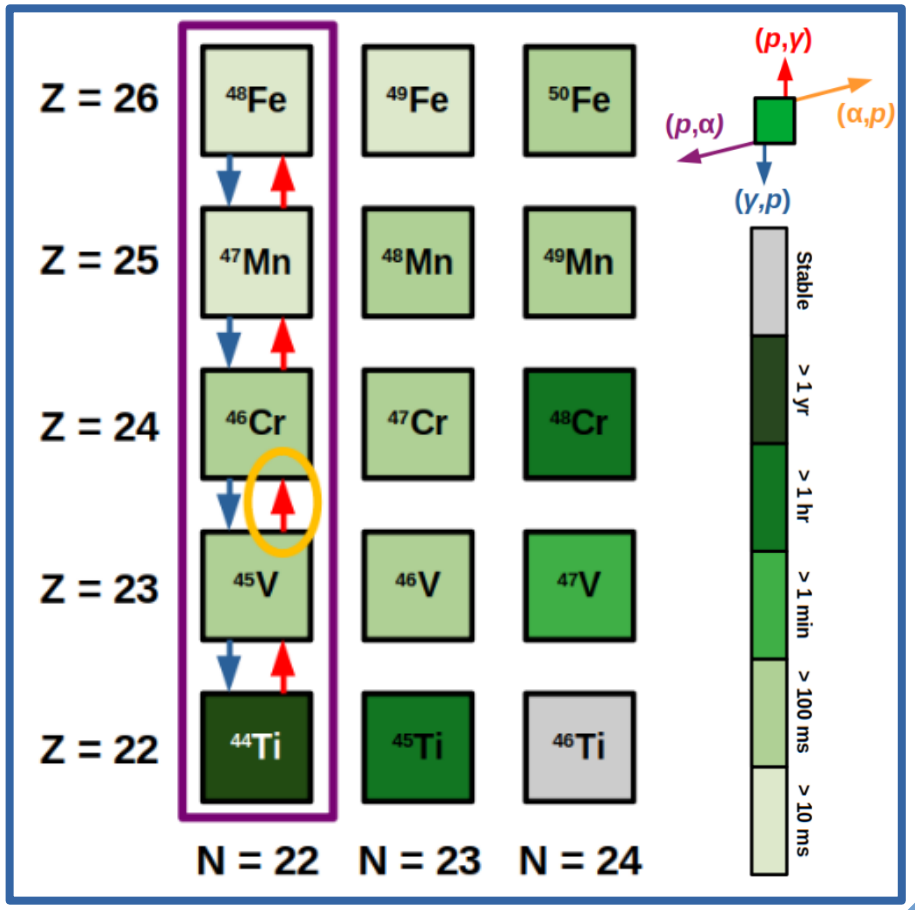
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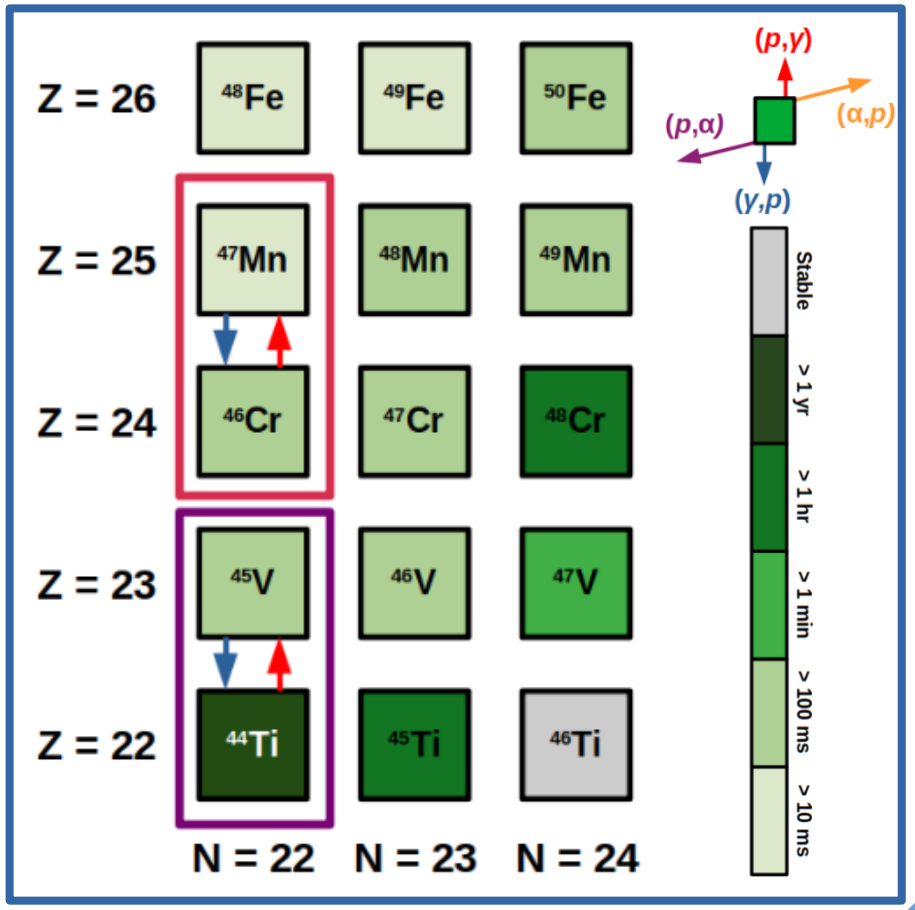
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- **$^{45}V(p,\gamma)^{46}Cr$** importance identified in **sensitivity studies** [1] – high Q value




[1] G. Magkotsios et al., Astrophys. J. Suppl. Ser. **191, p. 66** (2010).

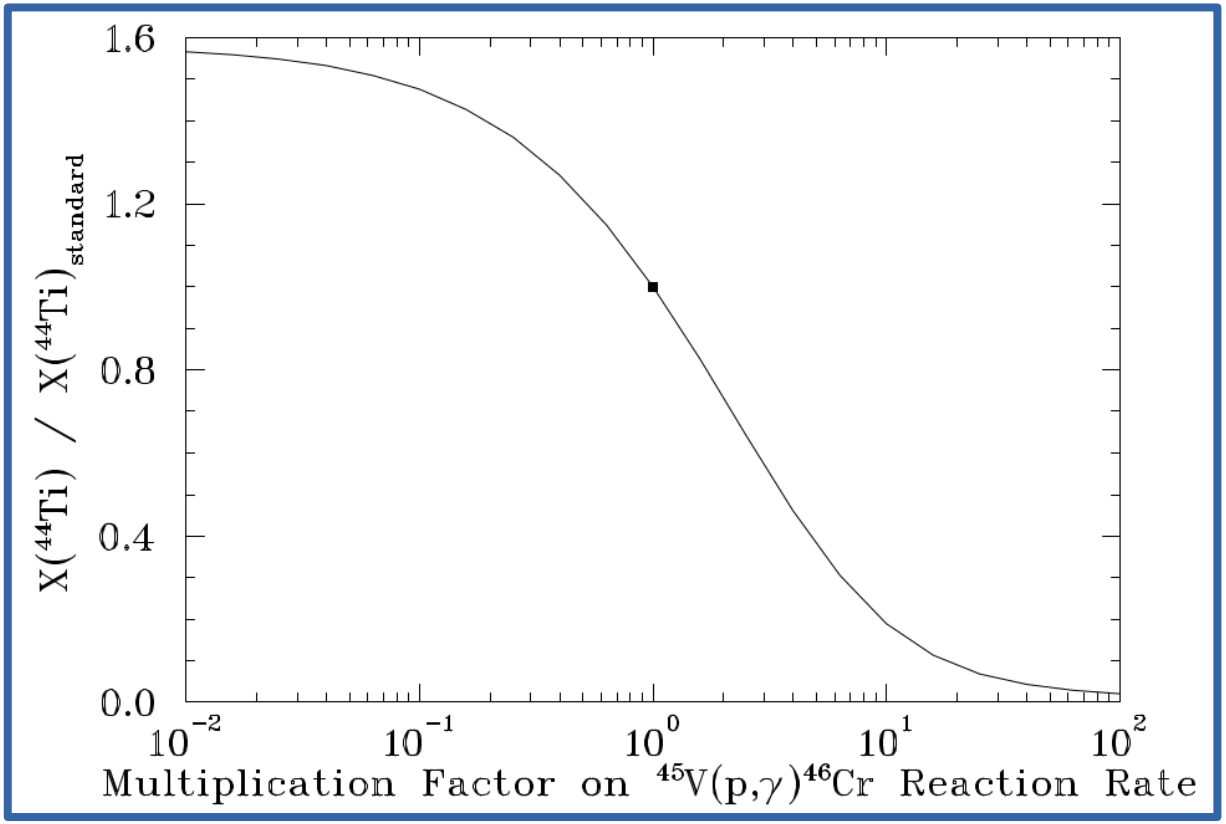
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- **$^{45}V(p,\gamma)^{46}Cr$** importance identified in **sensitivity studies** [1] – high Q value
- $^{44}Ti$ and $^{45}V$ **cut off** from the rest of *N*=22 isotone chain – yield determined at **freeze out**




[1] G. Magkotsios et al., Astrophys. J. Suppl. Ser. **191, p. 66** (2010).

# Importance of $^{45}V(p,\gamma)^{46}Cr$ for $^{44}Ti$ Destruction – α-rich Freeze Out




L.-S. The et al., Astrophys. J **504**, 500 (1998).

# Finding the Reaction Rate

- Reaction governed by **low-spin resonant states** above proton separation energy ($S_p$ = 4874(11) keV)
- ***γ*-ray spectroscopy of $^{46}$Cr** – identifying proton-unbound resonant states
- Use resonant **energies**, **spins, and spectroscopic factors** to constrain the reaction rate

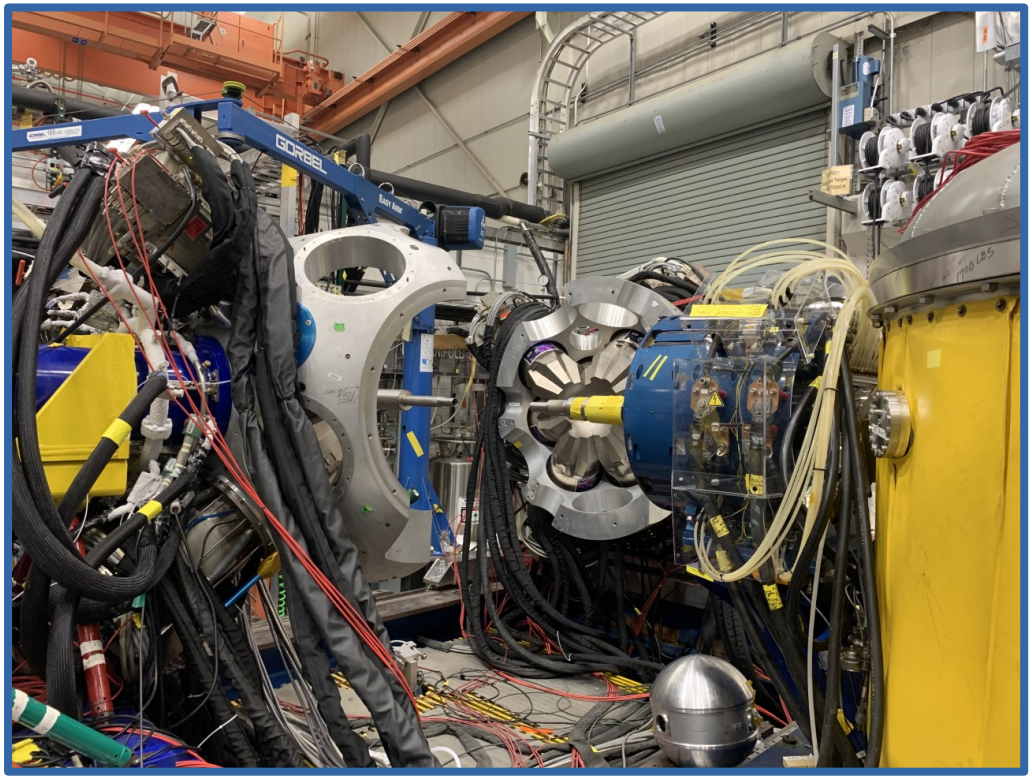
$$N_A < \sigma\nu > = \frac{1.5399 \times 10^{11}}{(\mu T_9)^{3/2}} \sum_i (\omega\gamma)_i \, e^{-11.605 E_{R,i}/T_9}$$

$$(\omega\gamma)_i = \left( \frac{2J_R + 1}{(2j_0 + 1)(2j_1 + 1)} \right) \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma}$$

$$\Gamma_p = \frac{2\hbar^2}{\mu a^2} P_l C^2 S \, \theta_{sp}^2$$

# Experimental Set-Up

- GRETINA+FMA, ATLAS facility, Argonne National Lab, March 2021
  - 120 MeV $^{36}$Ar beam
  - ~200 μg.cm$^{-2}$ thick $^{12}$C target
  - Produces $^{46}$Cr in excited states via fusion-evaporation



# Fusion-Evaporation Channels

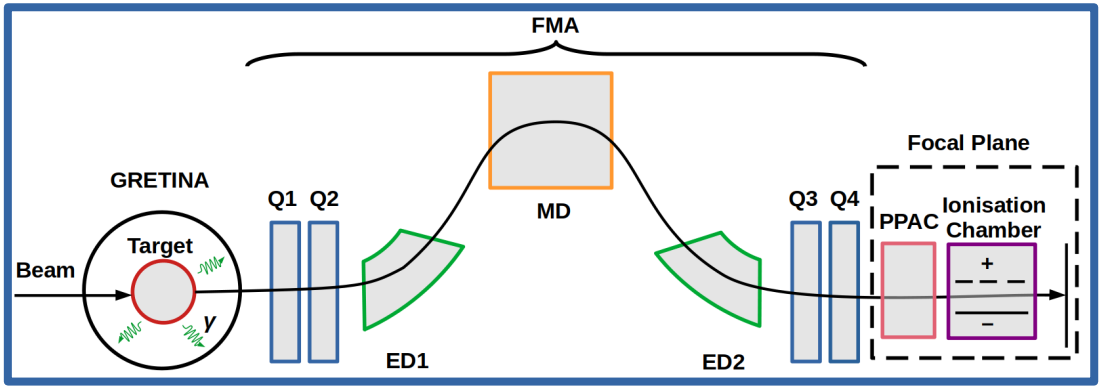
- Can't measure directly – **$^{45}$V $t_{1/2}$ ~ 500 ms**
- Fusion-evaporation reaction – **$^{12}$C($^{36}$Ar,2*n*)$^{46}$Cr**
- Other channels dominate this reaction – *p*-rich side of stability
- **Contamination** from oxygen on target – significant production of $^{49}$Cr

| Channel | Mode | Yield (%) |
|---|---|---|
| $^{46}$Ti | *2p* | 28.6 |
| $^{46}$V | *pn* | 18.5 |
| $^{45}$Ti | *2pn* | 16.9 |
| $^{43}$Sc | *αp* | 16.4 |
| $^{40}$Ca | *2α* | 9.02 |
| ⋮ | ⋮ | ⋮ |
| **$^{46}$Cr** | ***2n*** | **0.025** |

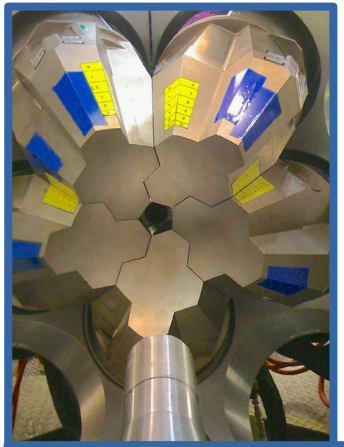
Calculations provided by PACE4

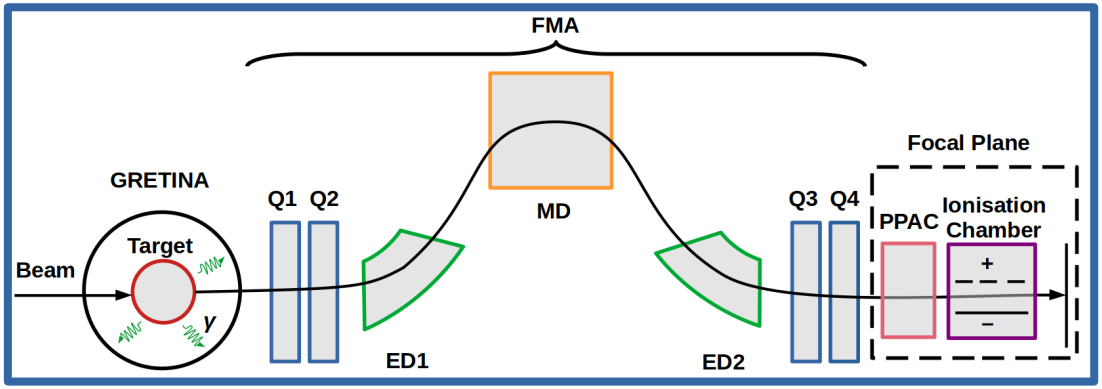
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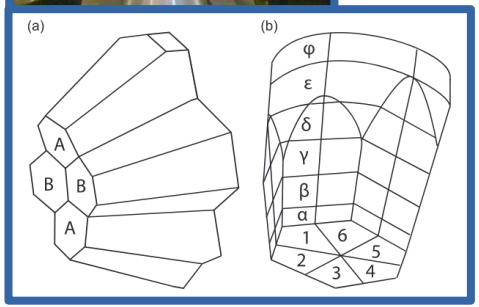
# GRETINA + FMA



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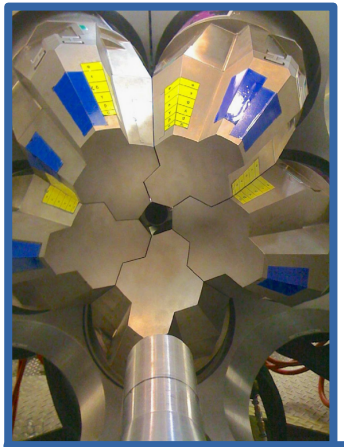


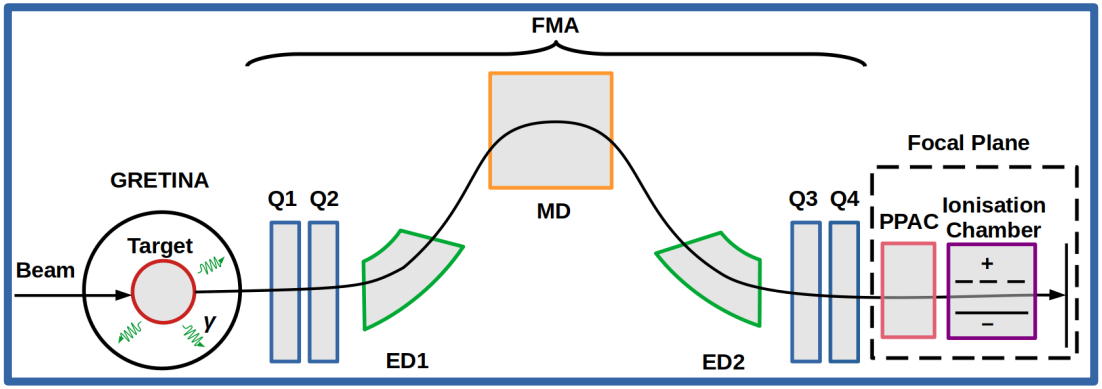



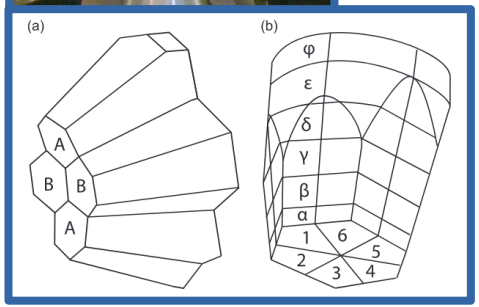

- **Tracking** → Improved Eff.

S. Paschalis et al., Nucl. Inst. Meth. Phys. Res. A **709**, 44 (2013).

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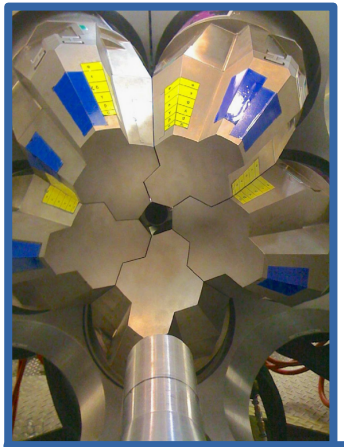


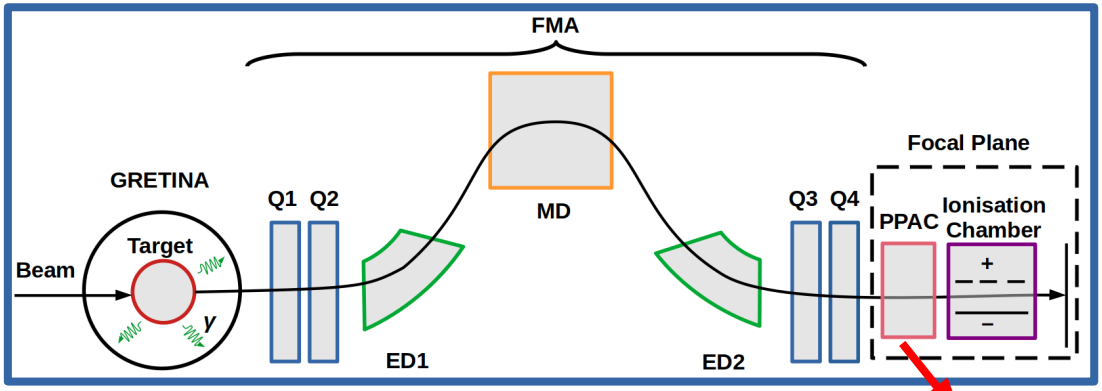



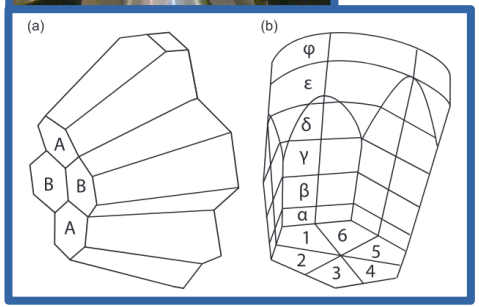

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- **Tracking** → Improved Eff.
- Separates recoils by **mass/charge** (*A/Q*) at the focal plane
  - Electric and magnetic dipoles
  - Magnetic quadrupoles

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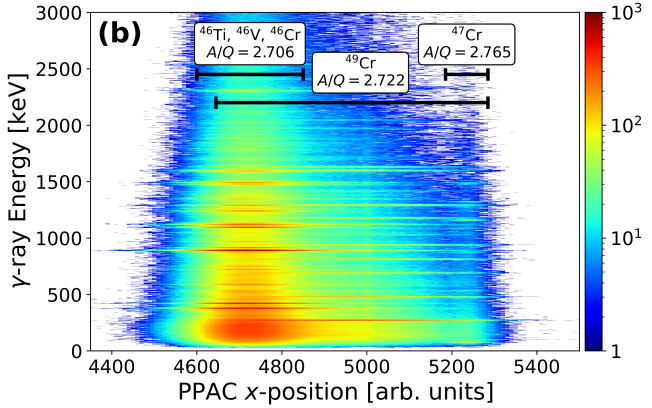




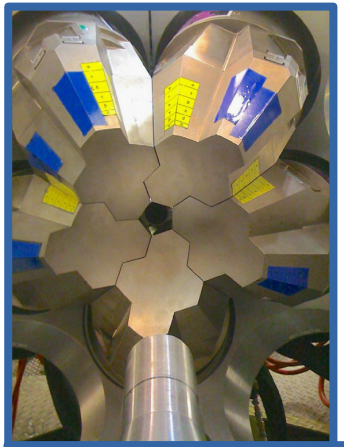



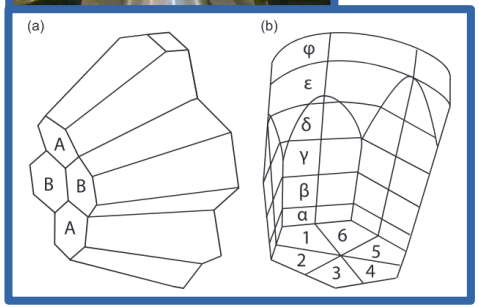

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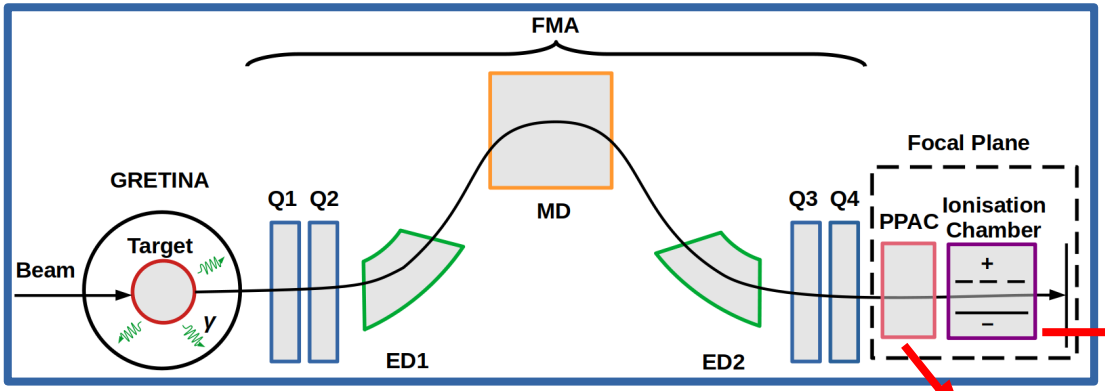


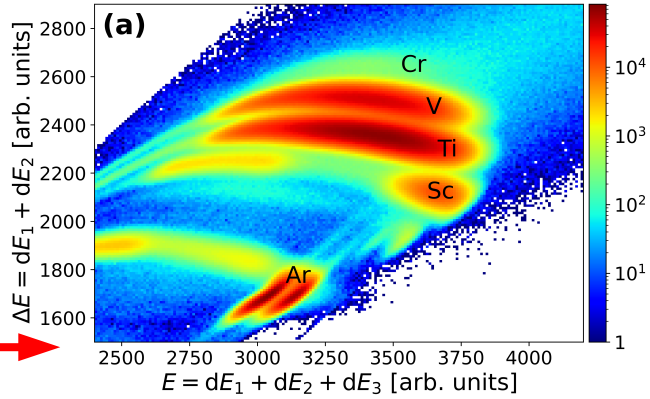
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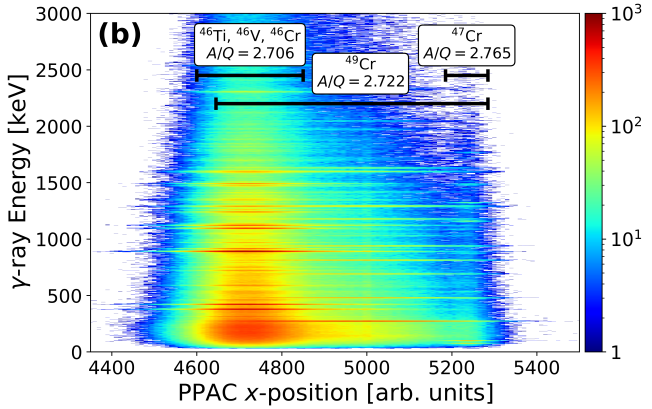





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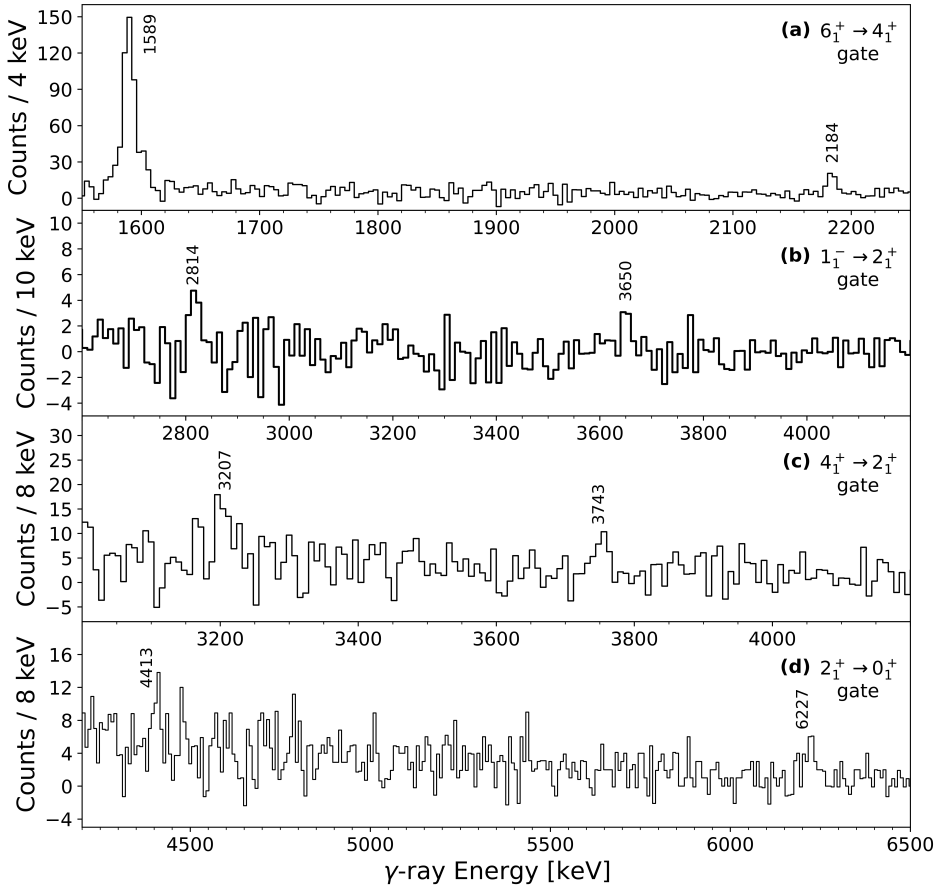




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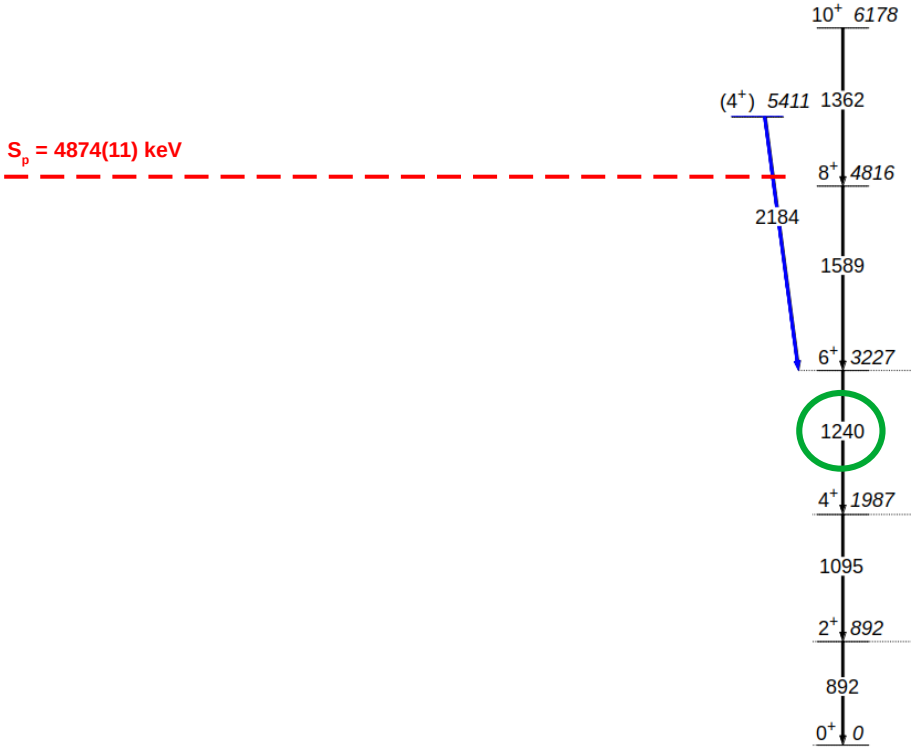
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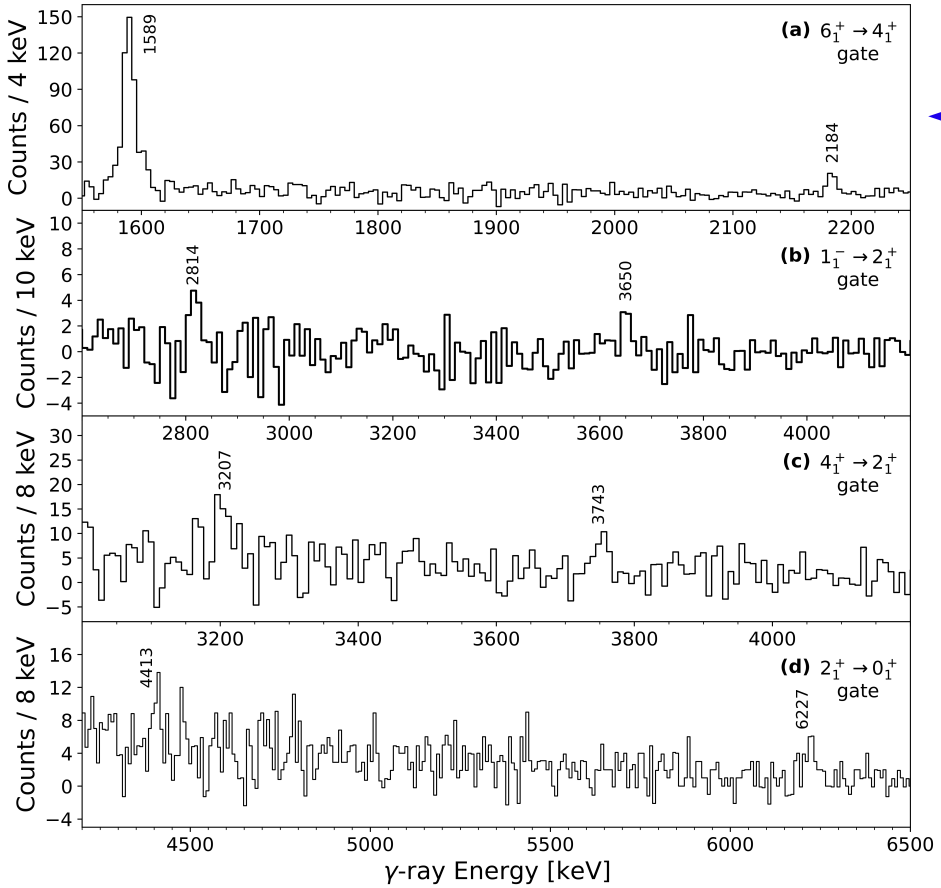
# Results – Resonant States



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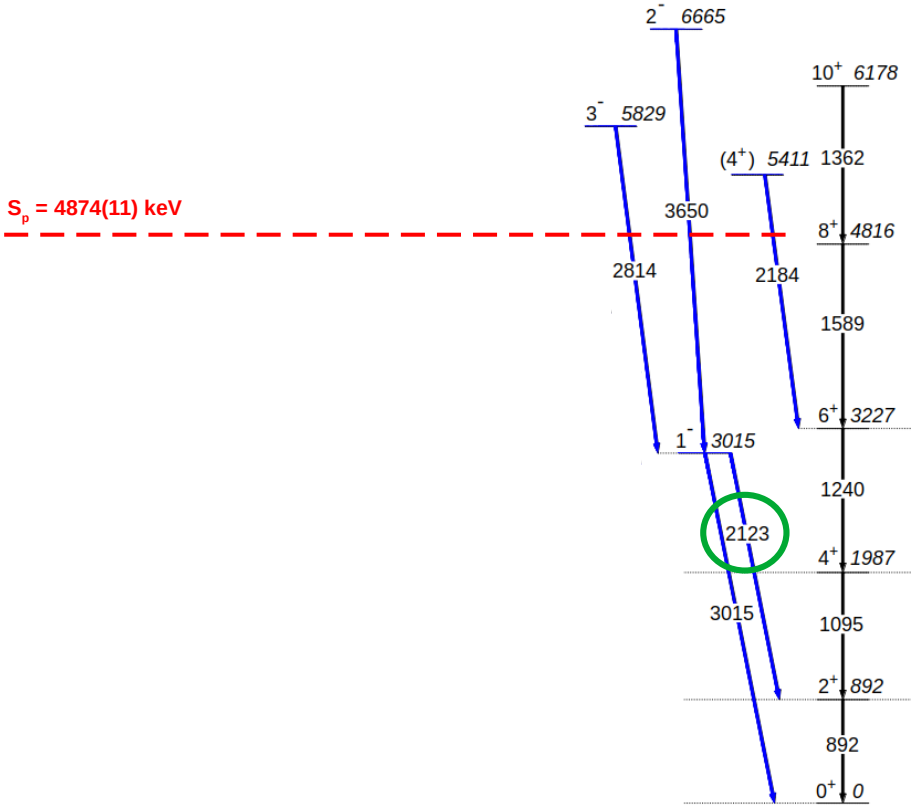
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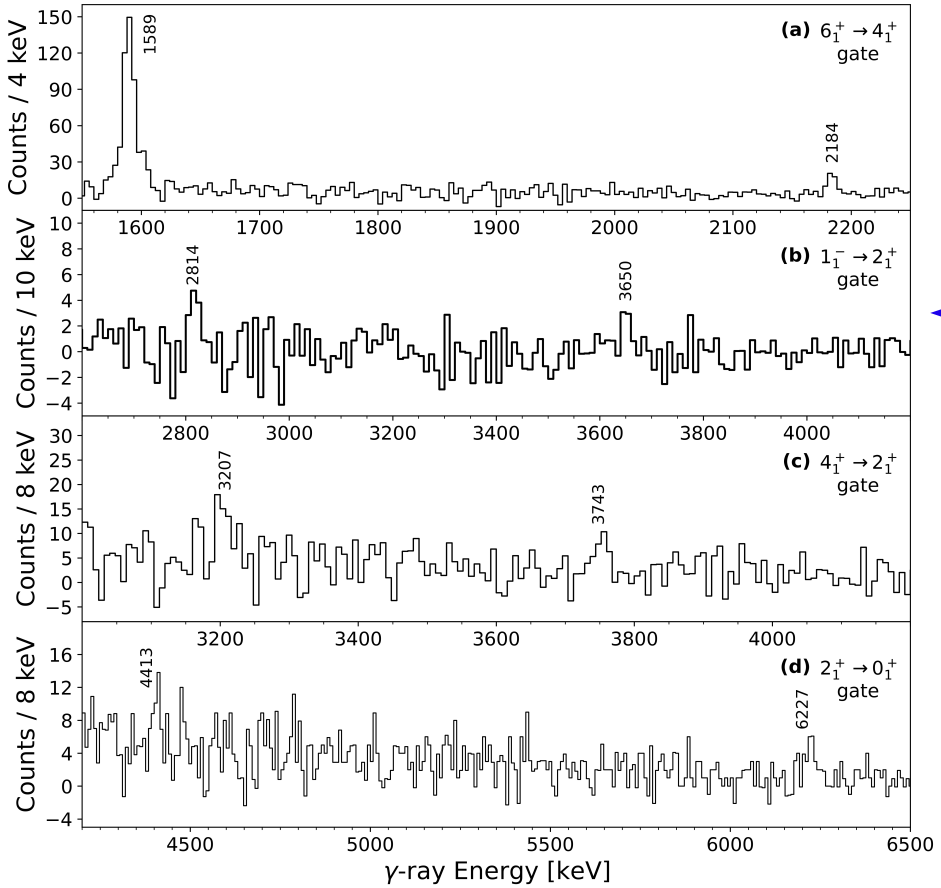


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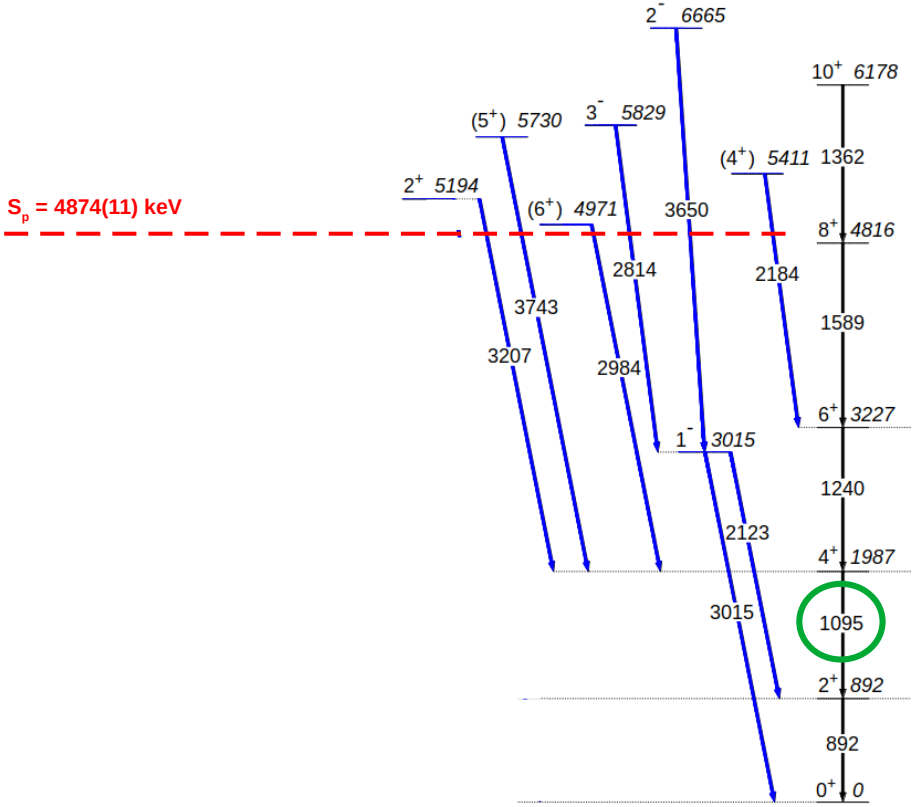
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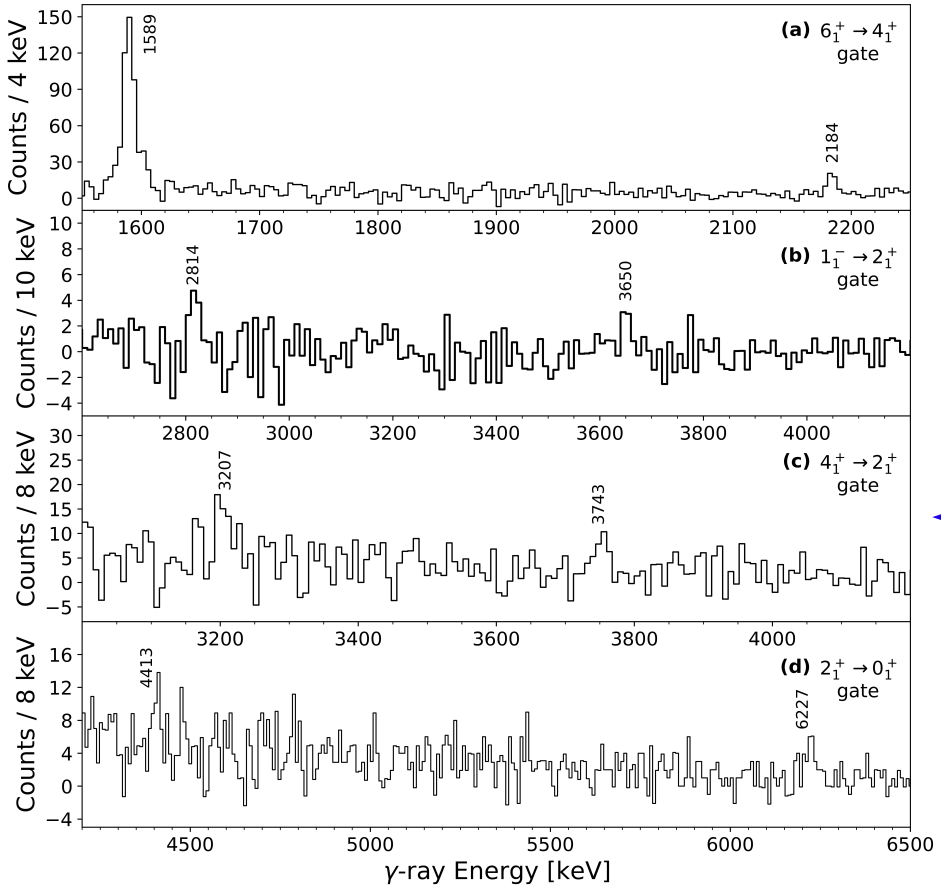


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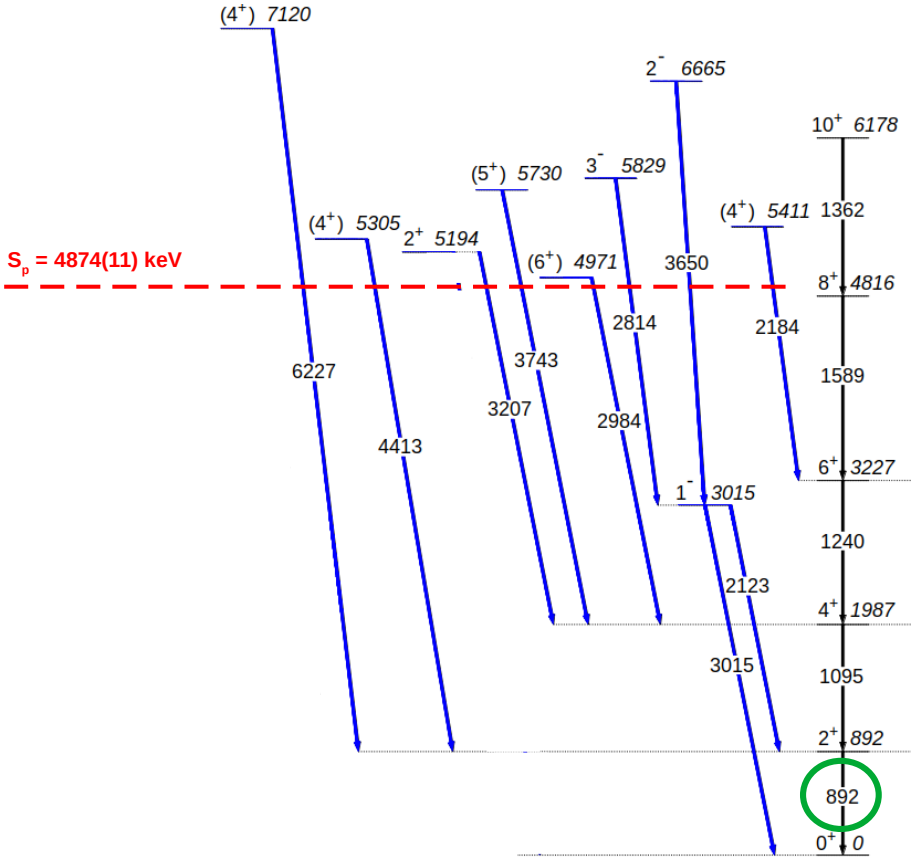
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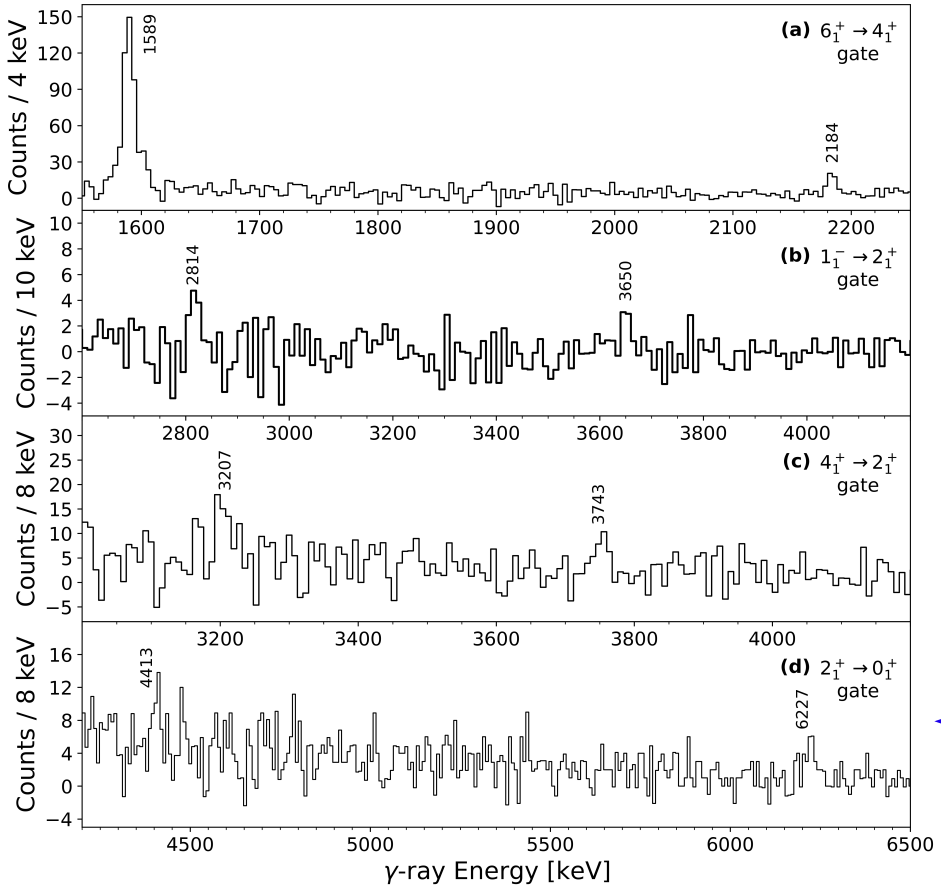


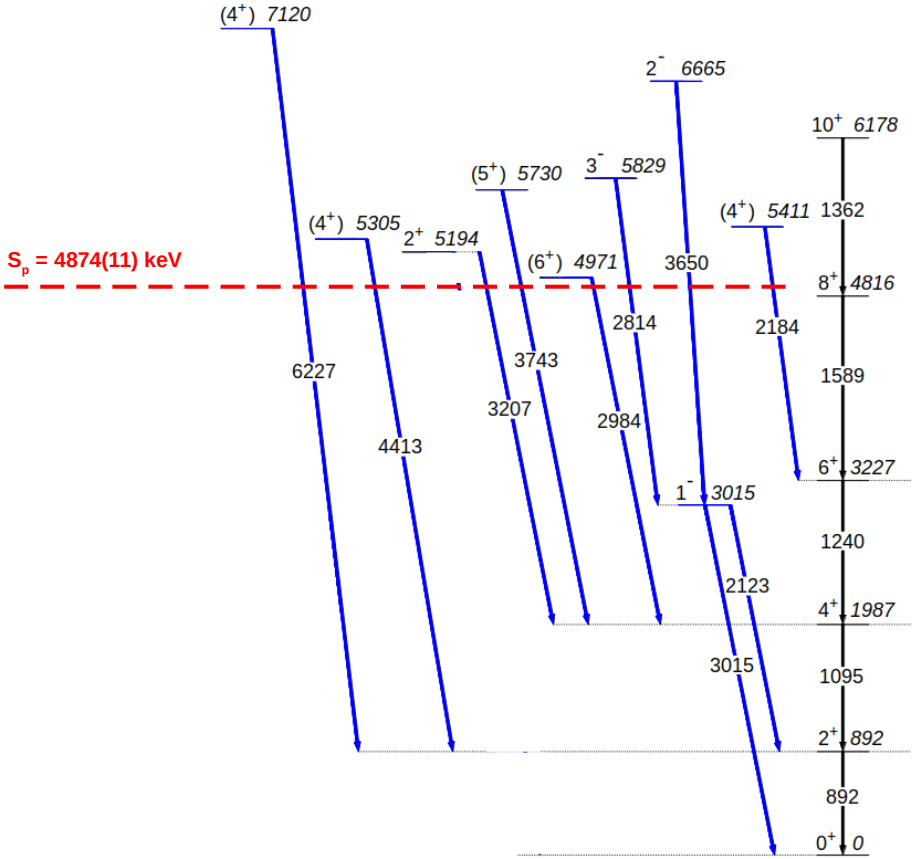
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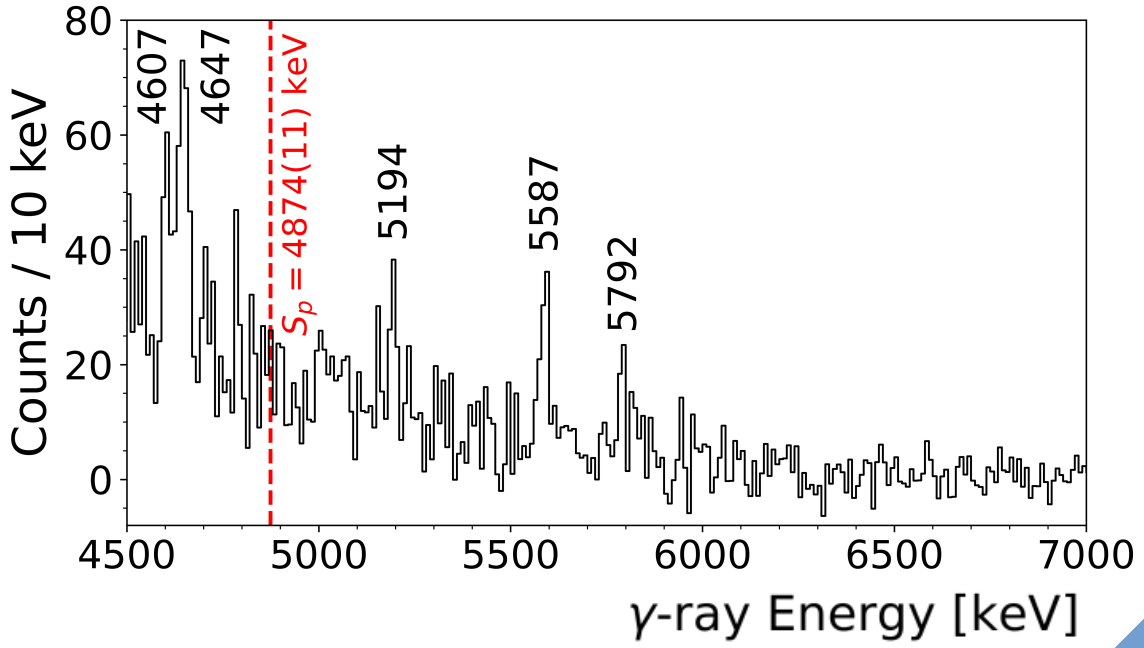
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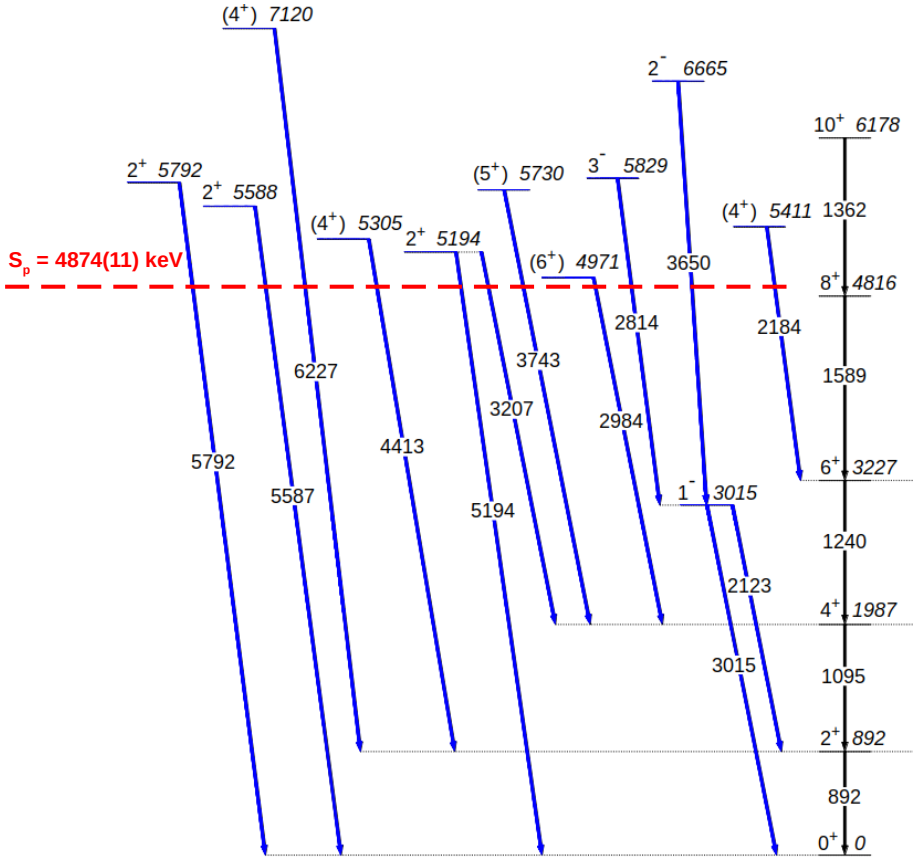



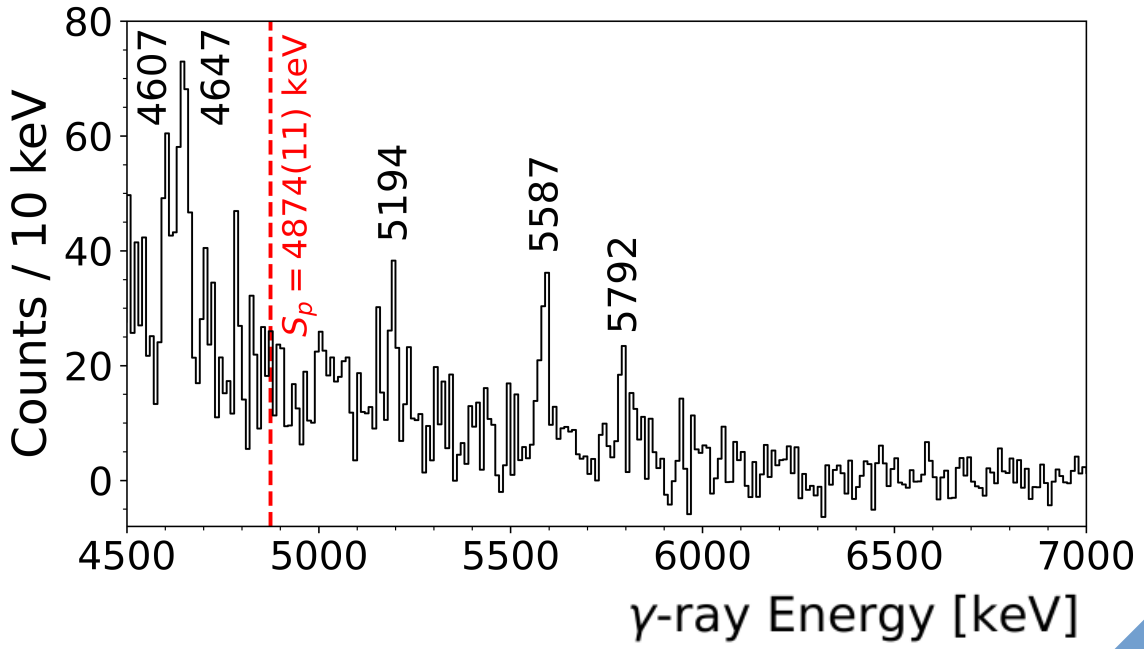
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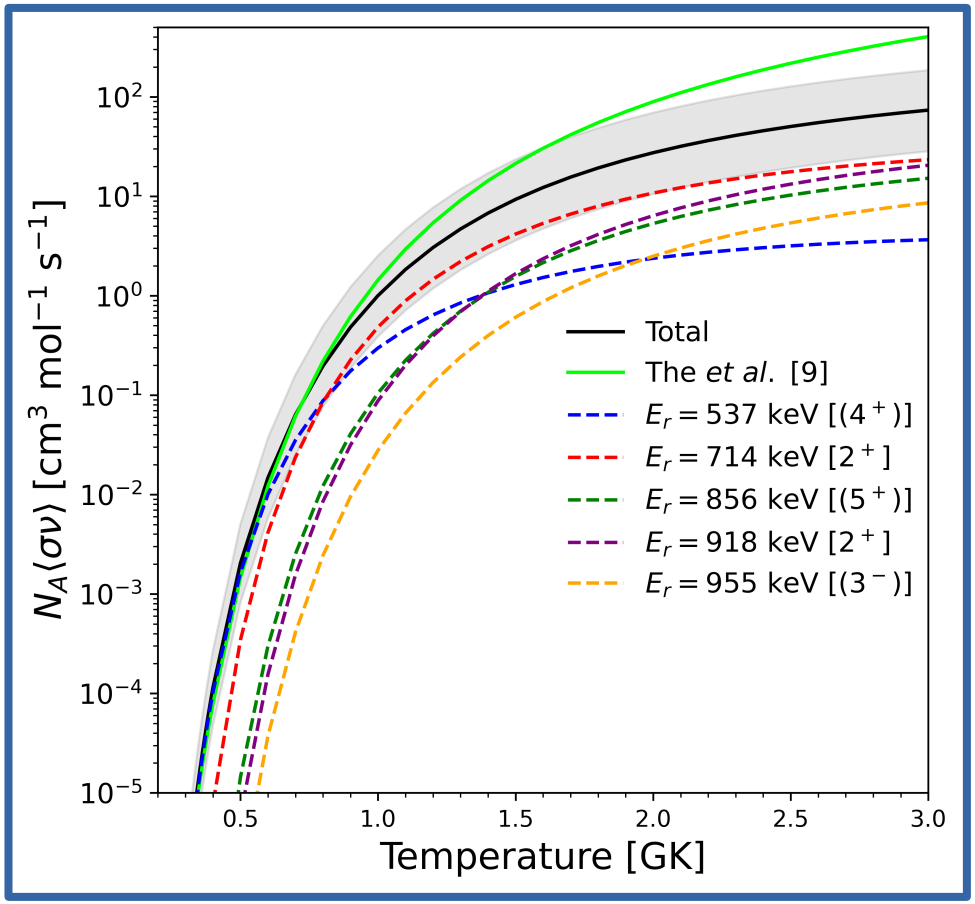



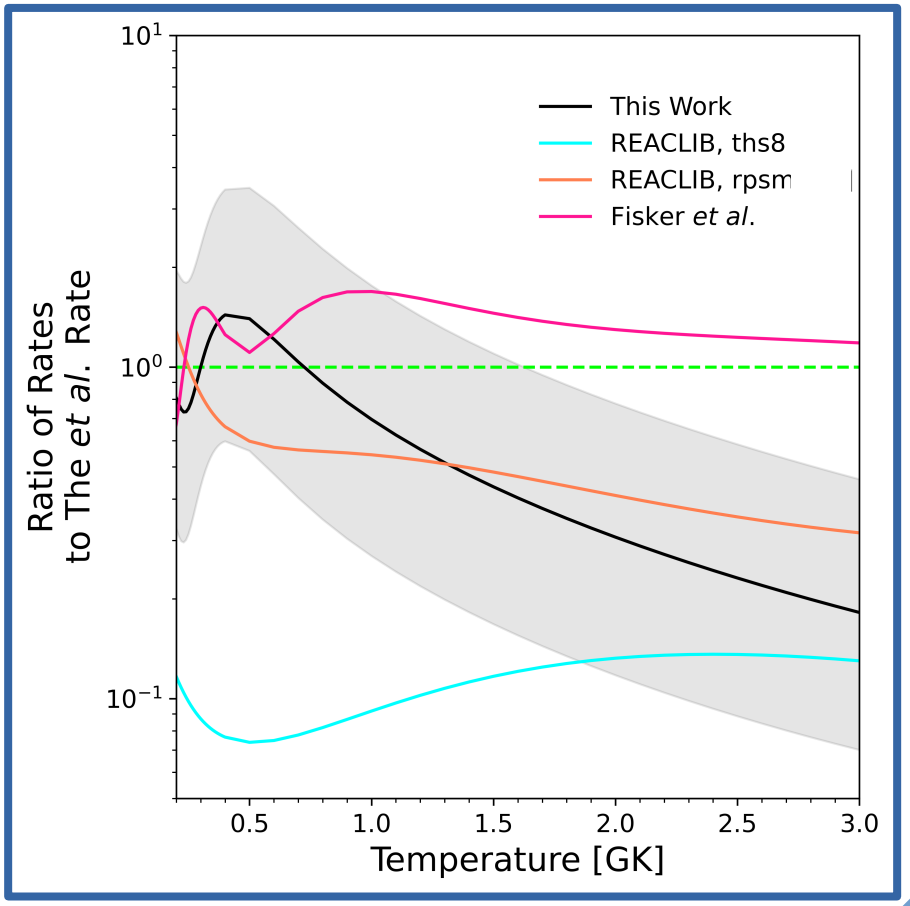
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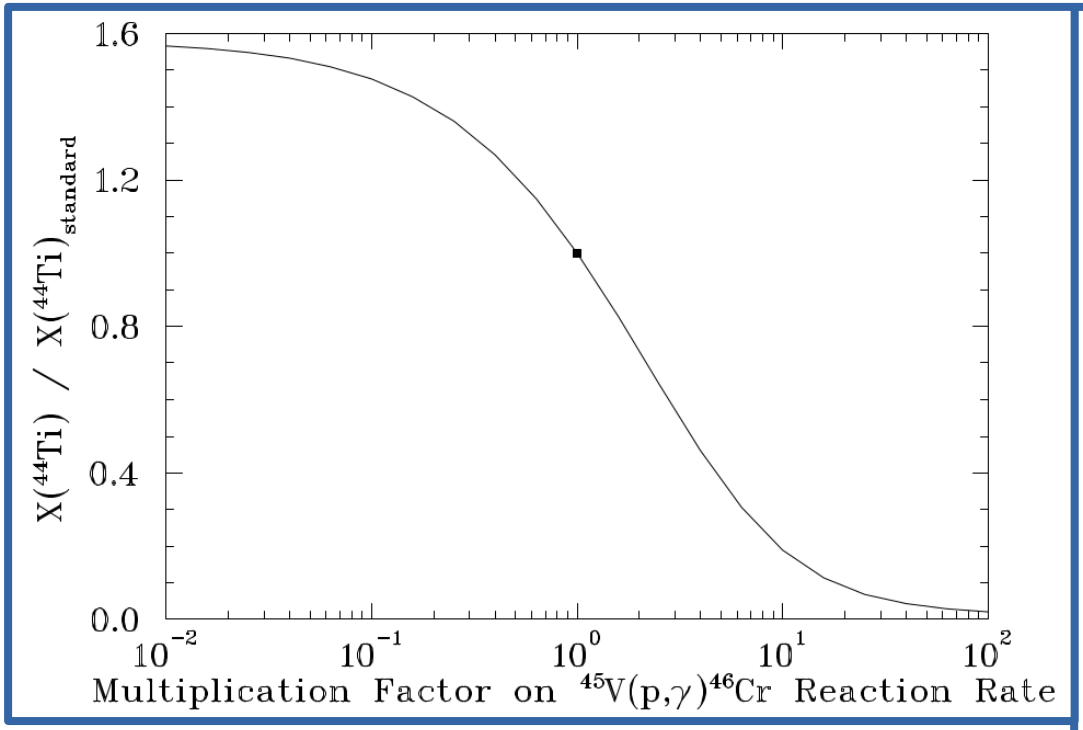
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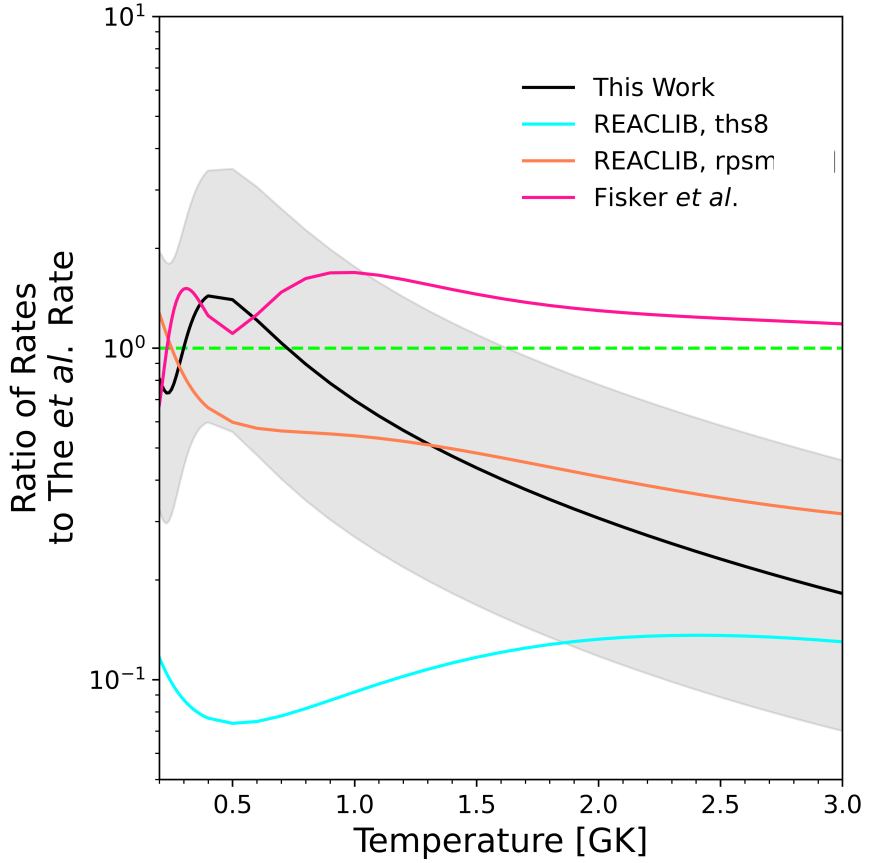


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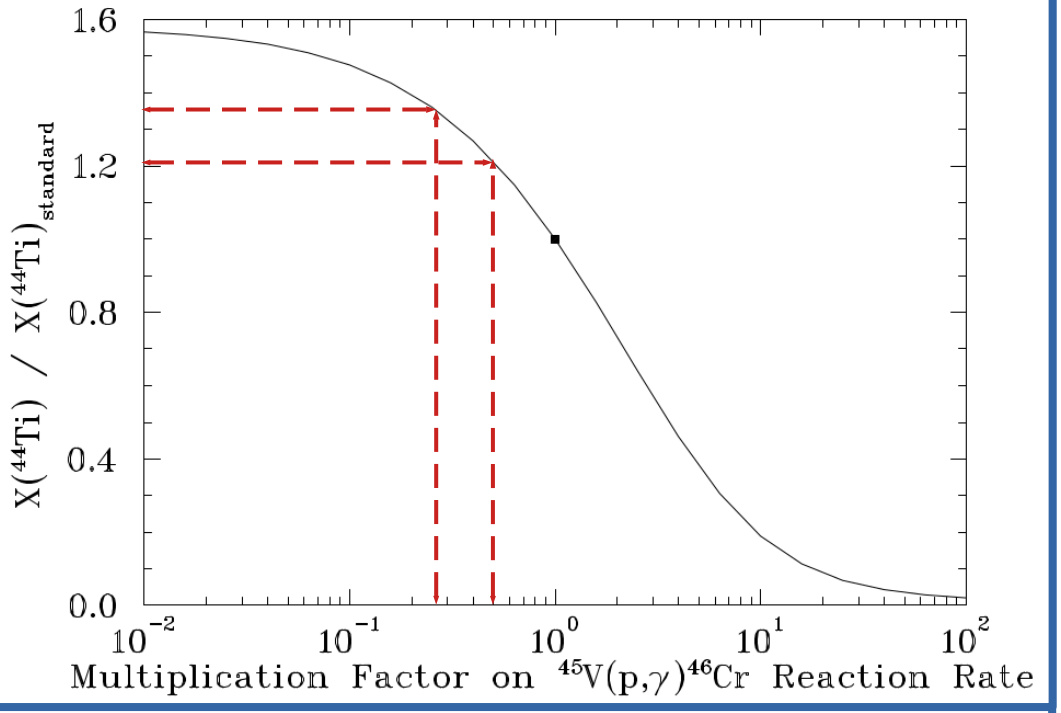
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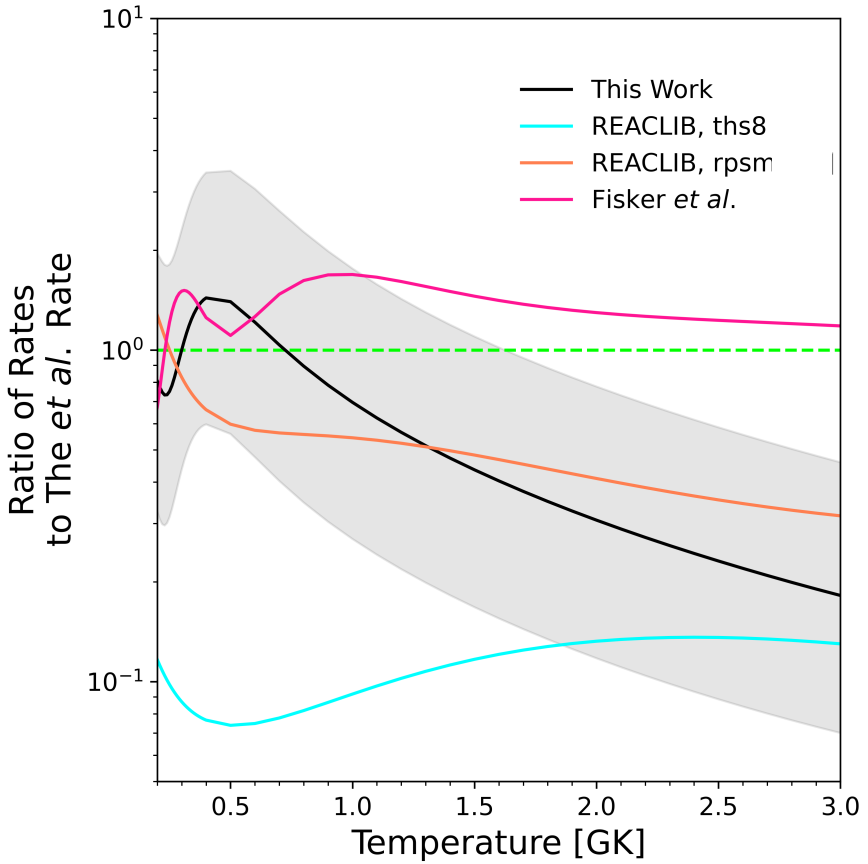


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# Results – Reaction Rate




- **~25 – 50%** of The *et al.* rate → **~20 – 35%** increase in $^{44}Ti$

# Spectroscopic Factors

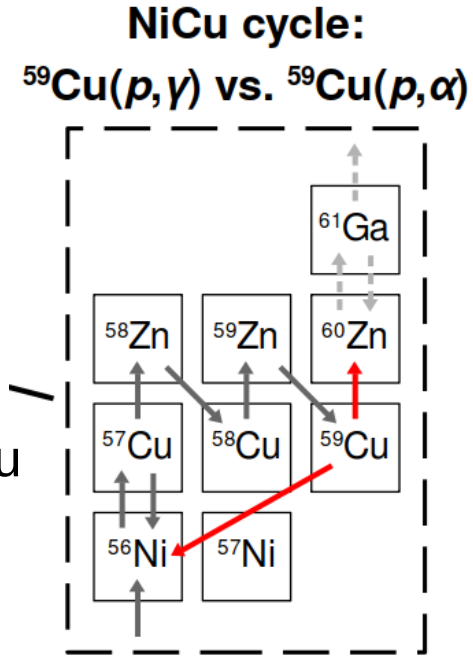
- First identification of states → no experimental spectroscopic factors ($C^2S$) available
- Shell-model $C^2S$ adopted → ~40% uncertainty from $^{50}$Ti survey
- Experiment constrain $C^2S$ → single-nucleon transfer reaction

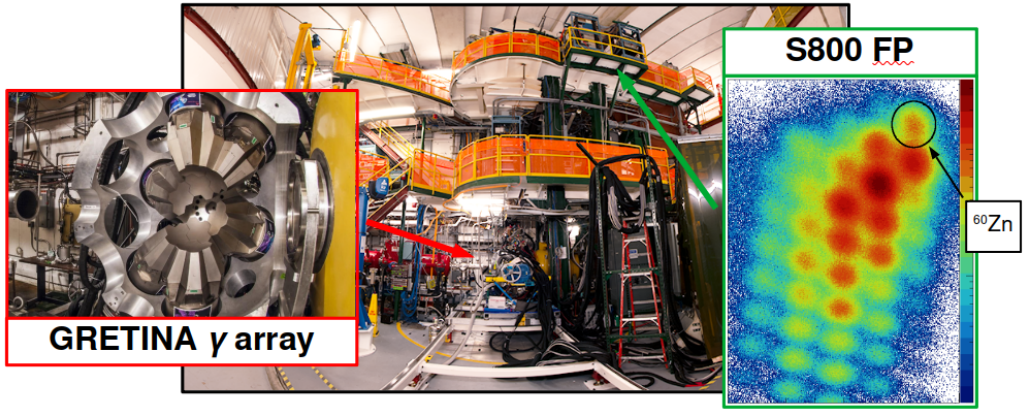
$$\Gamma_p = \frac{2\hbar^2}{\mu a^2} P_l \boxed{C^2 S} \theta_{sp}^2 \qquad \left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = C^2 S \left(\frac{d\sigma}{d\Omega}\right)_{\text{theo}}$$

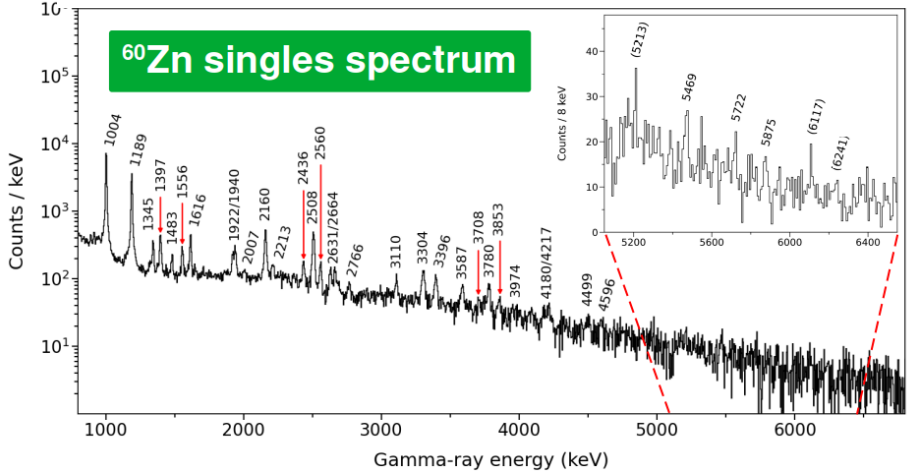
# (*d*,*n*) Reactions

**$^{59}$Cu(*d*,*n*)$^{60}$Zn, C. O'Shea *et al*., PRL 137, 022701 (2026)**

- X-ray Bursts – NiCu cycle
- γ-ray intensities → angle integrated cross sections → $C^2S$
- Constraint on NiCu cycling (~60% → ~40%)



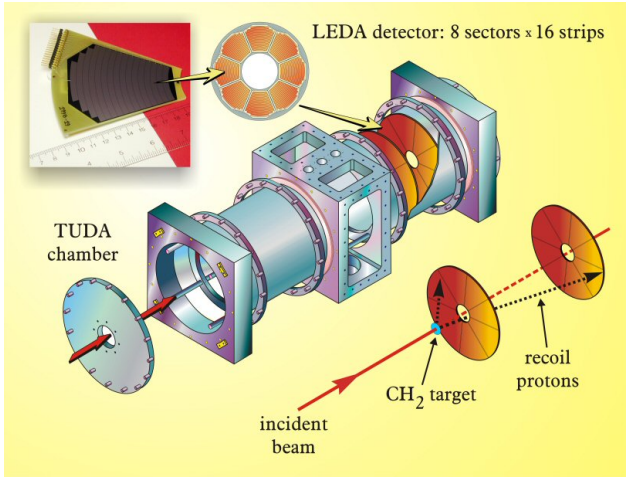



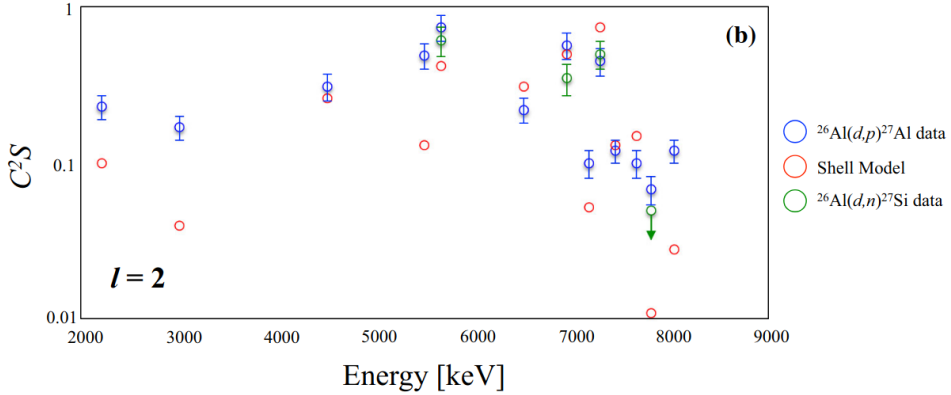



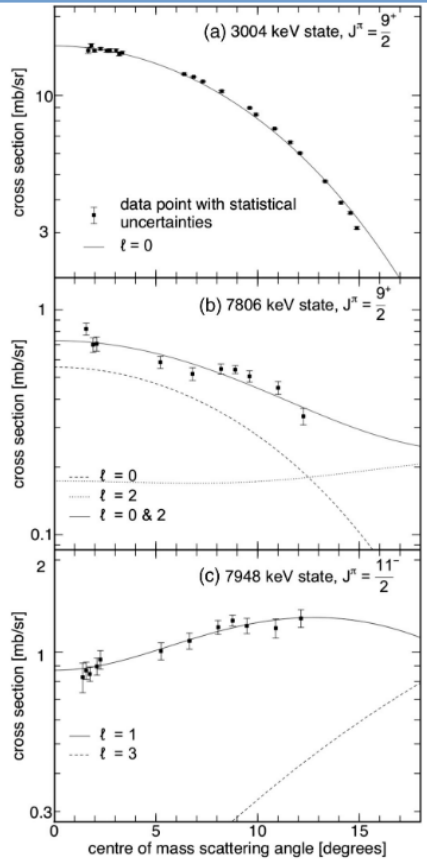
# (*d*,*p*) Reactions

**$^{26}$Al(*d*,*p*)$^{27}$Al, G. Lotay *et al*., Eur. Phys. J. A (2020) 56:3 (2020)**

- $^{26}$Al(*p*,*γ*)$^{27}$Si in WR & AGB stars
- Excitation energy spectra → differential cross sections → $C^2S$
- Mirror neutron $C^2S$ may be adopted as proton $C^2S$, also compare well to direct measurement



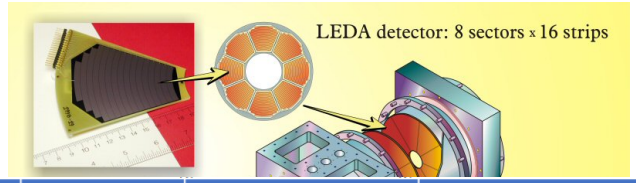



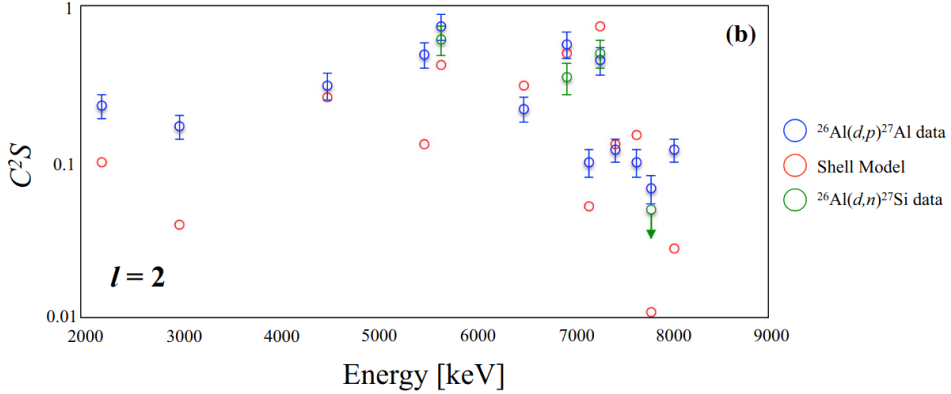
# (*d*,*p*) Reactions

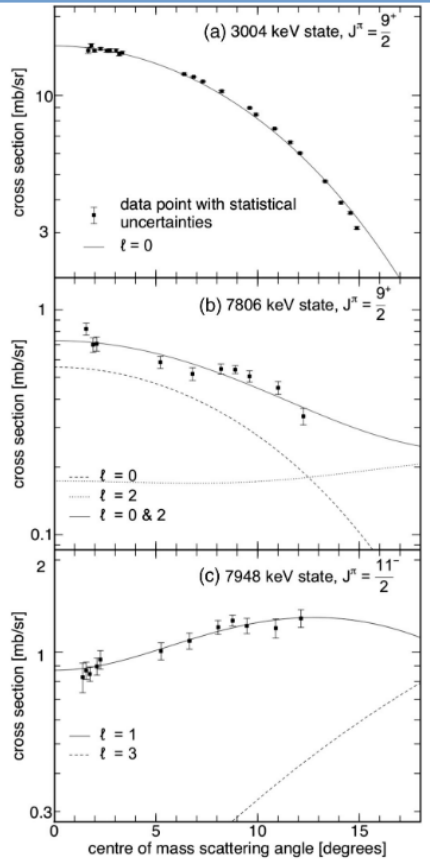
**$^{26}$Al(*d*,*p*)$^{27}$Al, G. Lotay *et al*., Eur. Phys. J. A (2020) 56:3 (2020)**

- $^{26}$Al(*p*,*γ*)$^{27}$Si in WR & AGB stars
- Excitation energy spectra → differential cross sections → $C^2S$
- Mirror neutron $C^2S$ may be adopted as proton $C^2S$, also compare well to direct measurement




| $E_x$ [keV] | $E_r$ [keV] | $\omega\gamma_{(d,p)}$ [meV] | $\omega\gamma_{(p,\gamma)}$ [meV] |
|---|---|---|---|
| 8043 | 369 | 45(22) | 69(7) |
| 7997 | 276 | 2.3(11) | 2.9(3) |
| 7948 | 189 | 0.026(12) | 0.035(7) |



# Summary and Future Work

- **$^{45}$V(*p*,*γ*)$^{46}$Cr** reaction rate is key to the **destruction of $^{44}$Ti** during the α-rich freeze-out of **CCSN**
- First identification of **18 γ rays**, leading to observation of **12 proton-unbound states in $^{46}$Cr** (more sub-$S_p$ states to be verified)
- New rate is **~25 – 50%** of previously known rate → **~20 – 35% more 44Ti** in ejecta
- Single-nucleon **transfer reaction** can further **constrain reaction rate**

- Transfer reaction to get $C^2S$ – $^{45}$V(*d*,*n*)$^{46}$Cr vs $^{45}$Ti(*d*,*p*)$^{46}$Ti
- Mass measurement of $^{46}$Cr (L. Canete *et al.* proposal at JYFL)
- Analyse sub-$S_p$ states

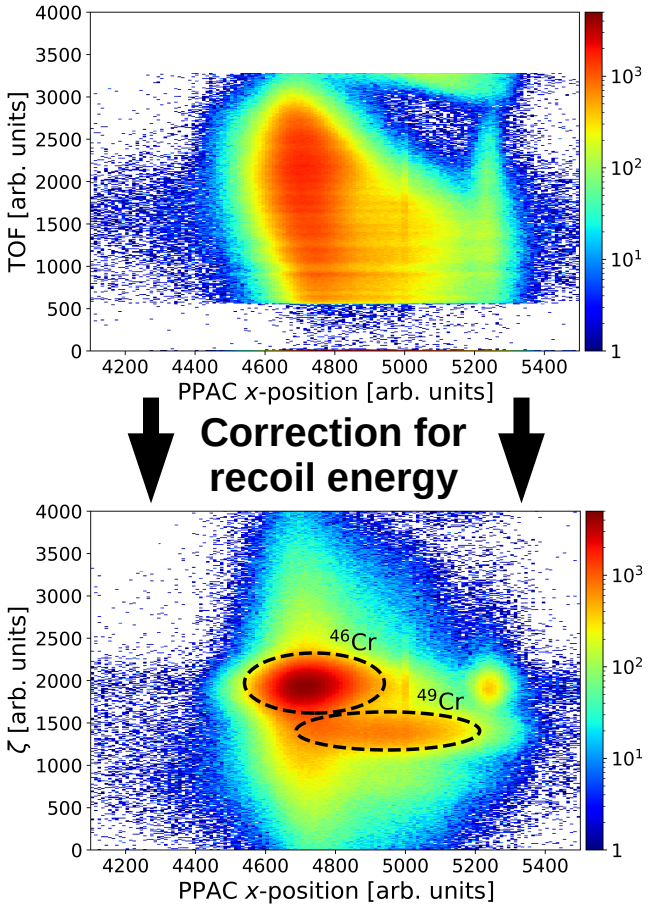
# Acknowledgments

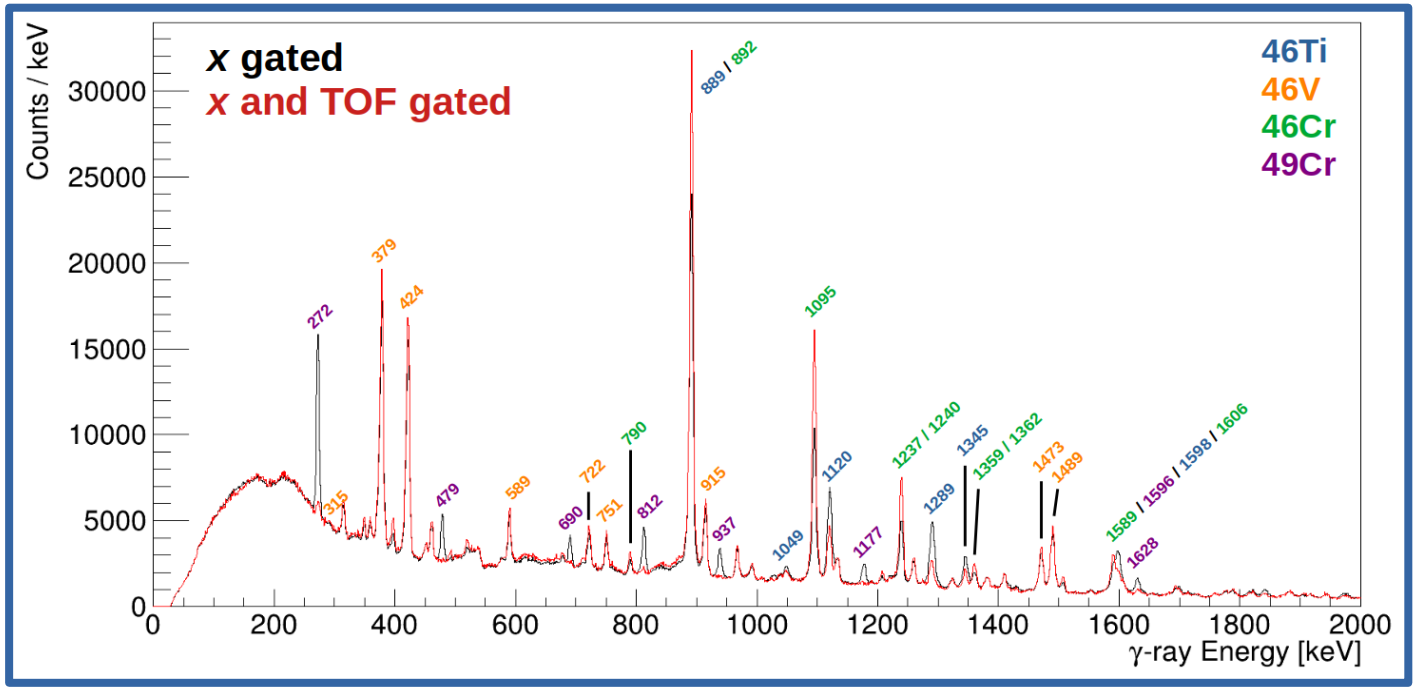
G. Lotay[1], D.T. Doherty[1], D.Seweryniak[2], C. Sarma[1], C. Campbell[3], L. Canete[1], M.P. Carpenter[2], W.N. Catford[1], K.A. Chipps[4], , J. Henderson[1], J. José[5], A.R.L. Kennington[1], T. Lauritsen[2], J. Li[2], M. Moukaddam[6], C. Müller-Gatermann[2], C. O'Shea[1], S.D. Pain[4], C. Paxman[1], B.J. Reed[1], P.H. Regan[1], W. Reviol[2], M. Siciliano[2], G.L. Wilson[2,7], S. Zhu[8]

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[4] Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[5] Universitat Politècnica De Catalunya, 08034 Barcelona, Spain
[6] Université de Strasbourg, IPHC, 67037 Strasbourg, France
[7] Louisiana State University, Baton Rouge, Louisiana 70803, USA
[8] Brookhaven National Laboratory, National Nuclear Data Center, New York 11973, USA

B

# Time-of-Flight (TOF) Gate




| $E_\gamma$ (keV) | % of counts reduced using *x* and TOF |
|---|---|
| 1120 ($^{46}$Ti) | 70(2) |
| 424 ($^{46}$V) | 40.4(4) |

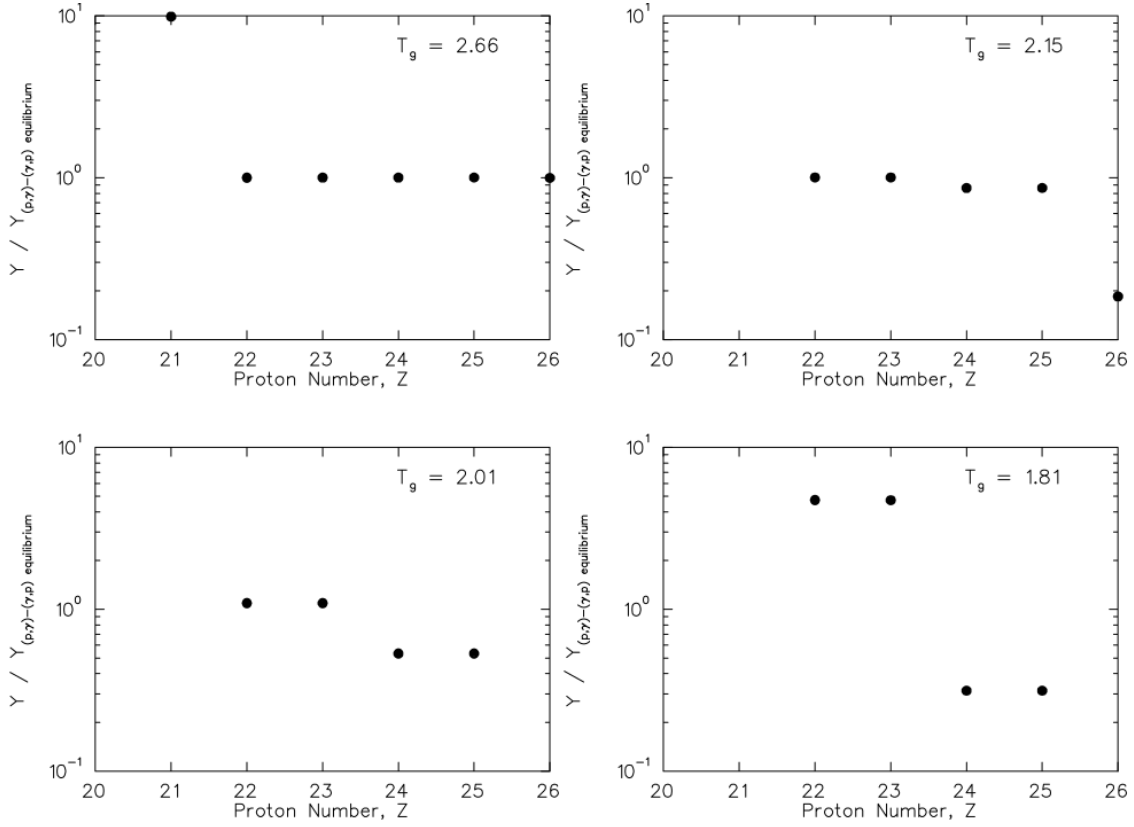



FIG. 13.—Evolution of the $(p, \gamma)$–$(\gamma, p)$ equilibrium for the $N = 22$ isotones as the temperature falls, with the standard $^{45}V(p, \gamma)^{46}Cr$ rate. The $^{44}Ti$ and $^{45}V$ pair ($Z = 22$ and 23) increasingly depart from equilibrium with the $^{46}Cr$ and $^{47}Mn$ pair ($Z = 24$ and 25) as the temperature declines.

TABLE 5

ORDER OF IMPORTANCE OF REACTIONS PRODUCING $^{44}Ti$ AT $\eta = 0$[a]

| Reaction | Slope |
|---|---|
| $^{44}Ti(\alpha, p)^{47}V$ ..... | −0.394 |
| $\alpha(2\alpha, \gamma)^{12}C$ ..... | +0.386 |
| $^{45}V(p, \gamma)^{46}Cr$ ..... | −0.361 |
| $^{40}Ca(\alpha, \gamma)^{44}Ti$ ..... | +0.137 |
| $^{57}Co(p, n)^{57}Ni$ ..... | +0.102 |
| $^{36}Ar(\alpha, p)^{39}K$ ..... | +0.037 |
| $^{44}Ti(\alpha, \gamma)^{48}Cr$ ..... | −0.024 |
| $^{12}C(\alpha, \gamma)^{16}O$ ..... | −0.017 |
| $^{57}Ni(p, \gamma)^{58}Cu$ ..... | +0.013 |
| $^{58}Cu(p, \gamma)^{59}Zn$..... | +0.011 |
| $^{36}Ar(\alpha, \gamma)^{40}Ca$ ..... | +0.008 |
| $^{44}Ti(p, \gamma)^{45}V$ ..... | −0.005 |
| $^{57}Co(p, \gamma)^{58}Ni$ ..... | +0.002 |
| $^{57}Ni(n, \gamma)^{58}Cu$ ..... | +0.002 |
| $^{54}Fe(\alpha, n)^{57}Ni$ ..... | +0.002 |
| $^{40}Ca(\alpha, p)^{43}Sc$ ..... | −0.002 |

[a] Order of importance of reactions producing $^{44}Ti$ at $\eta = 0$ according to the slope of $X(^{44}Ti)$ near the standard reaction rates.

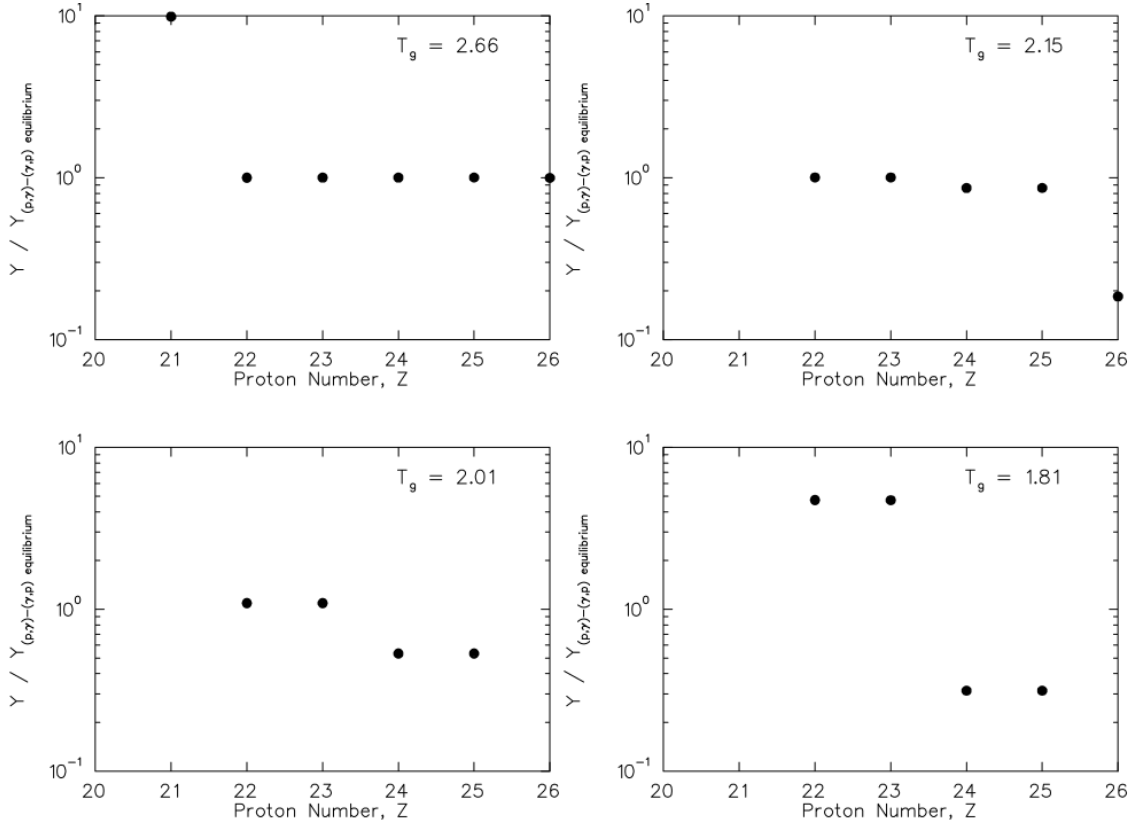



FIG. 13.—Evolution of the $(p, \gamma)$–$(\gamma, p)$ equilibrium for the $N = 22$ isotones as the temperature falls, with the standard $^{45}V(p, \gamma)^{46}Cr$ rate. The $^{44}Ti$ and $^{45}V$ pair ($Z = 22$ and 23) increasingly depart from equilibrium with the $^{46}Cr$ and $^{47}Mn$ pair ($Z = 24$ and 25) as the temperature declines.

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| $^{58}Cu(p, \gamma)^{59}Zn$..... | +0.011 |
| $^{36}Ar(\alpha, \gamma)^{40}Ca$ ..... | +0.008 |
| $^{44}Ti(p, \gamma)^{45}V$ ..... | −0.005 |
| $^{57}Co(p, \gamma)^{58}Ni$ ..... | +0.002 |
| $^{57}Ni(n, \gamma)^{58}Cu$ ..... | +0.002 |
| $^{54}Fe(\alpha, n)^{57}Ni$ ..... | +0.002 |
| $^{40}Ca(\alpha, p)^{43}Sc$ ..... | −0.002 |

[a] Order of importance of reactions producing $^{44}Ti$ at $\eta = 0$ according to the slope of $X(^{44}Ti)$ near the standard reaction rates.

TABLE 4

ORDER OF IMPORTANCE OF REACTIONS PRODUCING $^{44}$Ti AT $\eta = 0$

| | Reaction Rate Multiplied by 1/100 | | Reaction Rate Multiplied by 100 | |
|---|---|---|---|---|
| Rank | Reaction | $^{44}$Ti Change (percent) | Reaction | $^{44}$Ti Change (percent) |
| 1 ..... | $^{44}$Ti($\alpha$, $p$)$^{47}$V | +173 | $^{45}$V($p$, $\gamma$)$^{46}$Cr | −98 |
| 2 ..... | $\alpha$(2$\alpha$, $\gamma$)$^{12}$C | −100 | $\alpha$(2$\alpha$, $\gamma$)$^{12}$C | +67 |
| 3 ..... | $^{40}$Ca($\alpha$, $\gamma$)$^{44}$Ti | −72 | $^{44}$Ti($\alpha$, $p$)$^{47}$V | −89 |
| 4 ..... | $^{45}$V($p$, $\gamma$)$^{46}$Cr | +57 | $^{44}$Ti($\alpha$, $\gamma$)$^{48}$Cr | −61 |
| 5 ..... | $^{57}$Ni($p$, $\gamma$)$^{58}$Cu | −47 | $^{57}$Co($p$, $n$)$^{57}$Ni | +25 |
| 6 ..... | $^{57}$Co($p$, $n$)$^{57}$Ni | −33 | $^{40}$Ca($\alpha$, $\gamma$)$^{44}$Ti | +22 |
| 7 ..... | $^{13}$N($p$, $\gamma$)$^{14}$O | −16 | $^{57}$Ni($n$, $\gamma$)$^{58}$Ni | +10 |
| 8 ..... | $^{58}$Cu($p$, $\gamma$)$^{59}$Zn | −14 | $^{54}$Fe($\alpha$, $n$)$^{57}$Ni | +9.4 |
| 9 ..... | $^{36}$Ar($\alpha$, $p$)$^{39}$K | −11 | $^{36}$Ar($\alpha$, $p$)$^{39}$K | +5.5 |
| 10..... | $^{12}$C($\alpha$, $\gamma$)$^{16}$O | +3.5 | $^{36}$Ar($\alpha$, $\gamma$)$^{40}$Ca | +5.3 |

# PACE4 Calculations

## On $^{12}C$

### 1. Yields of residual nuclei

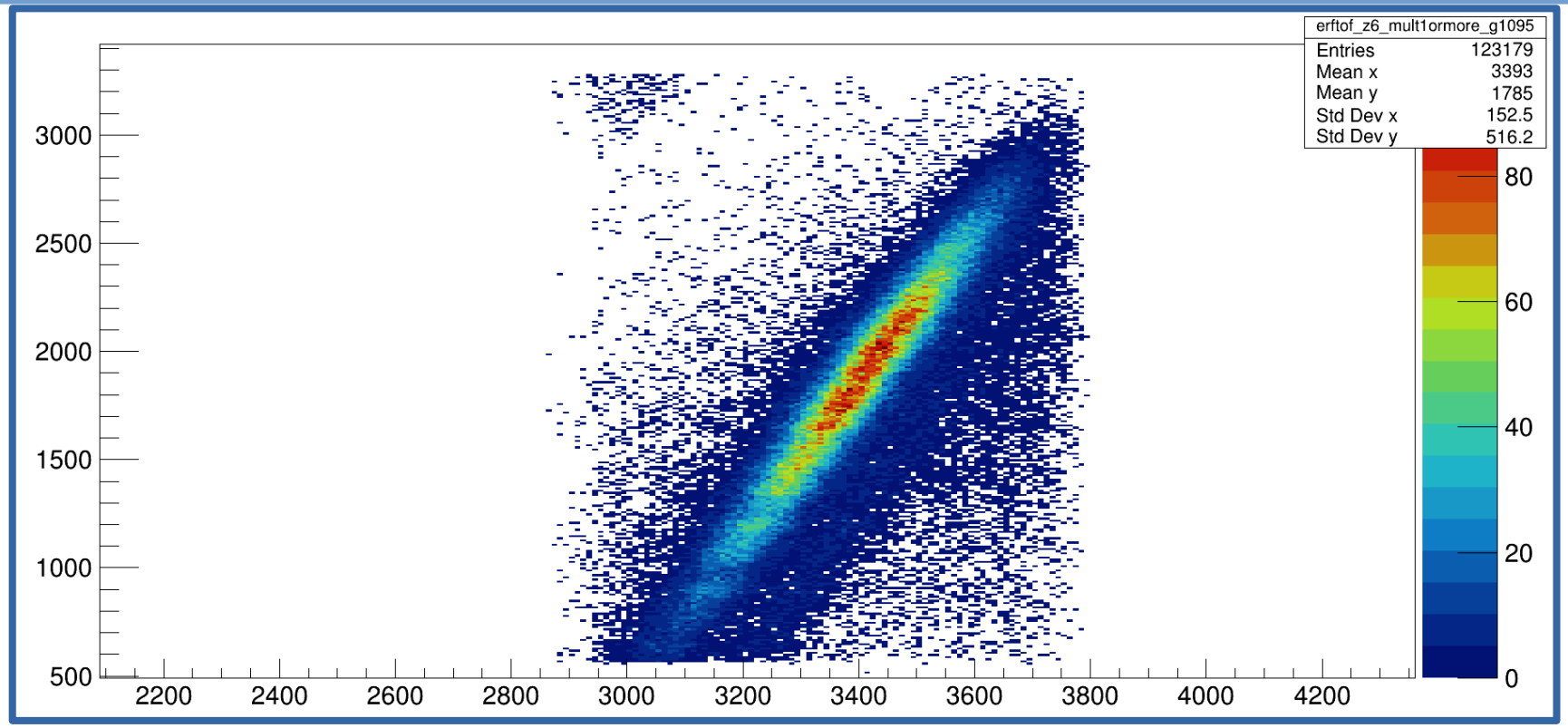
| Z | N | A | | events | percent | x-section(mb) |
|---|---|---|---|---|---|---|
| 24 | 23 | **47** | **Cr** | 63 | 0.063% | 0.595 |
| 23 | 24 | **47** | **V** | 380 | 0.38% | 3.59 |
| 24 | 22 | **46** | **Cr** | 25 | 0.025% | 0.236 |
| 23 | 23 | **46** | **V** | 18520 | 18.5% | 175 |
| 22 | 24 | **46** | **Ti** | 28646 | 28.6% | 270 |
| 23 | 22 | **45** | **V** | 10 | 0.01% | 0.0944 |
| 22 | 23 | **45** | **Ti** | 16937 | 16.9% | 160 |
| 21 | 24 | **45** | **Sc** | 5540 | 5.54% | 52.3 |
| 22 | 22 | **44** | **Ti** | 1193 | 1.19% | 11.3 |
| 22 | 21 | **43** | **Ti** | 364 | 0.364% | 3.44 |
| 21 | 22 | **43** | **Sc** | 16405 | 16.4% | 155 |
| 21 | 21 | **42** | **Sc** | 44 | 0.044% | 0.415 |
| 20 | 22 | **42** | **Ca** | 397 | 0.397% | 3.75 |
| 20 | 20 | **40** | **Ca** | 9020 | 9.02% | 85.2 |
| 19 | 20 | **39** | **K** | 2455 | 2.46% | 23.2 |
| TOTAL | | | | 99999 | 100 | 944.208 |

## On $^{16}O$

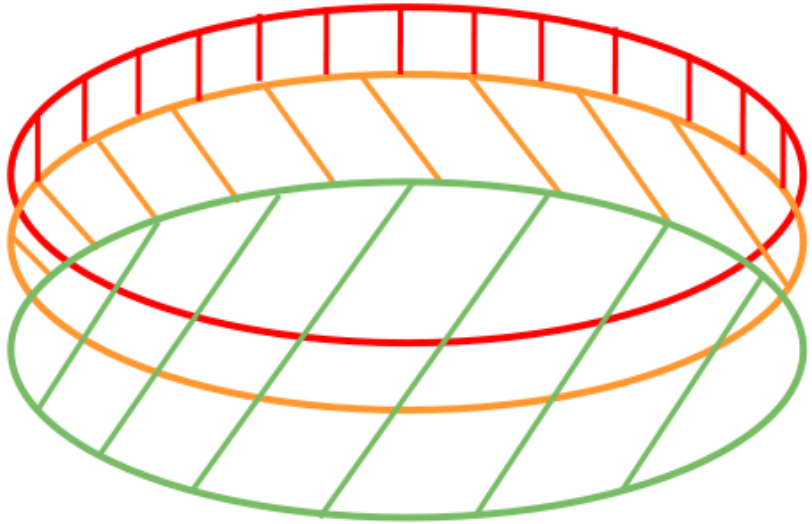
### 1. Yields of residual nuclei

| Z | N | A | | events | percent | x-section(mb) |
|---|---|---|---|---|---|---|
| 26 | 25 | **51** | **Fe** | 3 | 0.003% | 0.0276 |
| 25 | 26 | **51** | **Mn** | 21 | 0.021% | 0.193 |
| 26 | 24 | **50** | **Fe** | 33 | 0.033% | 0.303 |
| 25 | 25 | **50** | **Mn** | 3489 | 3.49% | 32.1 |
| 24 | 26 | **50** | **Cr** | 5878 | 5.88% | 54.1 |
| 25 | 24 | **49** | **Mn** | 247 | 0.247% | 2.27 |
| 24 | 25 | **49** | **Cr** | 40569 | 40.6% | 373 |
| 23 | 26 | **49** | **V** | 15421 | 15.4% | 142 |
| 24 | 24 | **48** | **Cr** | 235 | 0.235% | 2.16 |
| 23 | 25 | **48** | **V** | 600 | 0.6% | 5.52 |
| 22 | 26 | **48** | **Ti** | 8 | 0.008% | 0.0736 |
| 24 | 23 | **47** | **Cr** | 686 | 0.686% | 6.31 |
| 23 | 24 | **47** | **V** | 14657 | 14.7% | 135 |
| 23 | 23 | **46** | **V** | 2222 | 2.22% | 20.4 |
| 22 | 24 | **46** | **Ti** | 12585 | 12.6% | 116 |
| 22 | 23 | **45** | **Ti** | 11 | 0.011% | 0.101 |
| 21 | 24 | **45** | **Sc** | 3 | 0.003% | 0.0276 |
| 22 | 22 | **44** | **Ti** | 2326 | 2.33% | 21.4 |
| 21 | 22 | **43** | **Sc** | 932 | 0.932% | 8.57 |
| 20 | 20 | **40** | **Ca** | 73 | 0.073% | 0.671 |
| TOTAL | | | | 99999 | 100 | 919.564 |

# TOF Dependence on Recoil Energy



# X-RFTOF Gates



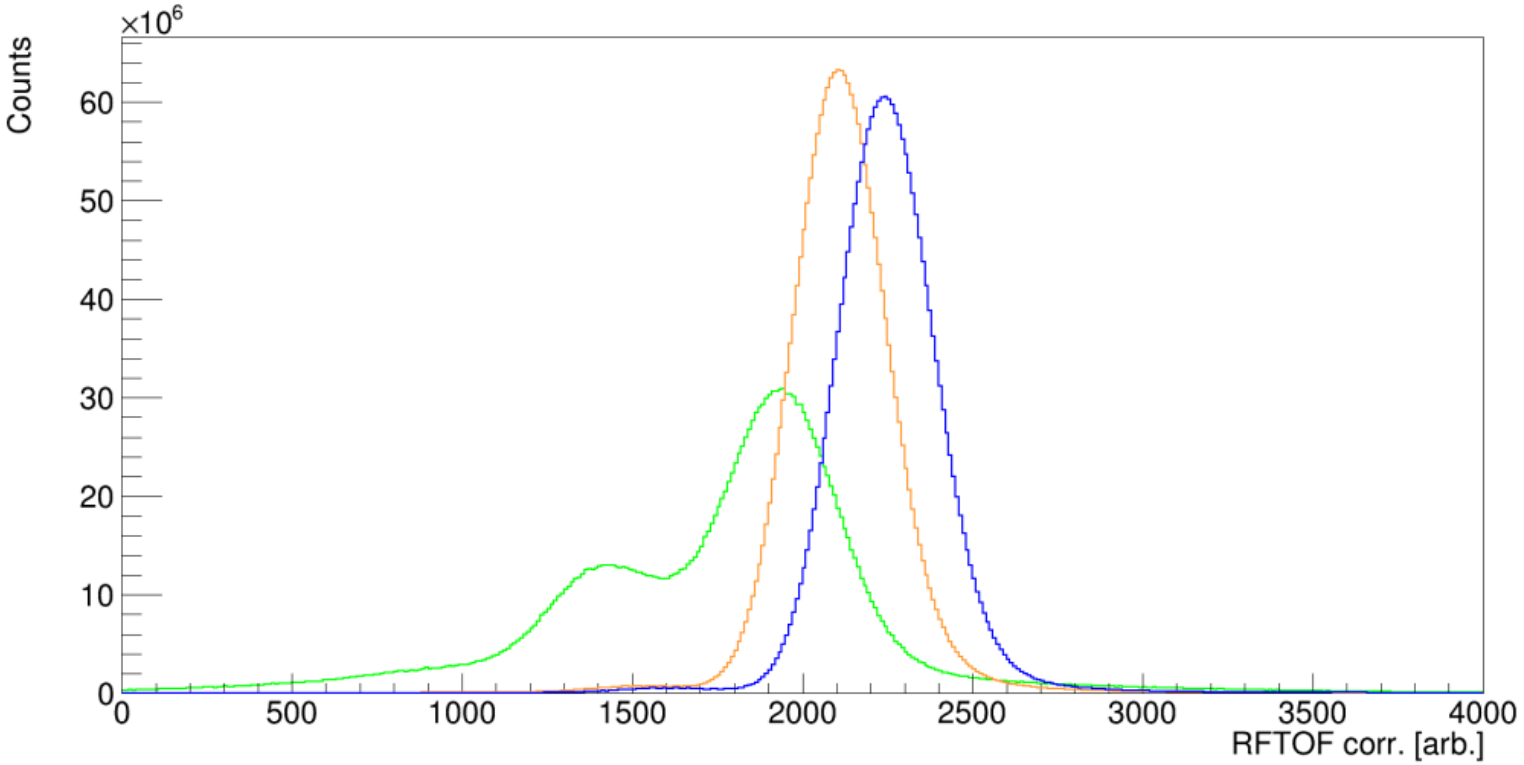
- 46Cr xrftof cut
- 46V xrftof cut
- 46Ti xrftof cut

1) in 46Cr cut

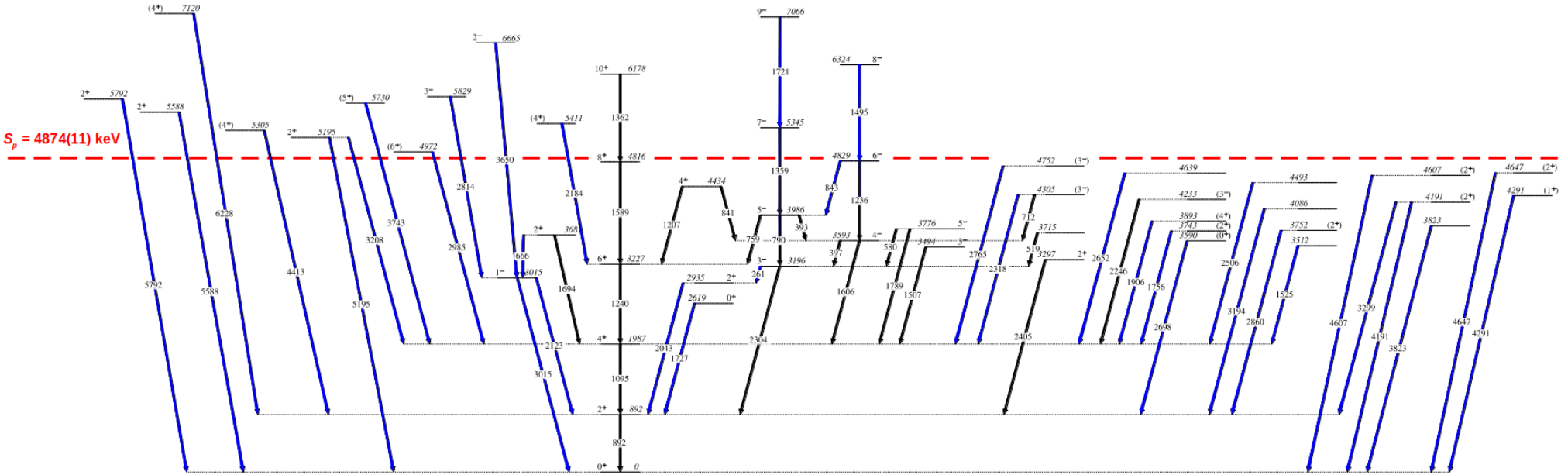
2) in 46V cut and not in 46Cr cut

3) in 46Ti cut and not in 46V and 46Cr cuts

# X-RFTOF Gates



# Results – Full Level Scheme

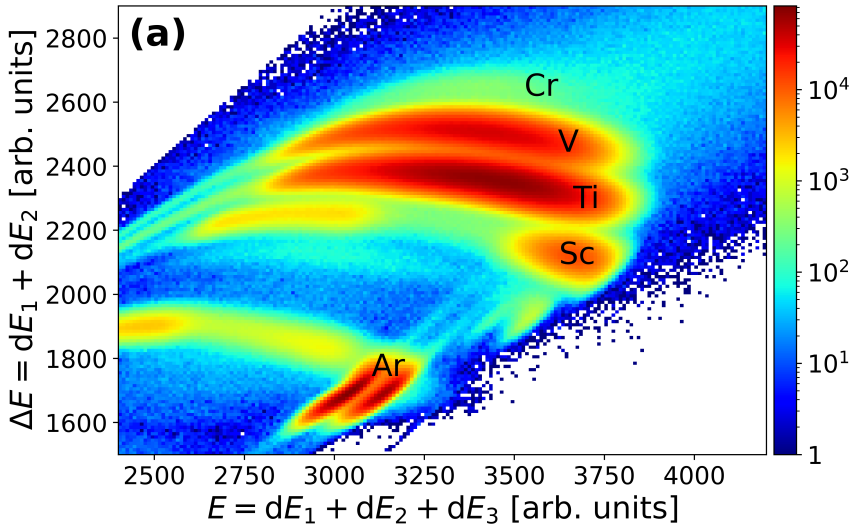


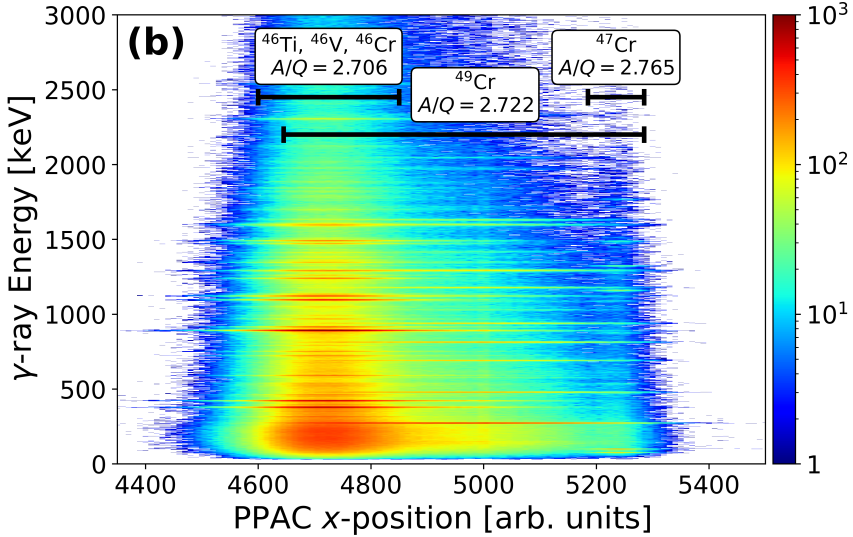
# *Z* and *A/Q* Gate

$$-\left\langle \frac{dE}{dx} \right\rangle \approx \frac{4\pi e^4}{m_e} \frac{Z_p^2}{\nu^2} \left( N_A \rho \frac{Z_t}{M_t} \right) \ln \left( \frac{2 m_e \nu^2}{I} \right)$$

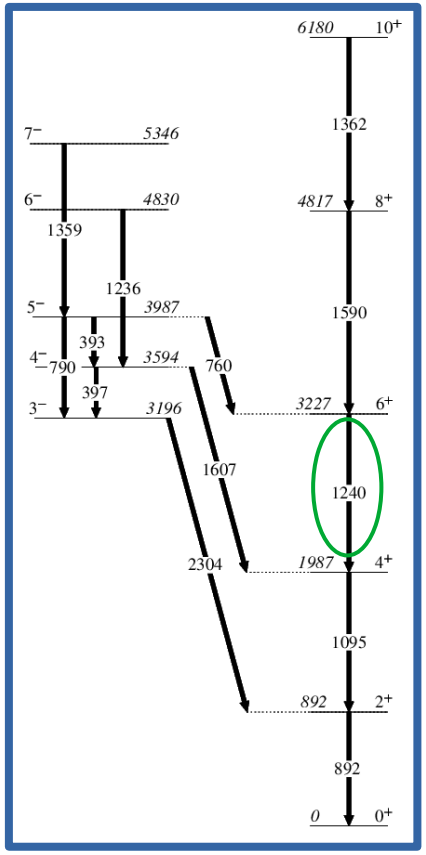
$$|\mathbf{F}| = Q|\mathbf{E} + \mathbf{v} \times \mathbf{B}| = \frac{A|\mathbf{v}|^2}{\rho}$$

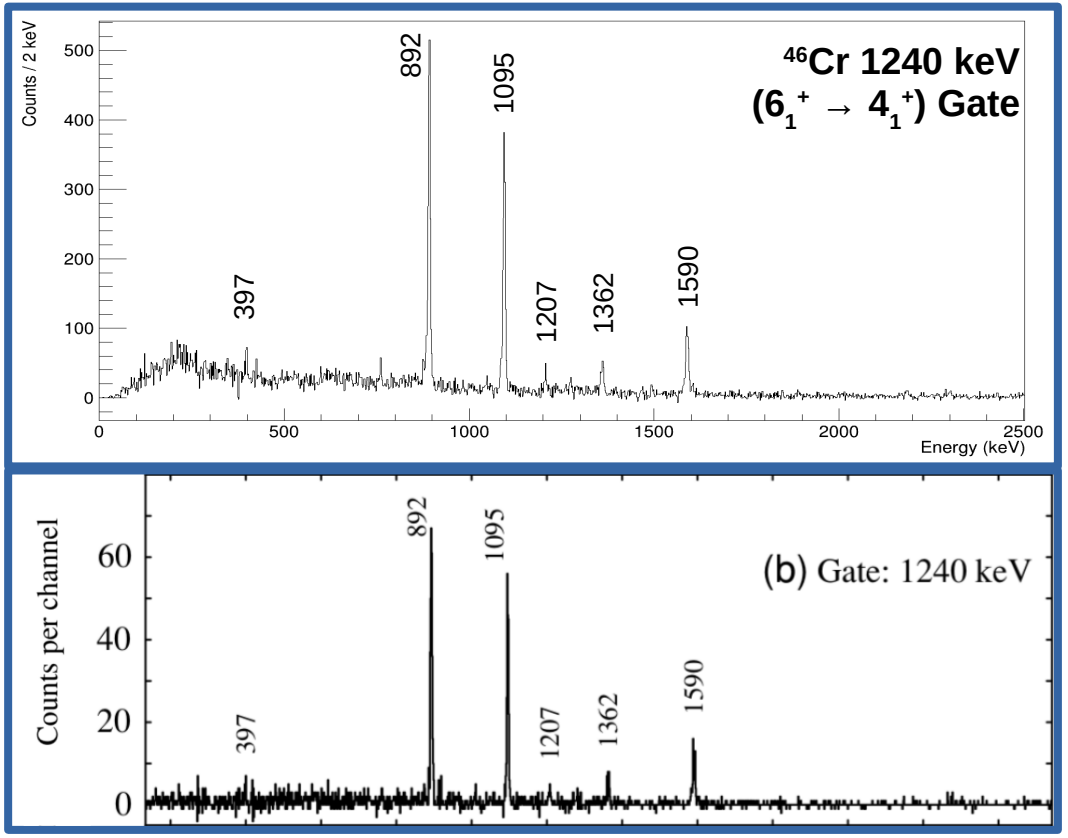
$$B\rho = \frac{Av}{Q} \qquad E\rho = \frac{Av^2}{Q}$$



# Results – Previous Studies Comparison




P. E. Garrett et al. Phys. Rev. C **75**, 014307 (2007).

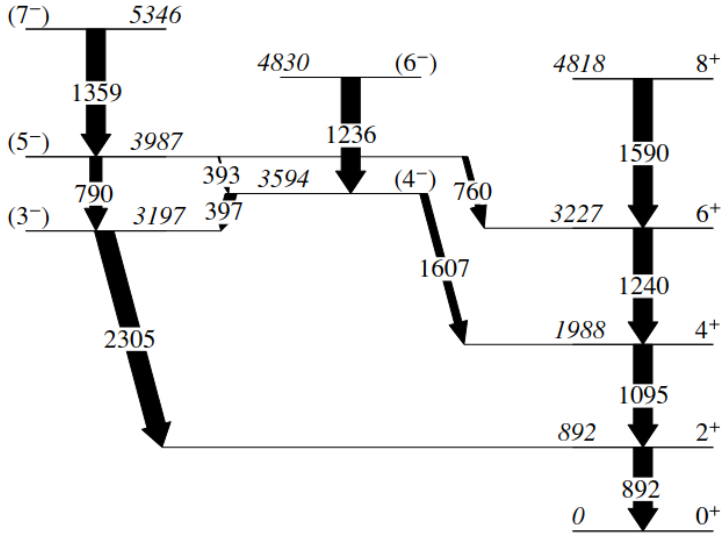
# Spectroscopic Factors

- First identification of states → no experimental spectroscopic factors ($C^2S$) available
- Shell-model $C^2S$ adopted → ~40% uncertainty from $^{46}$Ti survey
- Experiments to obtain these → single-nucleon transfer reaction → comparison of experimental to theoretical (e.g. TWOFNR) cross sections

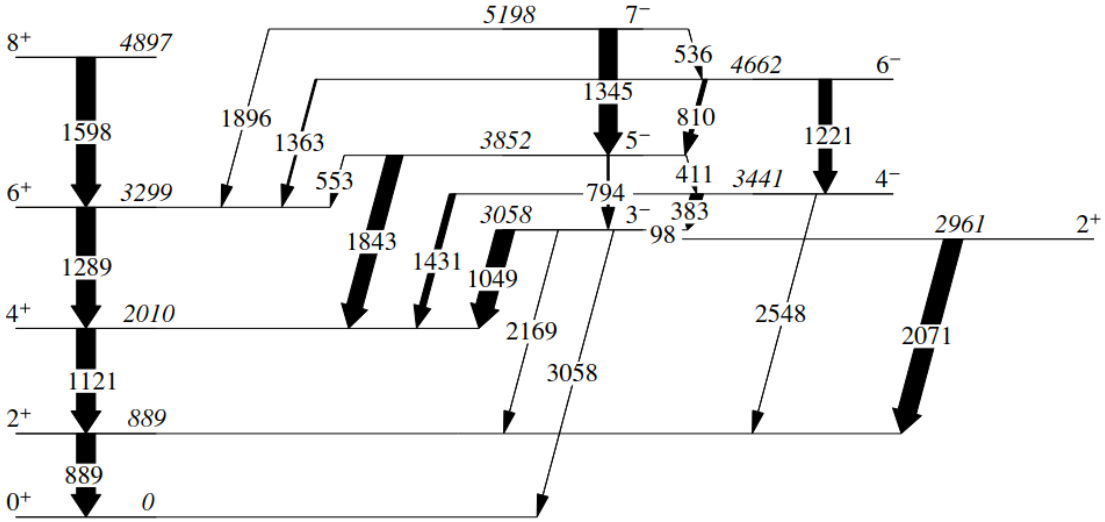
$$\Gamma_p = \frac{2\hbar^2}{\mu a^2} P_l \boxed{C^2 S} \theta_{sp}^2 \qquad \left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = C^2 S \left(\frac{d\sigma}{d\Omega}\right)_{\text{theo}}$$

# Mirror Nucleus Comparison

$T = 1$, $A = 46$ Mirror Pair




$^{46}$Cr (Z=24, N=22)




$^{46}$Ti (Z=22, N=24)

P. E. Garrett et al. Phys. Rev. C **75**, 014307 (2007).