

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

Chris Cousins

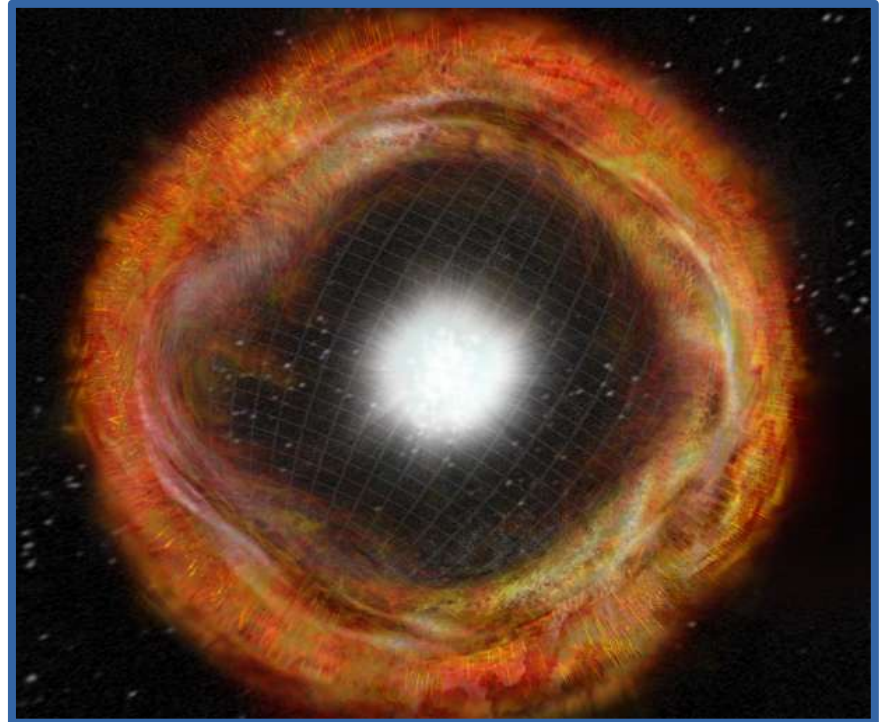
IOP Nuclear Physics Conference 2026



UNIVERSITY OF  
**SURREY**

# Motivation and Astrophysical Background

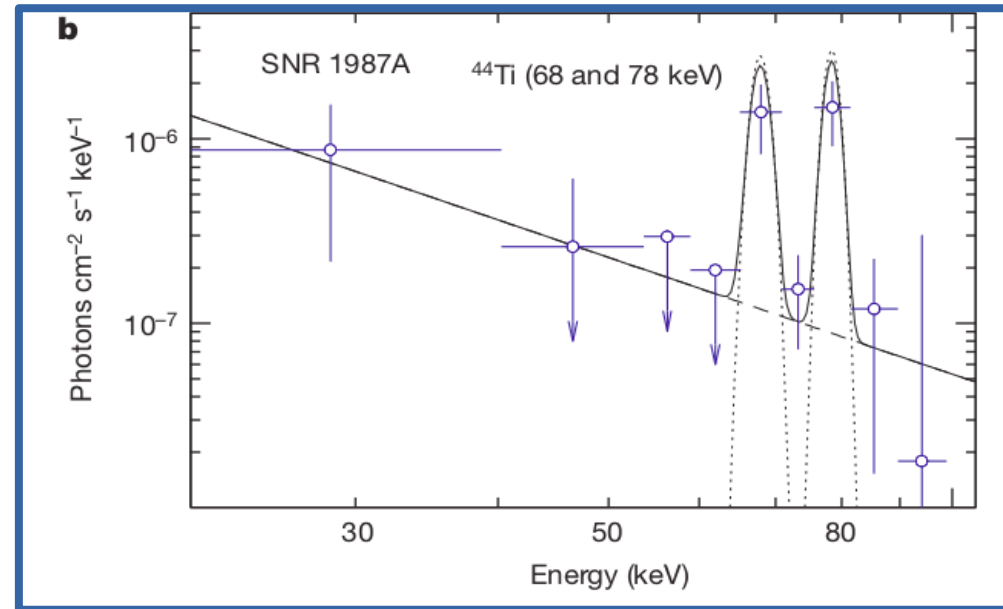
- Core-collapse supernovae (CCSNe) mechanism:
  - $M \gtrsim 8M_{\odot}$  progenitor
  - Core  $\rightarrow$  Chandrasekhar mass ( $1.44 M_{\odot}$ )
  - Rapid core collapse  $\rightarrow$  bounce
  - Shock formation and stagnation
- After this point, **uncertainty in explosion mechanism** of CCSNe –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



Bill Saxton (NRAO/AUI/NSF)

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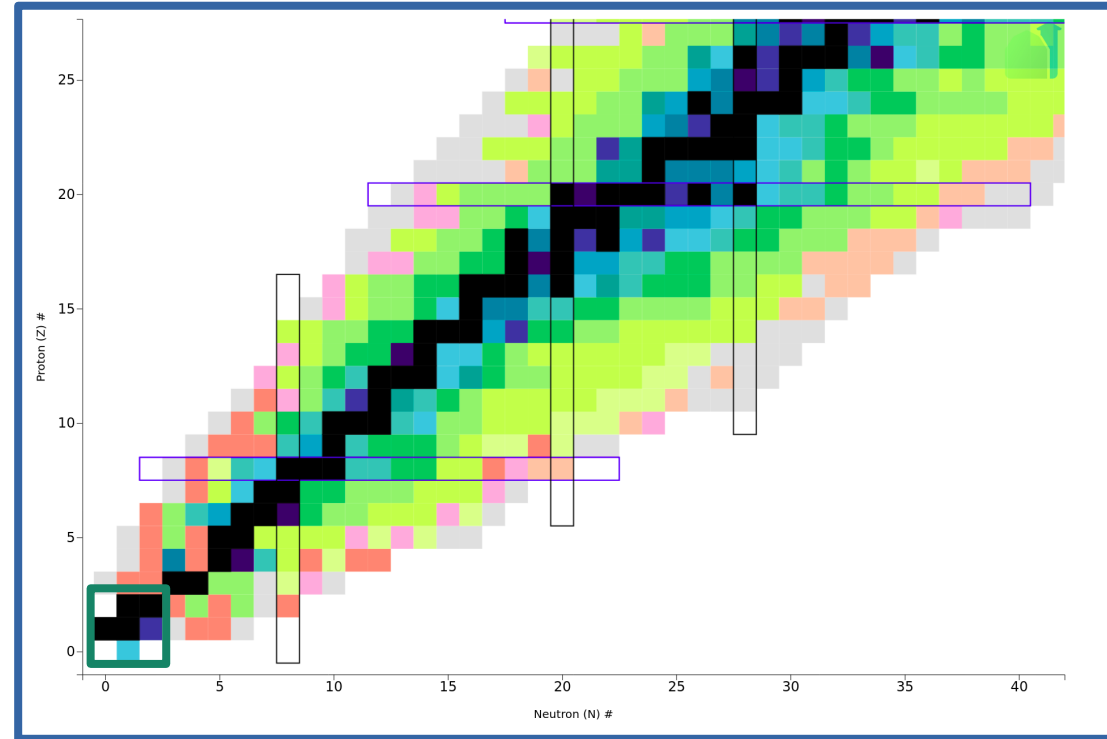
- New insight – observing  $^{44}\text{Ti}$  **cosmic  $\gamma$  rays** ( $t_{1/2} \approx 60$  yr) – INTEGRAL
- $^{44}\text{Ti}$  synthesised in same region as **mass cut point**
- $^{44}\text{Ti}$  abundances  $\rightarrow$  mass cut location
- Road block! – **uncertainty** in nuclear reactions that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



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

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

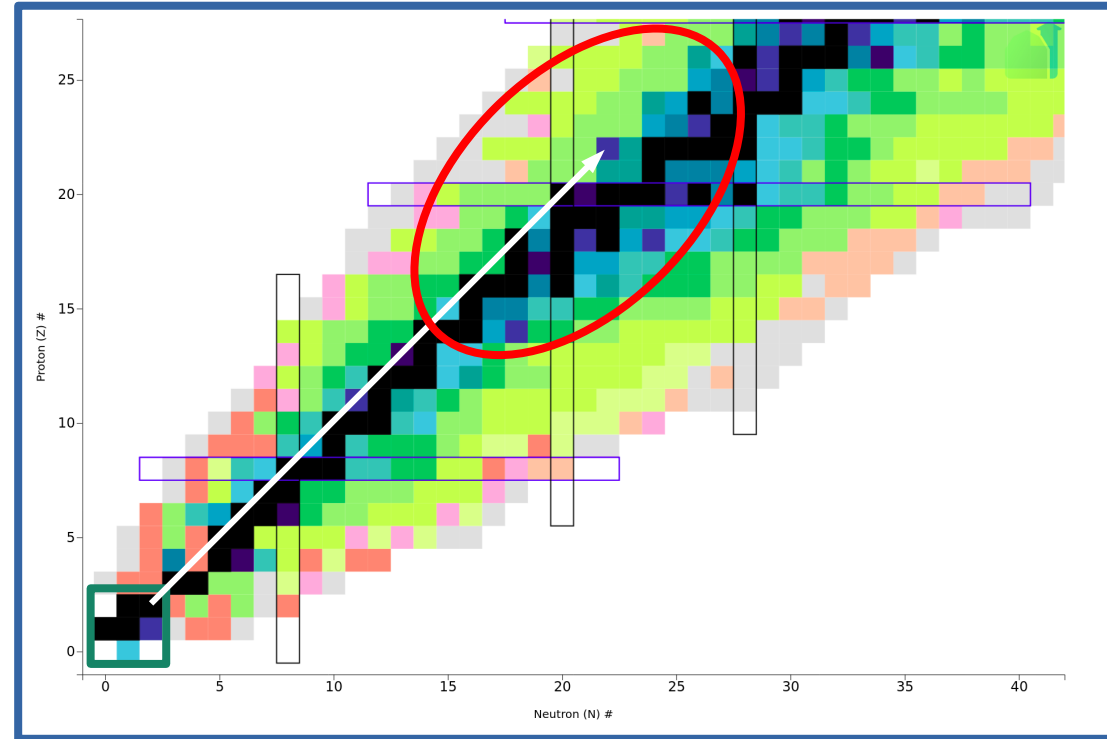
- **Shock wave** breaks nuclei into free nucleons and  $\alpha$  particles



<https://www.nndc.bnl.gov/>

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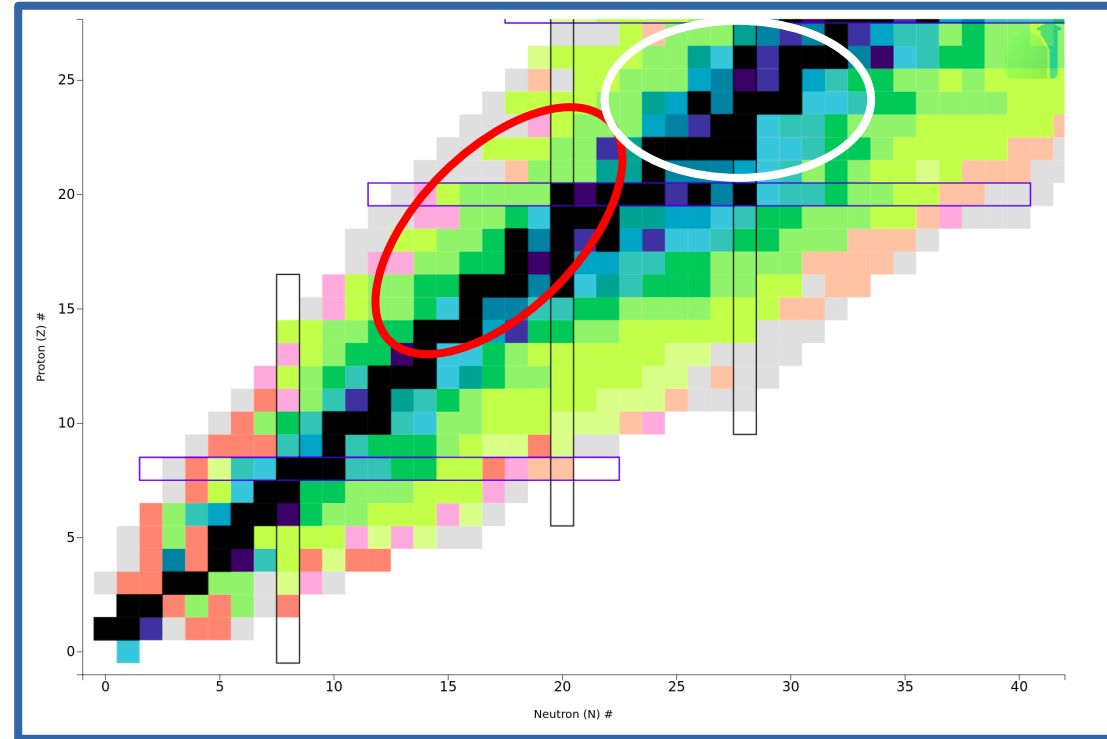
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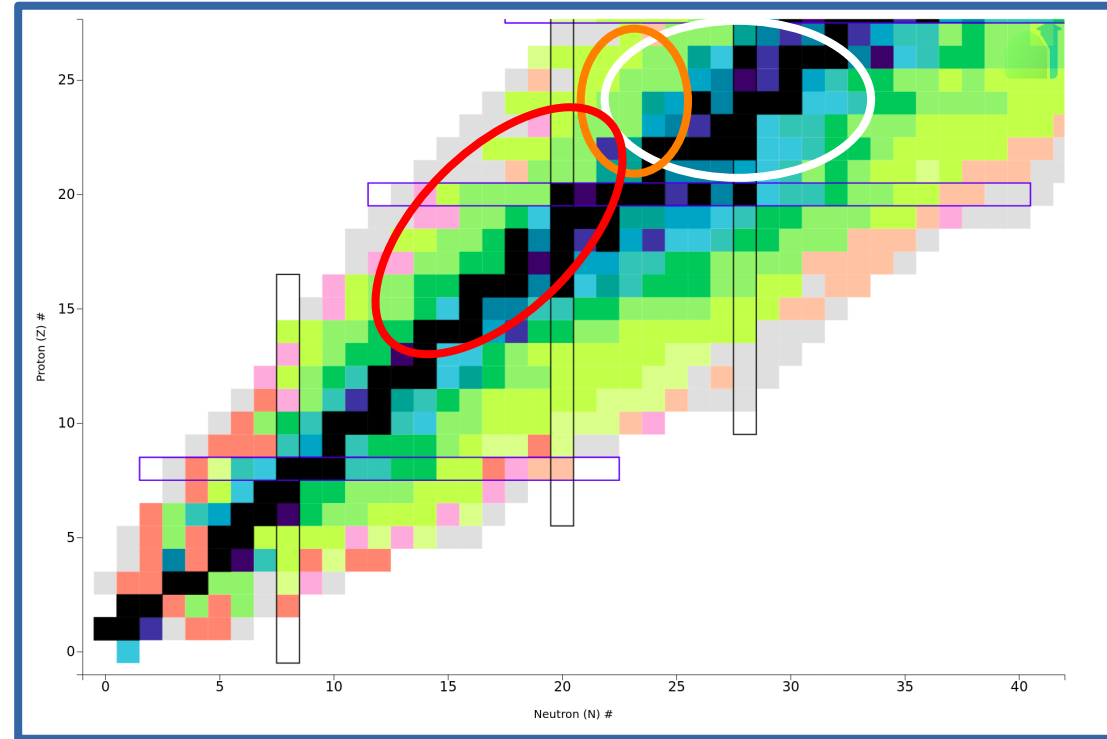
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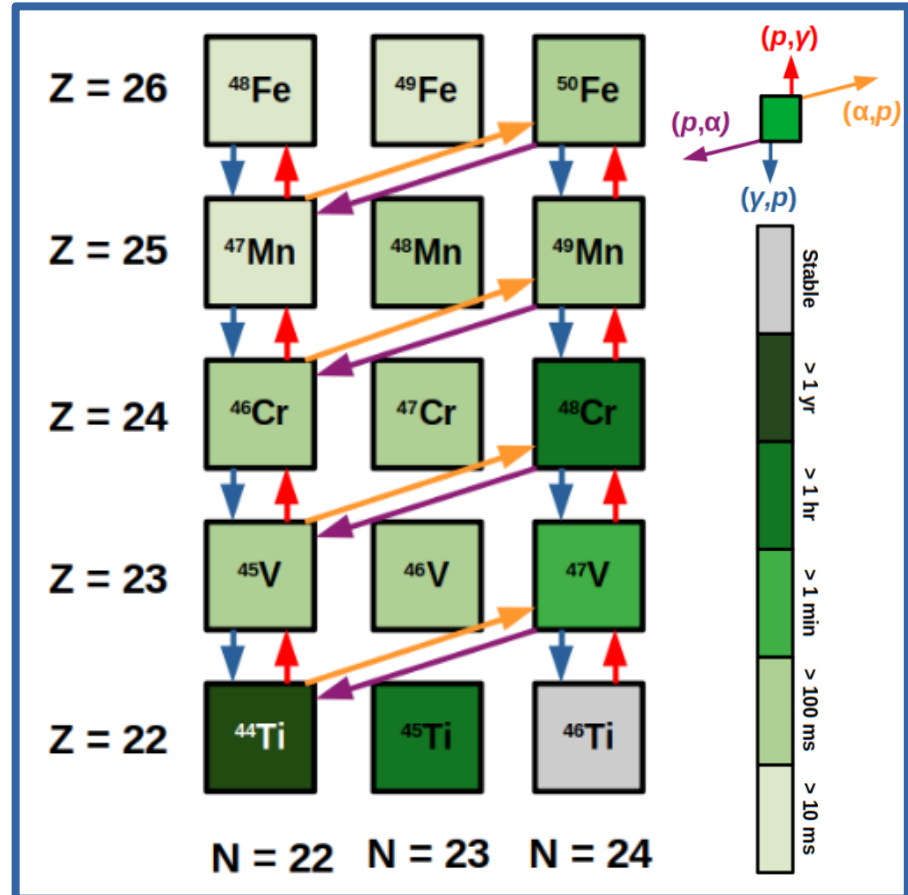
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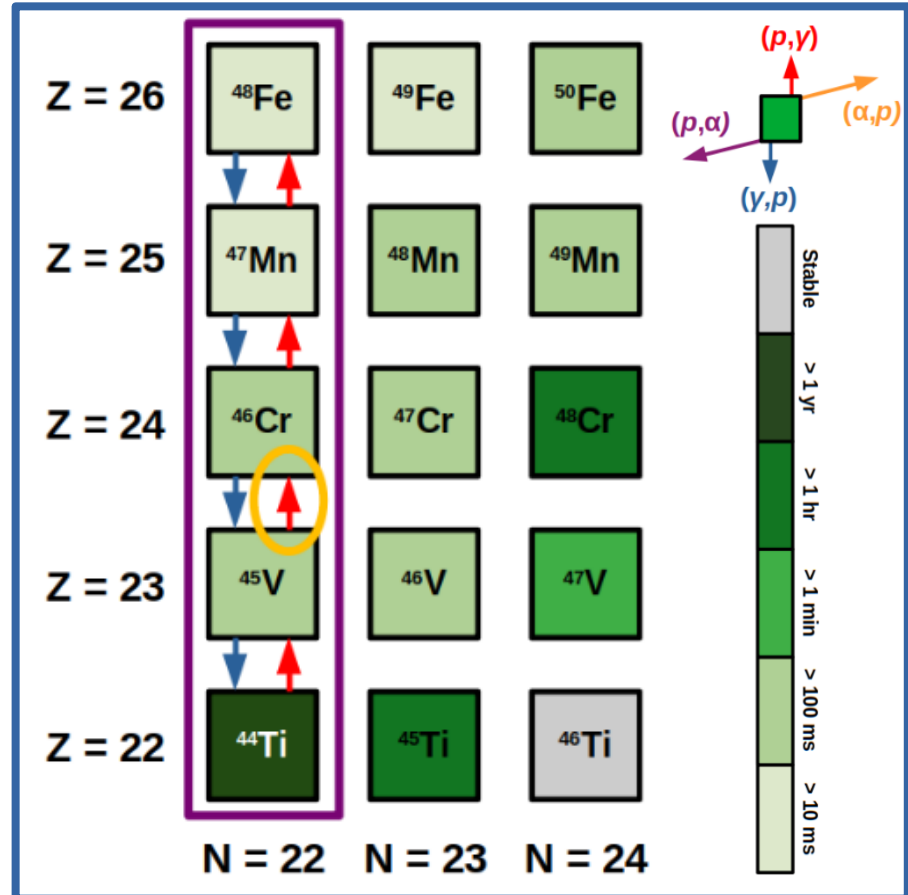
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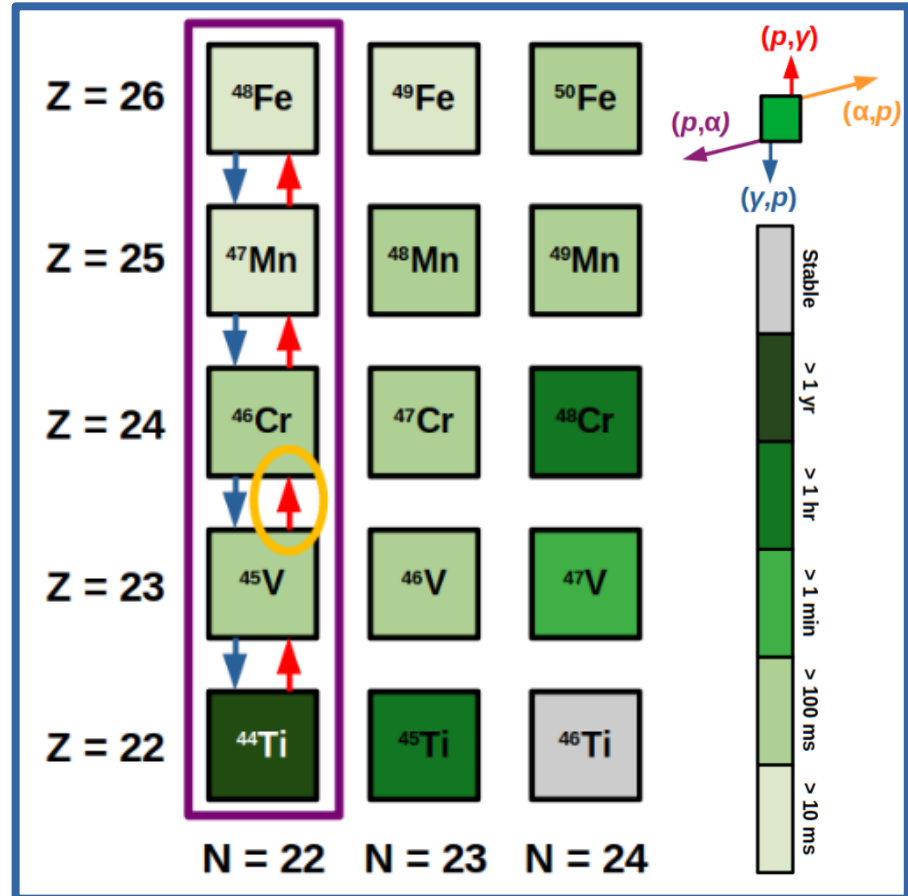
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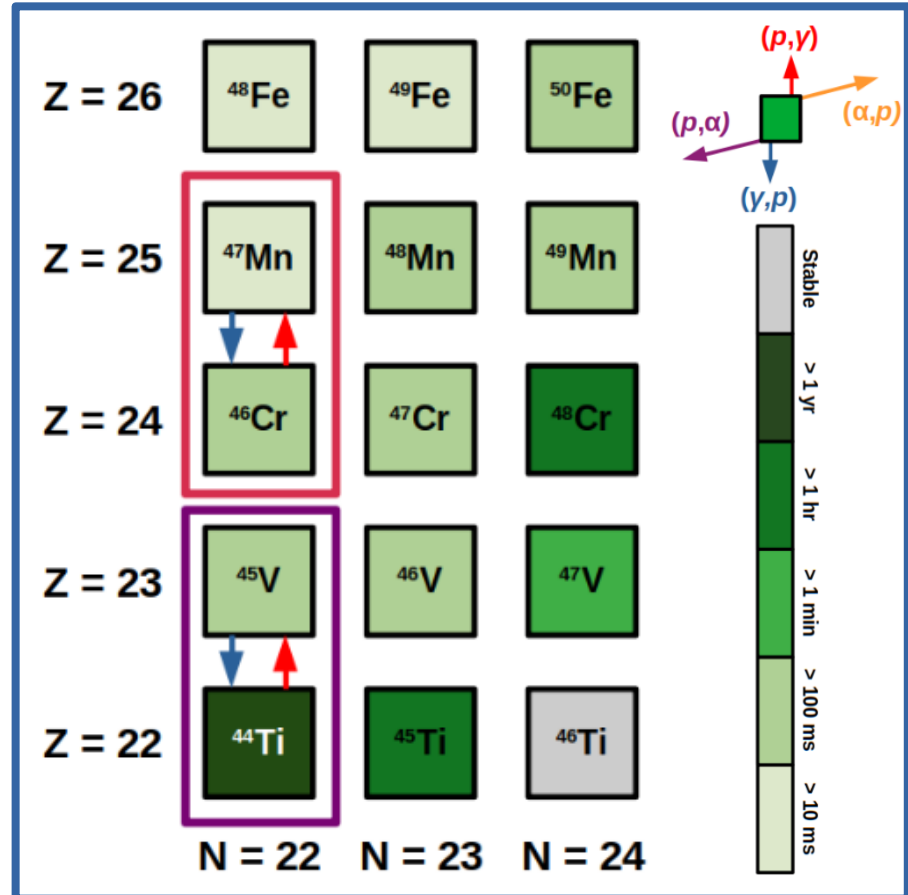
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- $^{45}\text{V}(p,\gamma)^{46}\text{Cr}$  importance identified in **sensitivity studies** [1] – high  $Q$  value



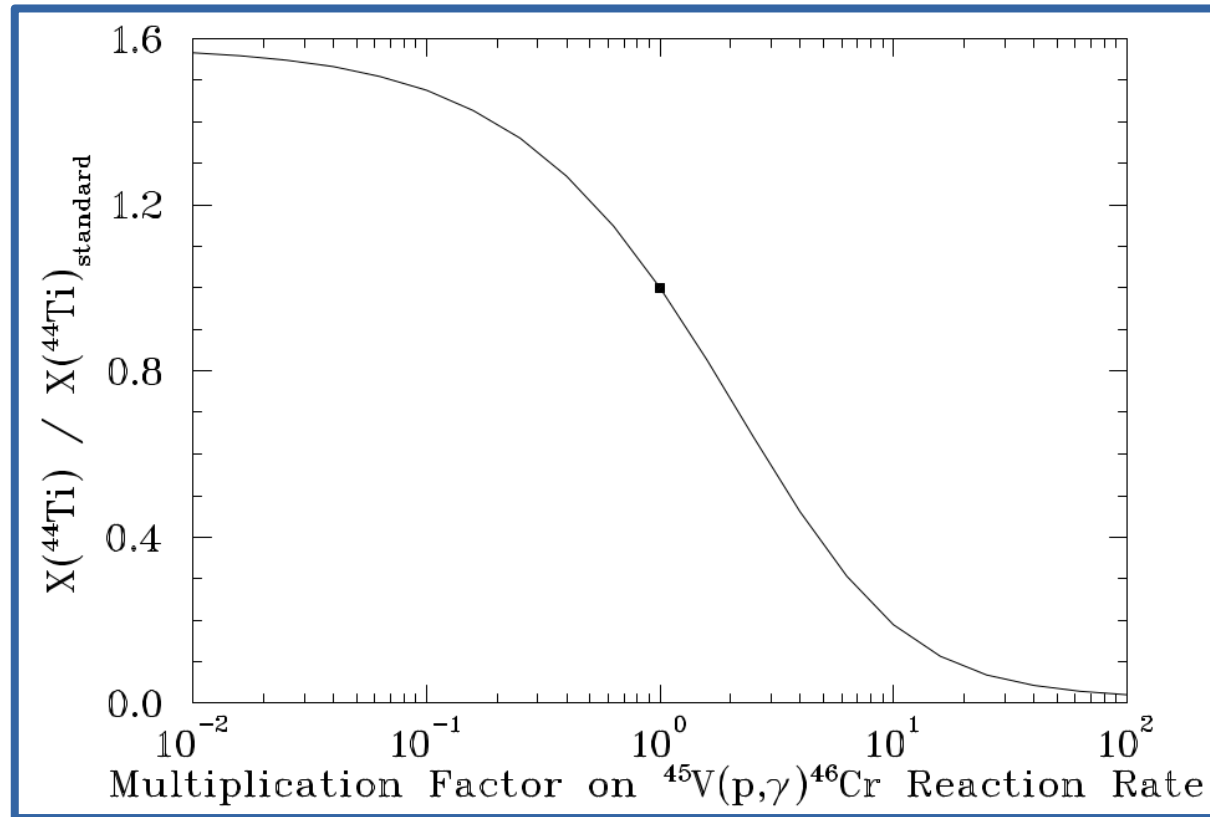
[1] G. Magkotsios et al., *Astrophys. J. Suppl. Ser.* **191**, p. 66 (2010).

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



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



# Finding the Reaction Rate

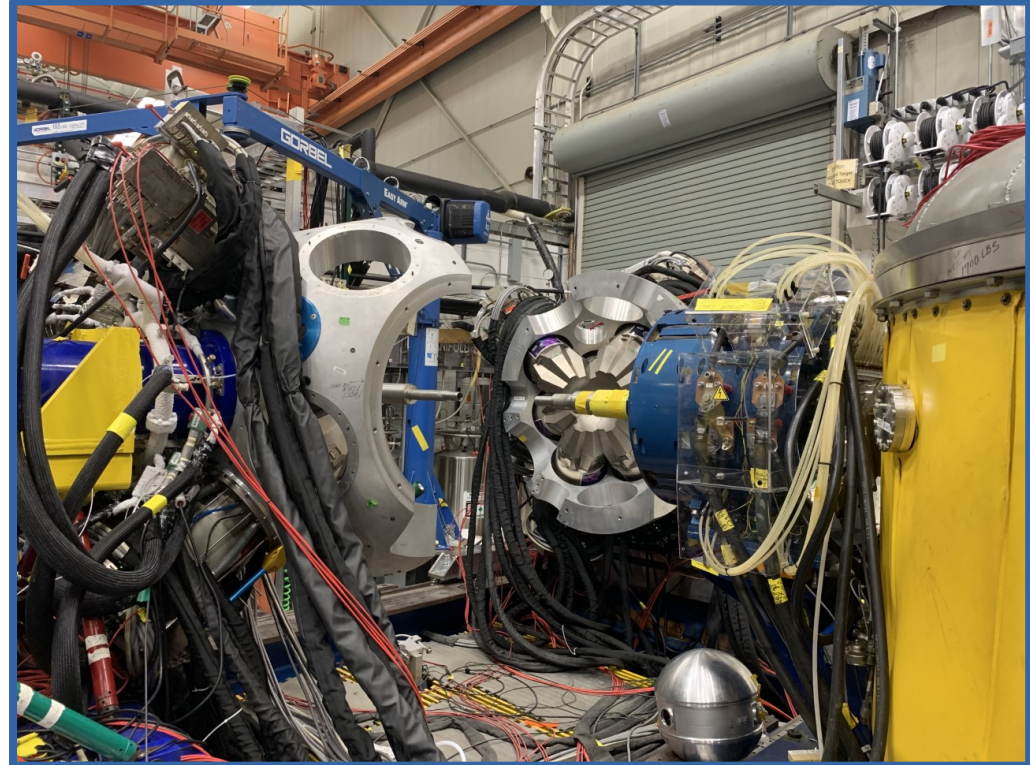
- Reaction governed by **low-spin resonant states** above proton separation energy ( $S_p = 4874(11)$  keV)
- **$\gamma$ -ray spectroscopy of  $^{46}\text{Cr}$**  – identifying proton-unbound resonant states
- Use resonant **energies** and **spins** to place constraints on  $^{45}\text{V}(\mathbf{p},\mathbf{\gamma})^{46}\text{Cr}$  stellar reaction rate in CCSN

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

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

# Experimental Set-Up

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



# Fusion-Evaporation Channels

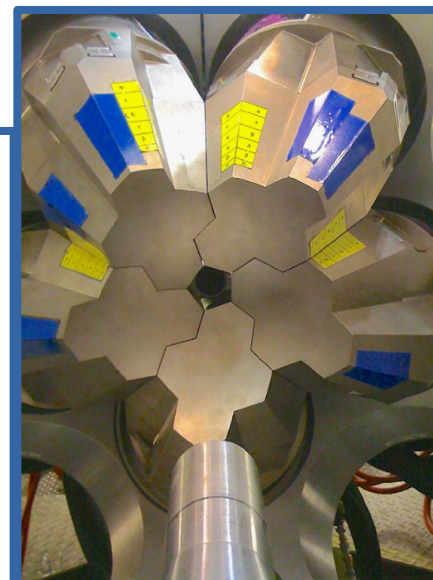
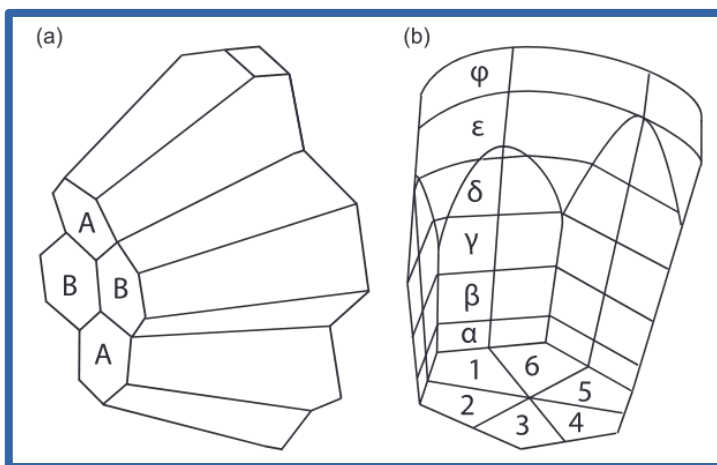
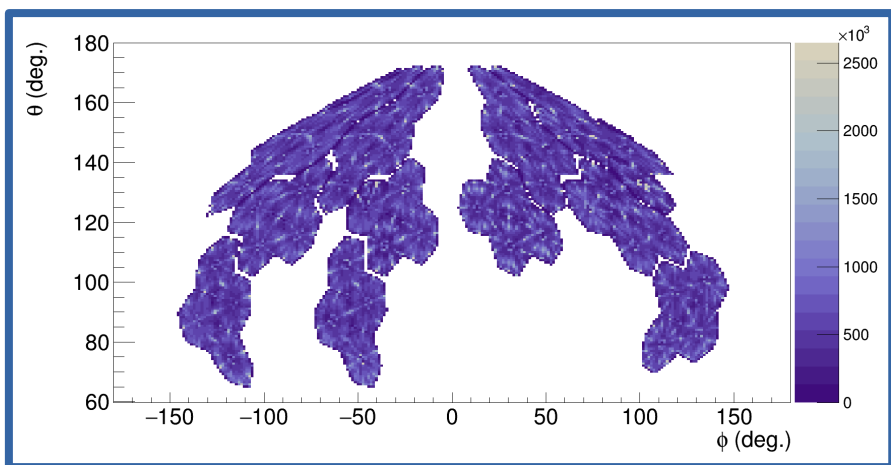
- Can't measure directly –  
 $^{45}\text{V}$   $t_{1/2} \sim 500$  ms
- Fusion-evaporation reaction –  
 $^{12}\text{C}(^{36}\text{Ar}, 2n)^{46}\text{Cr}$
- Other channels dominate this reaction –  $p$ -rich side of stability
- **Contamination** from oxygen on target – significant production of  $^{49}\text{Cr}$

Channel	Mode	Yield (%)
$^{46}\text{Ti}$	$2p$	28.6
$^{46}\text{V}$	$pn$	18.5
$^{45}\text{Ti}$	$2pn$	16.9
$^{43}\text{Sc}$	$\alpha p$	16.4
$^{40}\text{Ca}$	$2\alpha$	9.02
⋮	⋮	⋮
$^{46}\text{Cr}$	$2n$	<b>0.025</b>

Calculations provided by PACE4

# GRETINA

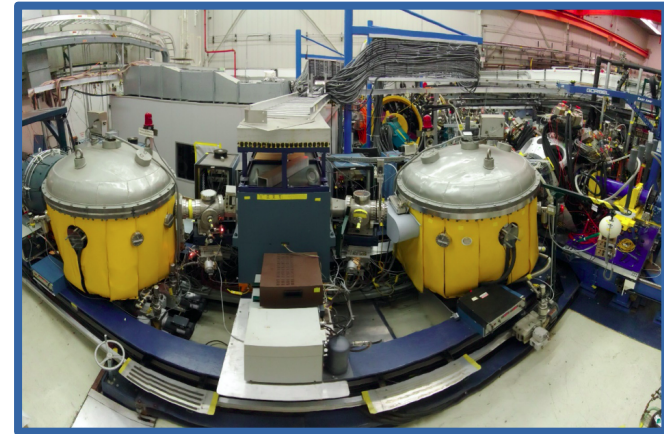
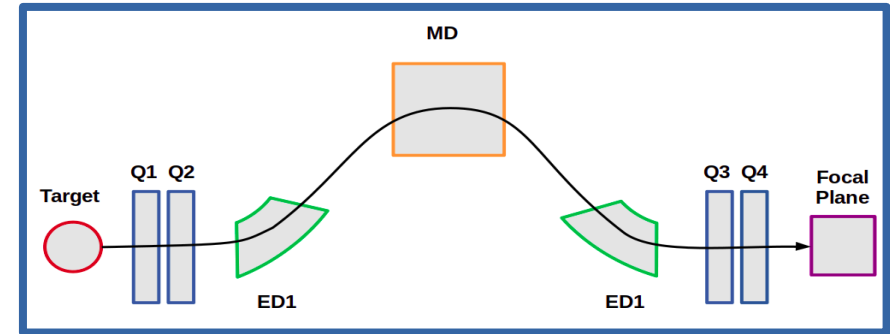
- State-of-the-art **HPGe**  $\gamma$ -ray detector array
- Detect **prompt  $\gamma$  rays** in coincidence with recoils
- **$\gamma$ -ray tracking** – reconstructs Compton scattered  $\gamma$  rays – high efficiency
- Operated with 11 modules, total of **44 crystals**



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

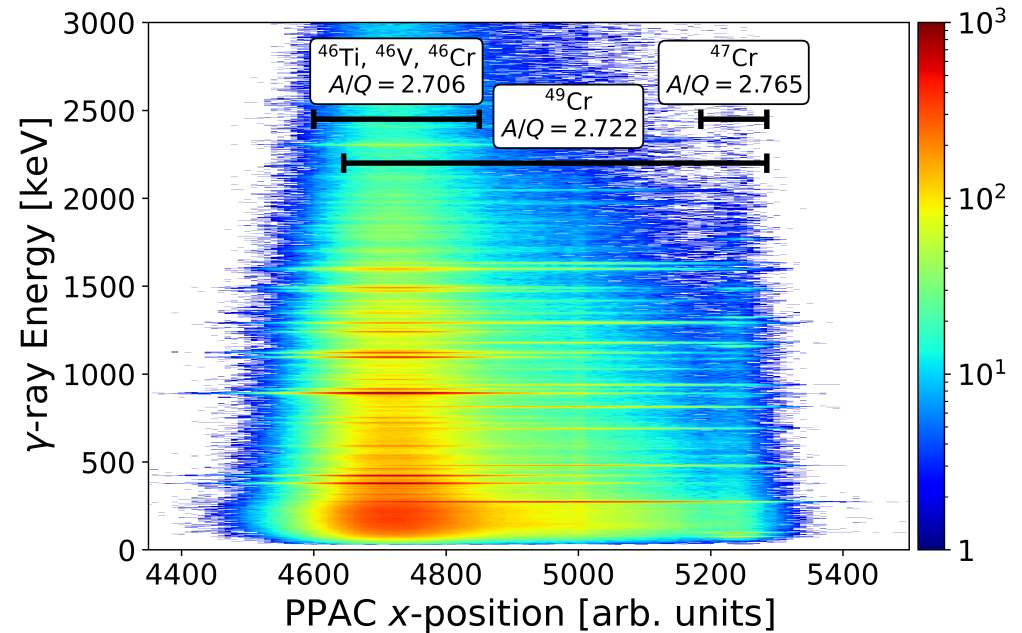
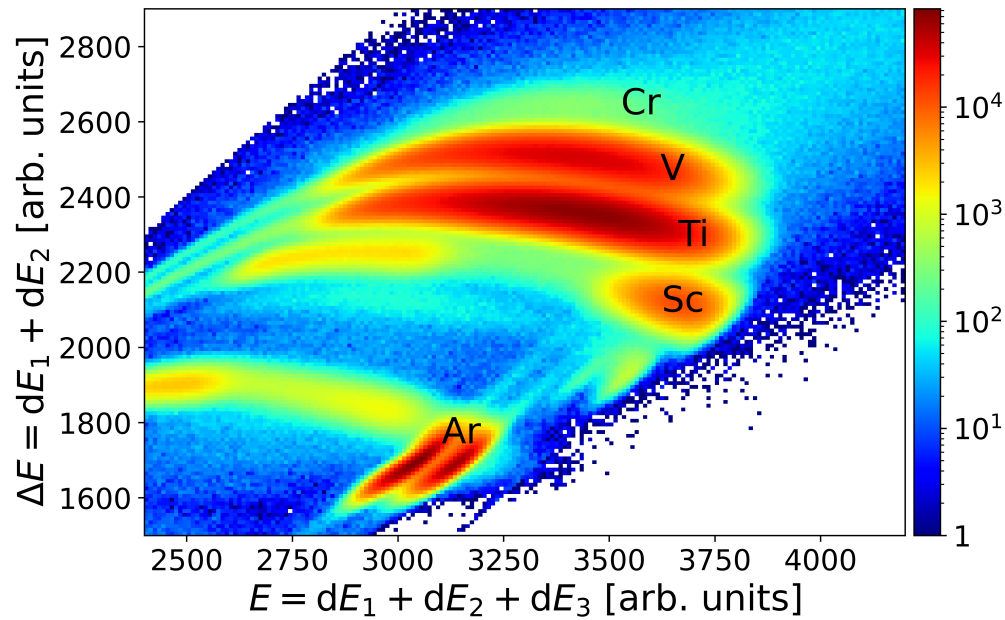
# FMA

- Separates recoils by **mass/charge ( $A/Q$ )** at the focal plane
  - Electric and magnetic dipoles
  - Magnetic quadrupoles
- **Ionisation chamber** at focal plane – identify recoil isotopes by  **$Z$**

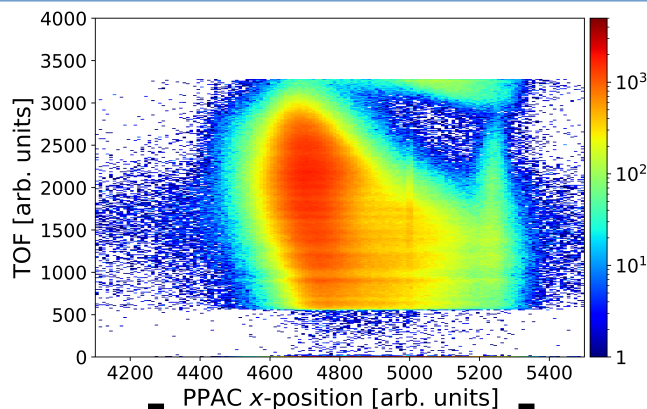


<https://www.anl.gov/phy/fragment-mass-analyzer>

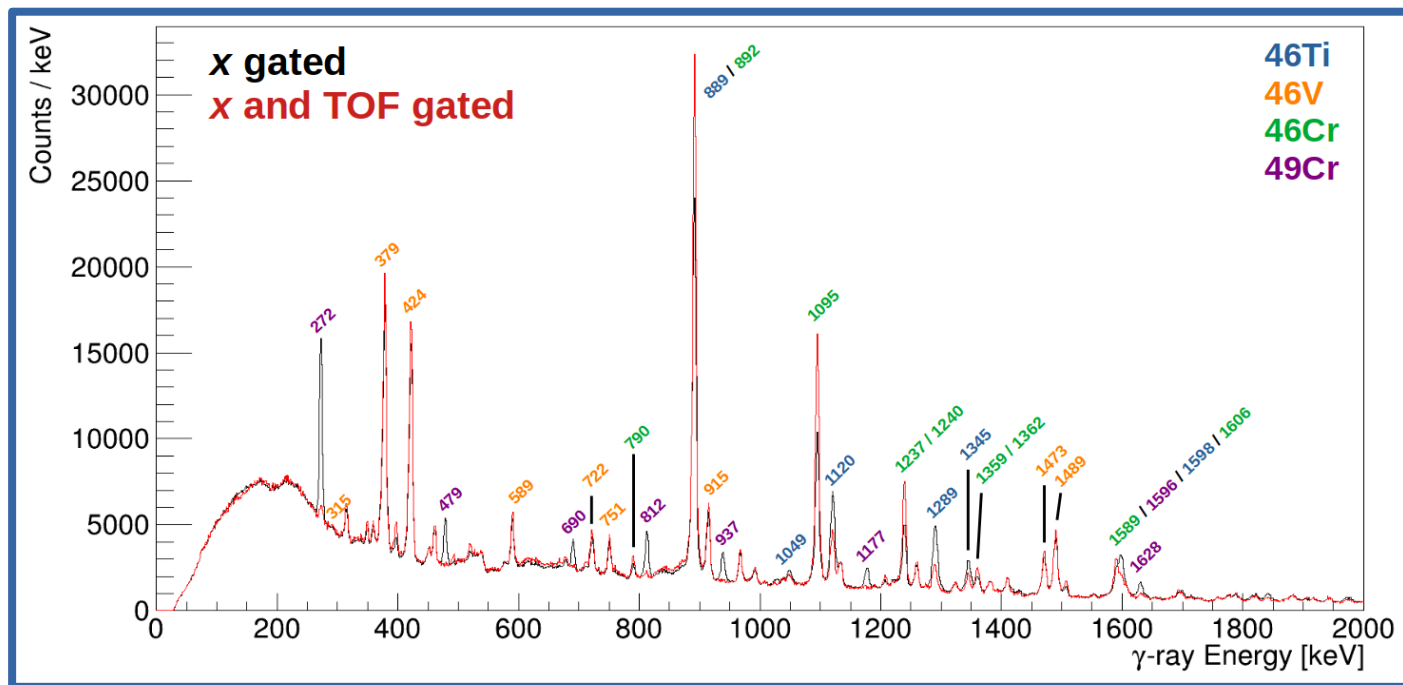
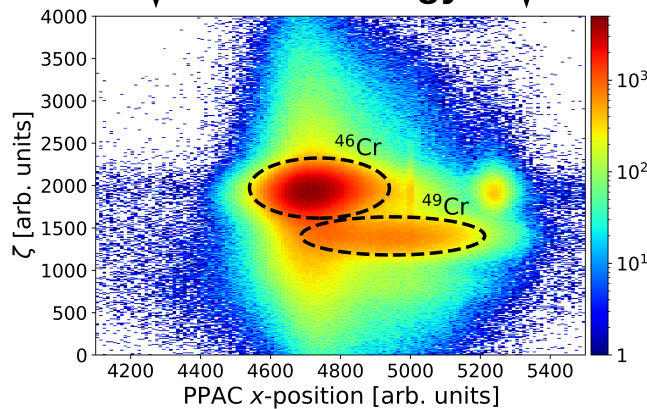
# Z and A/Q Gate



# TOF Gate

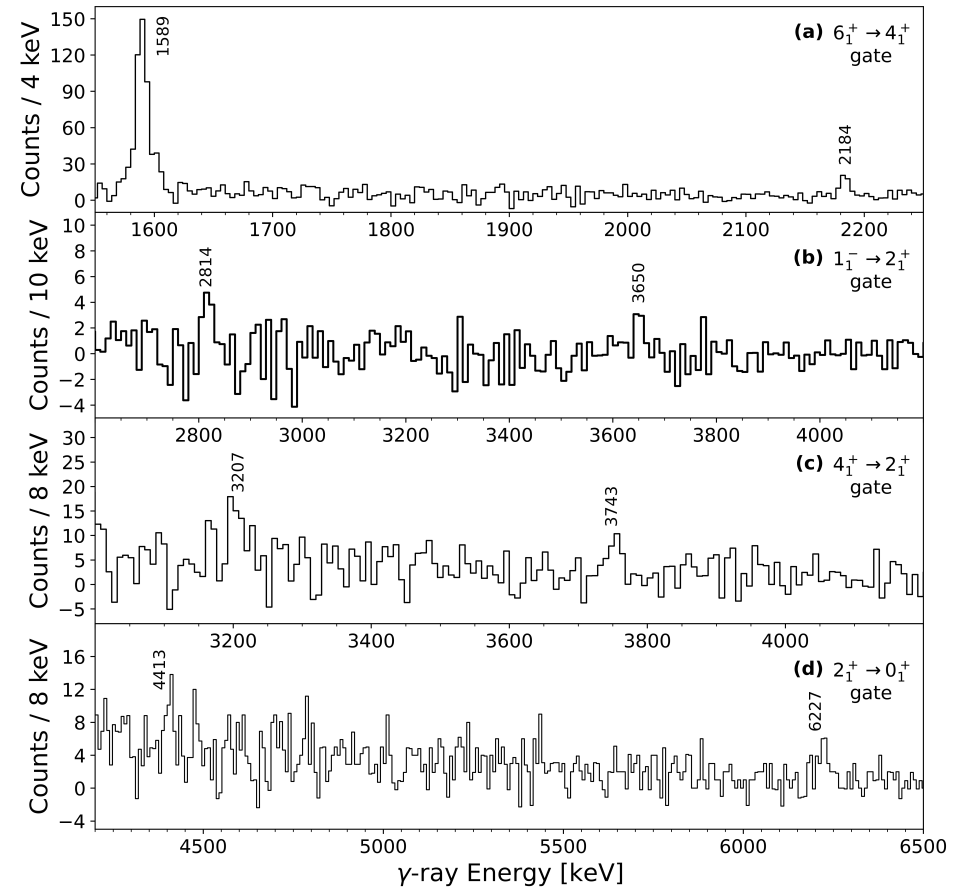


Correction for  
recoil energy

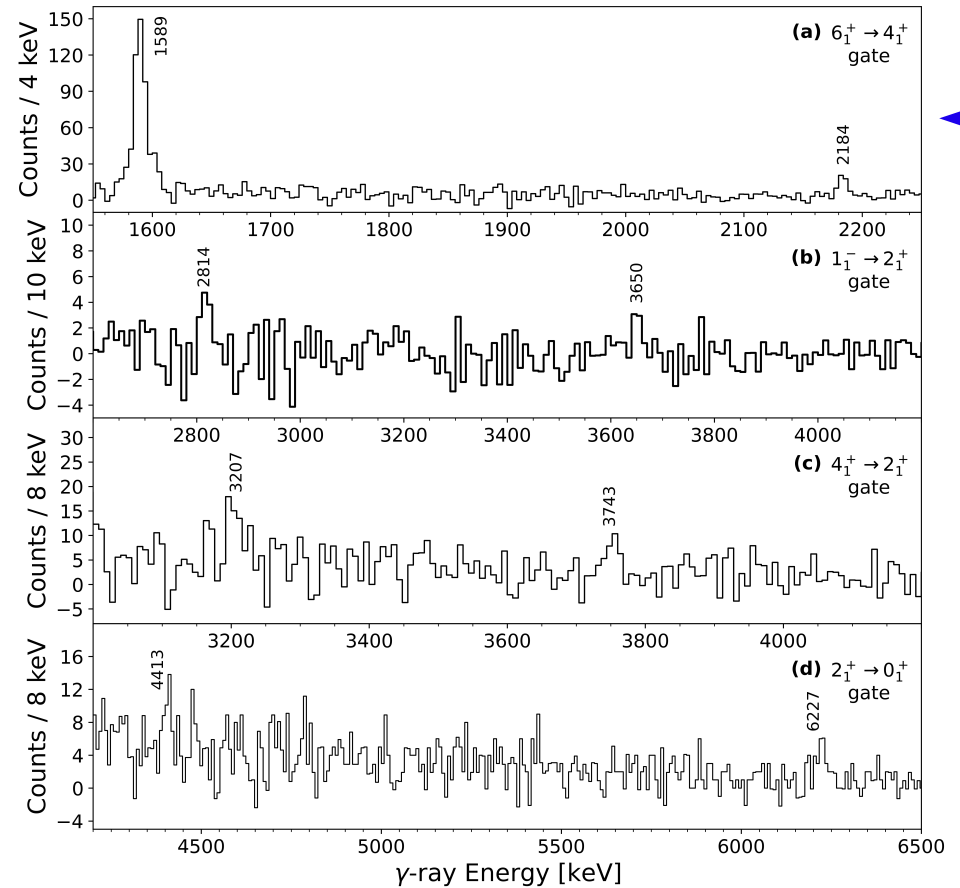
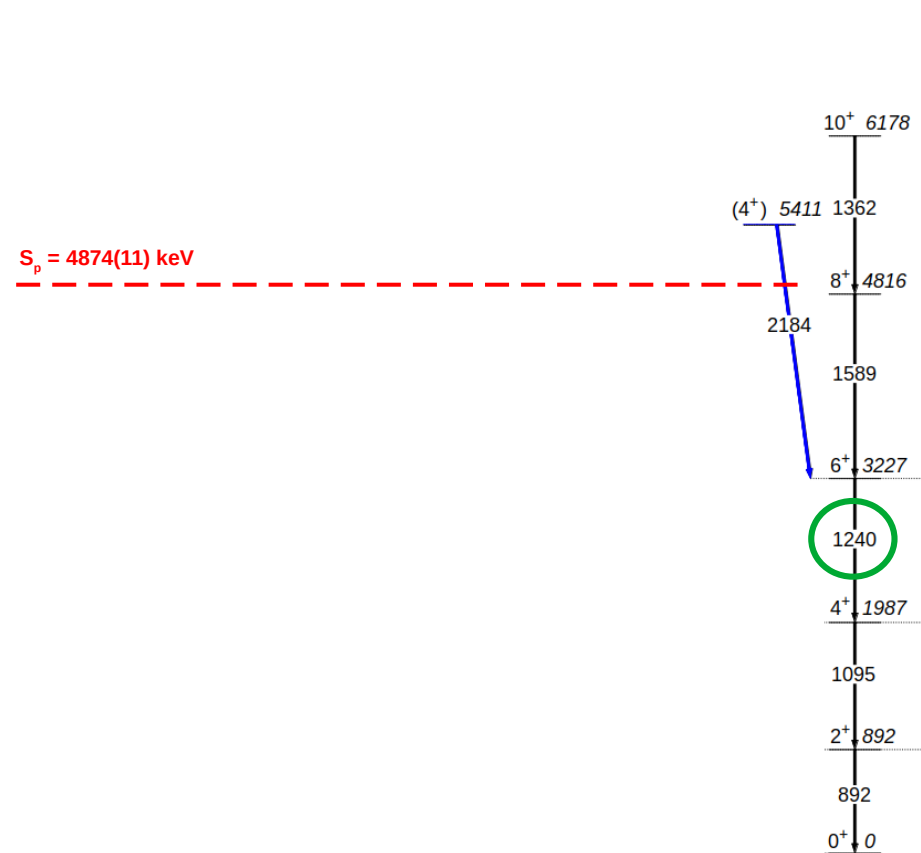


$E_\gamma$ (keV)	% of counts reduced using x and TOF
1120 ( $^{46}\text{Ti}$ )	70(2)
424 ( $^{46}\text{V}$ )	40.4(4)

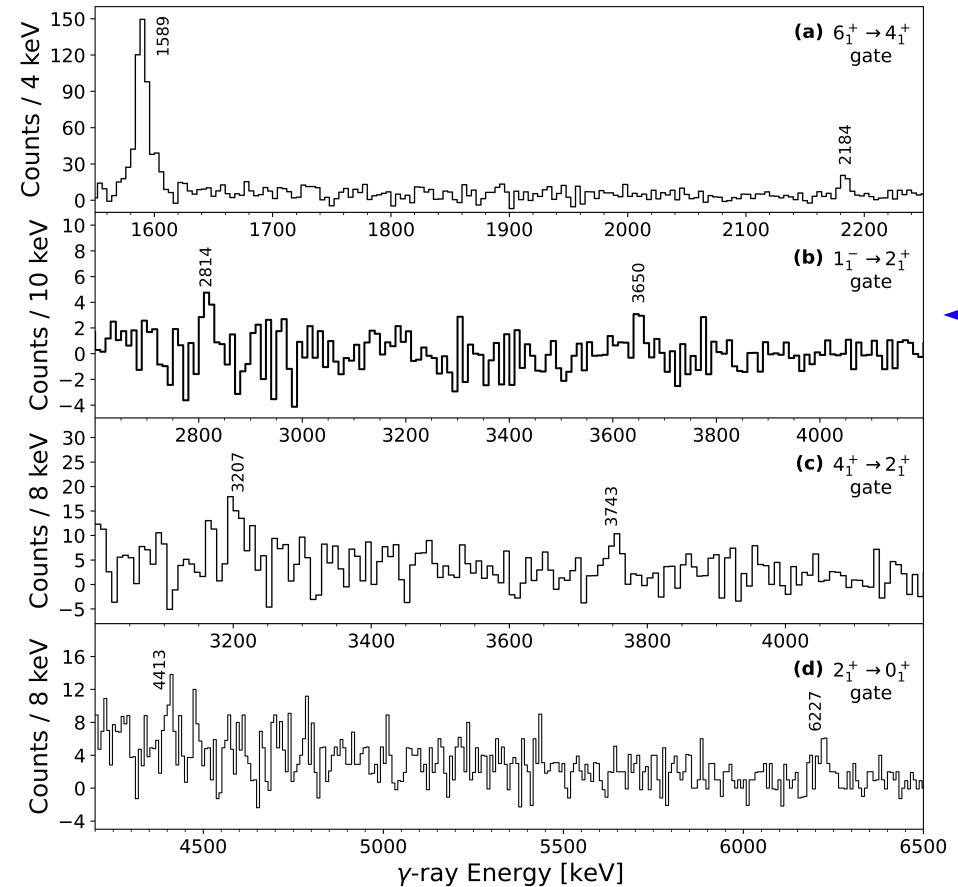
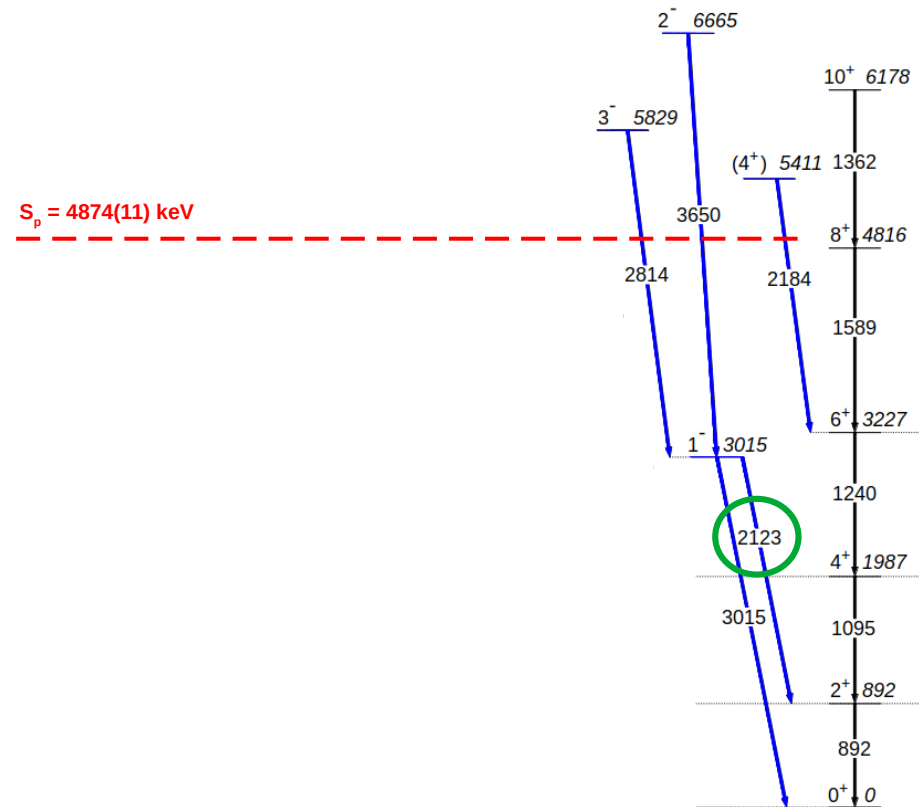
# Results – Resonant States



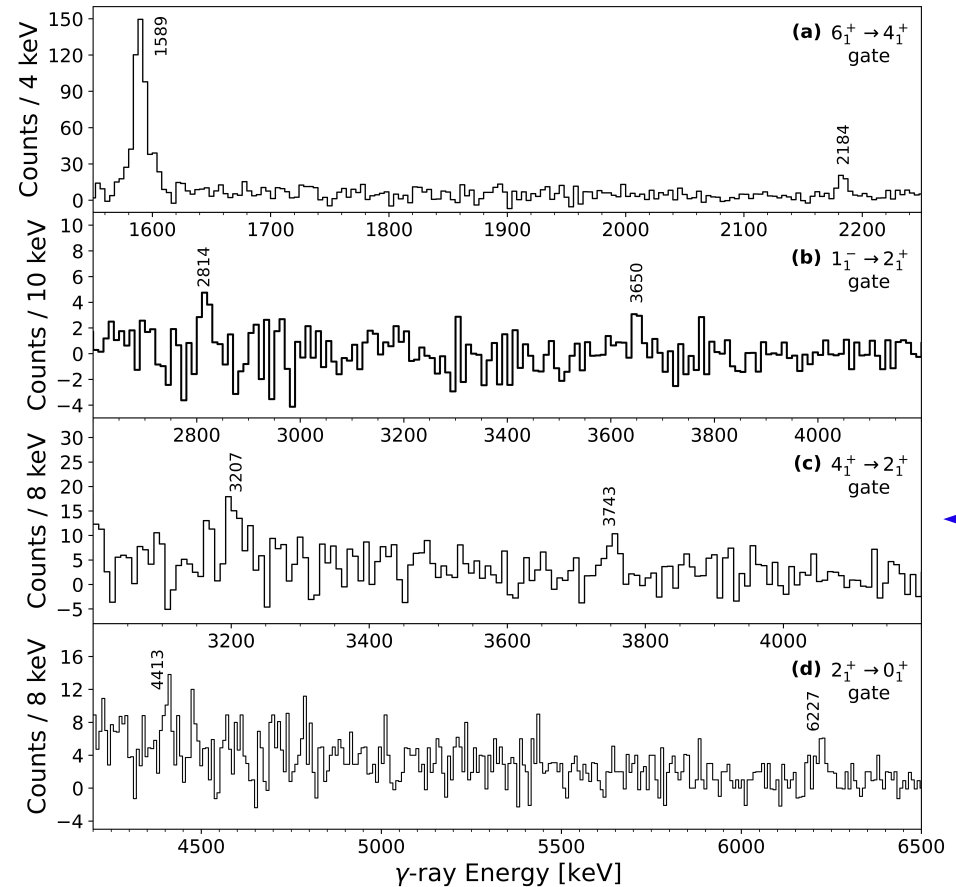
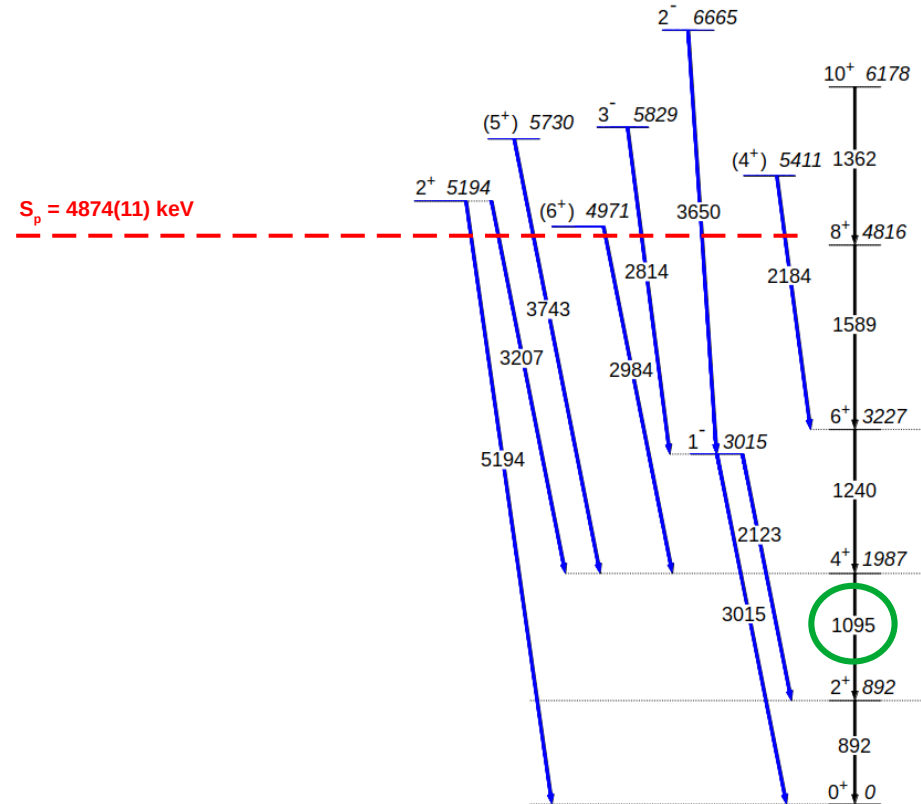
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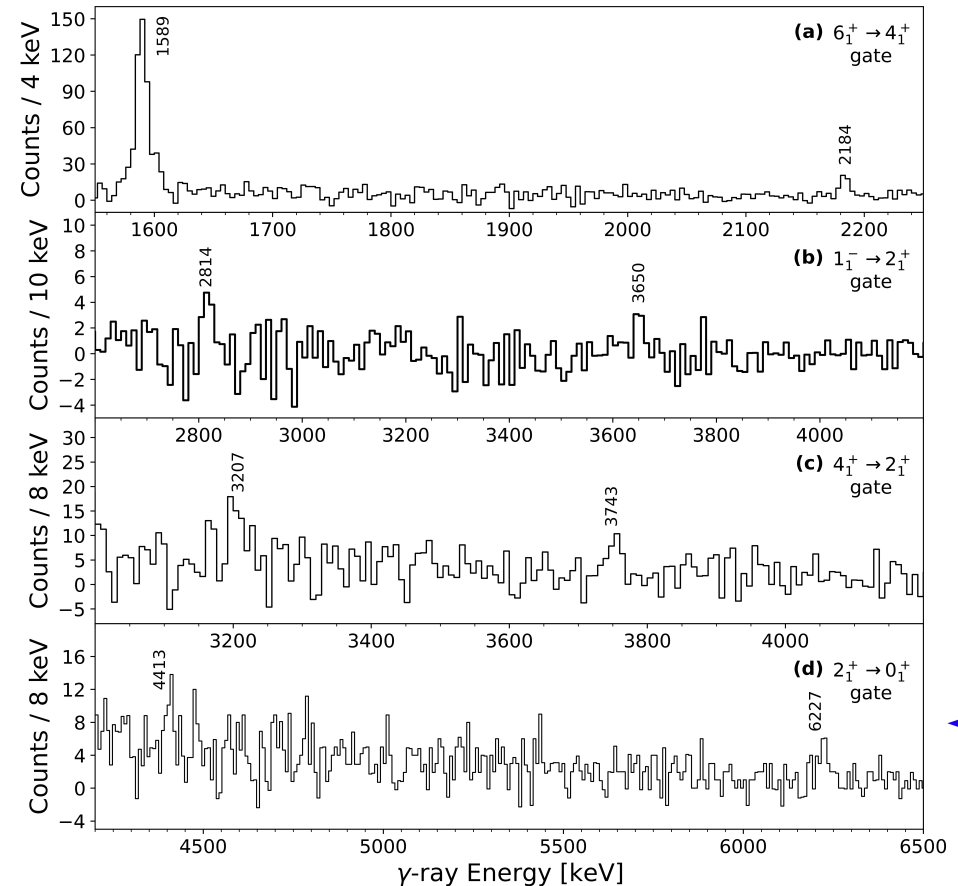
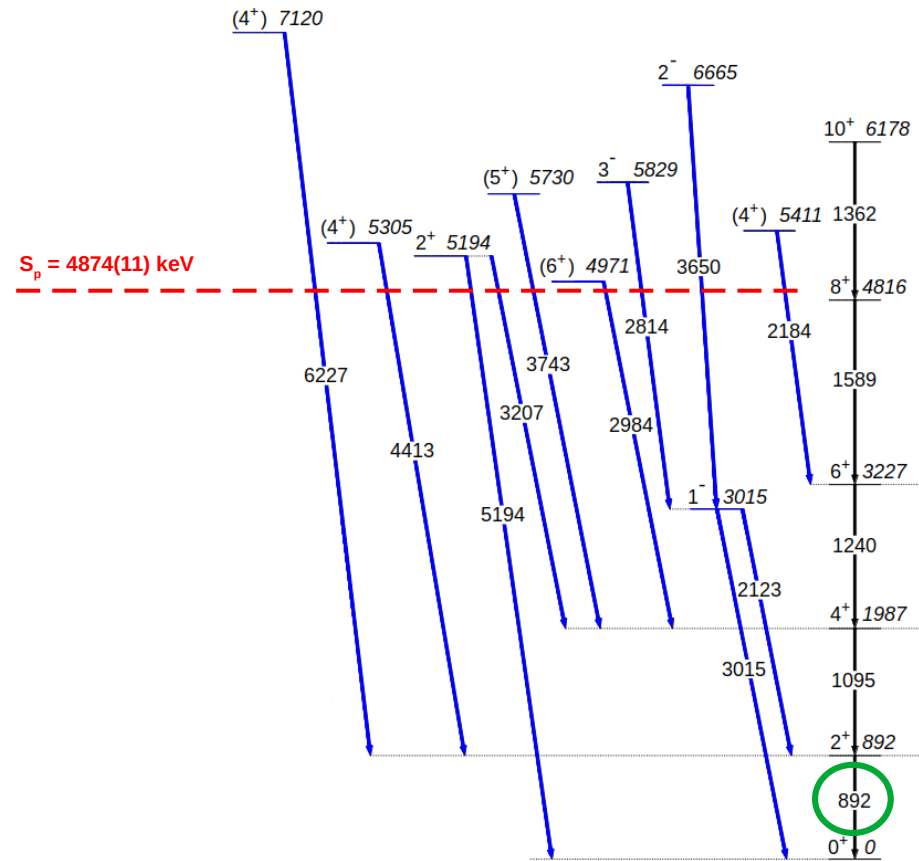
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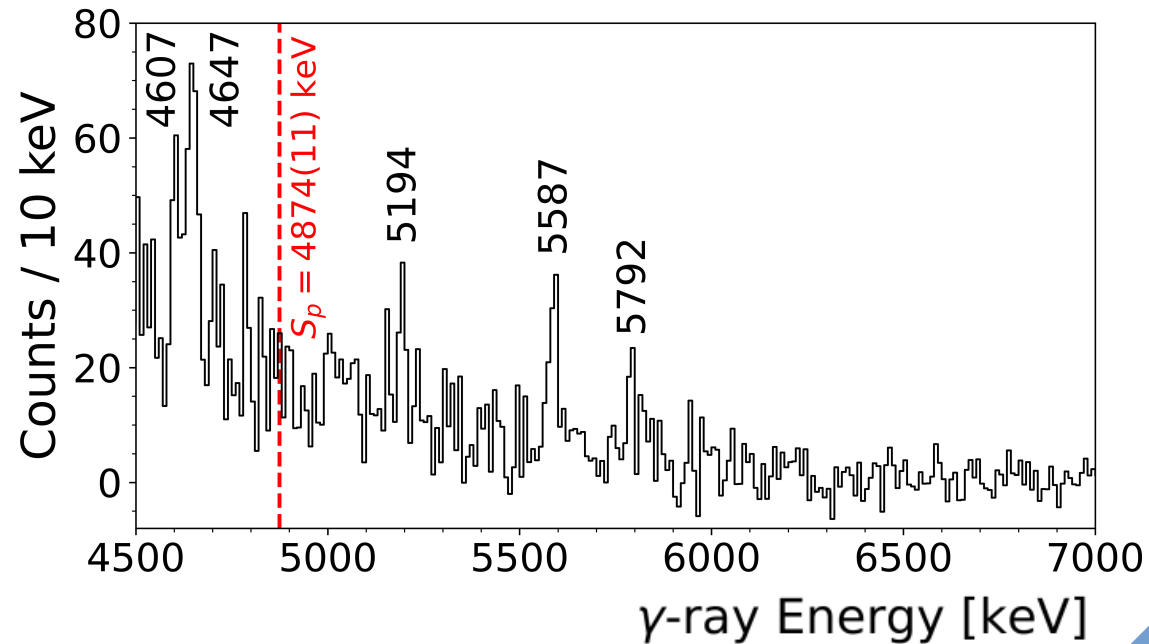
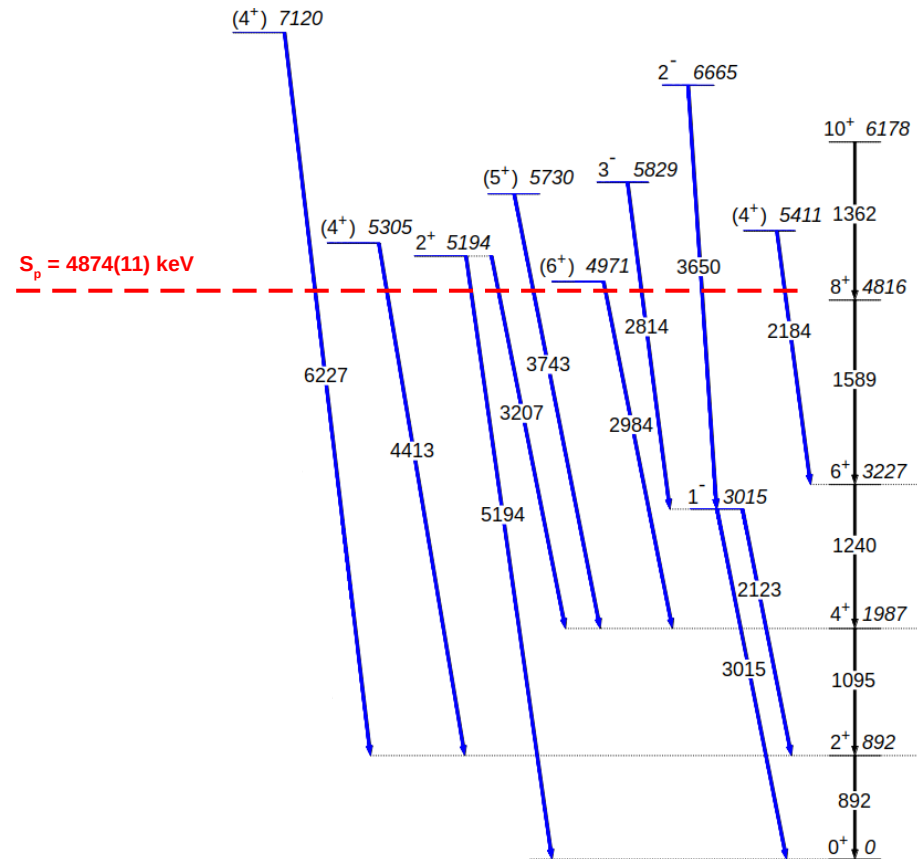
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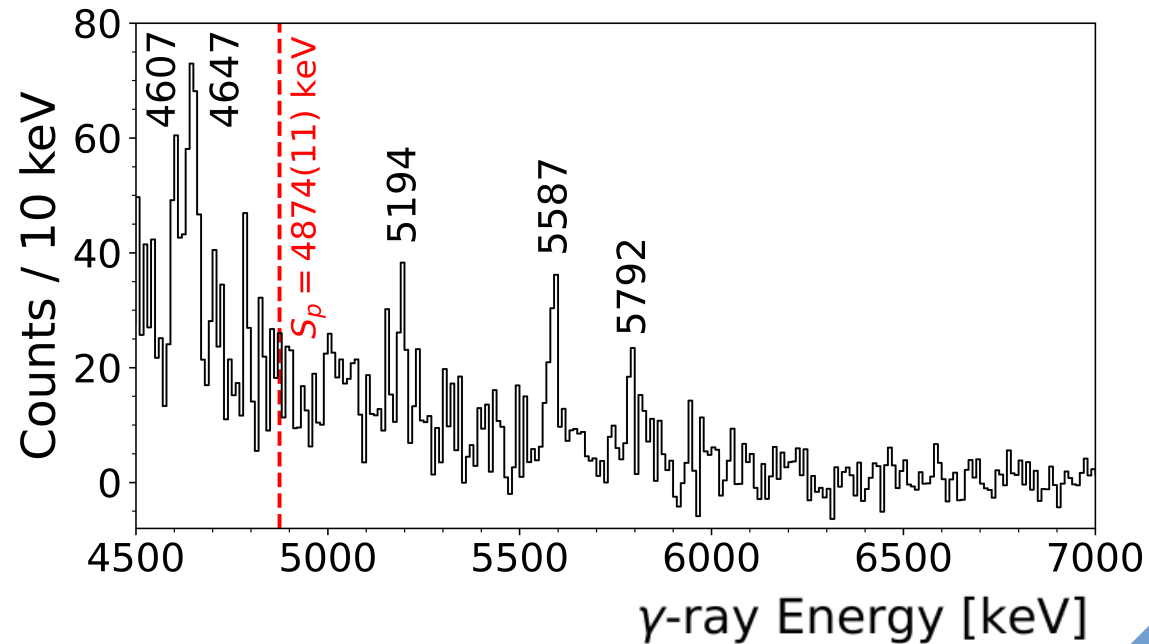
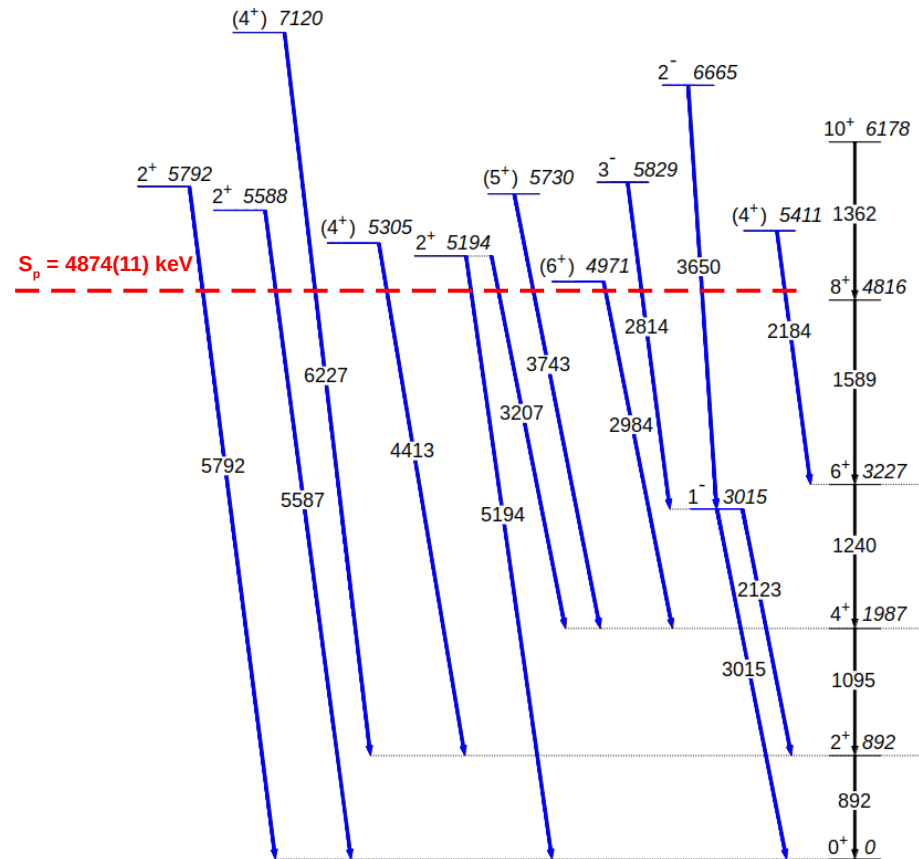
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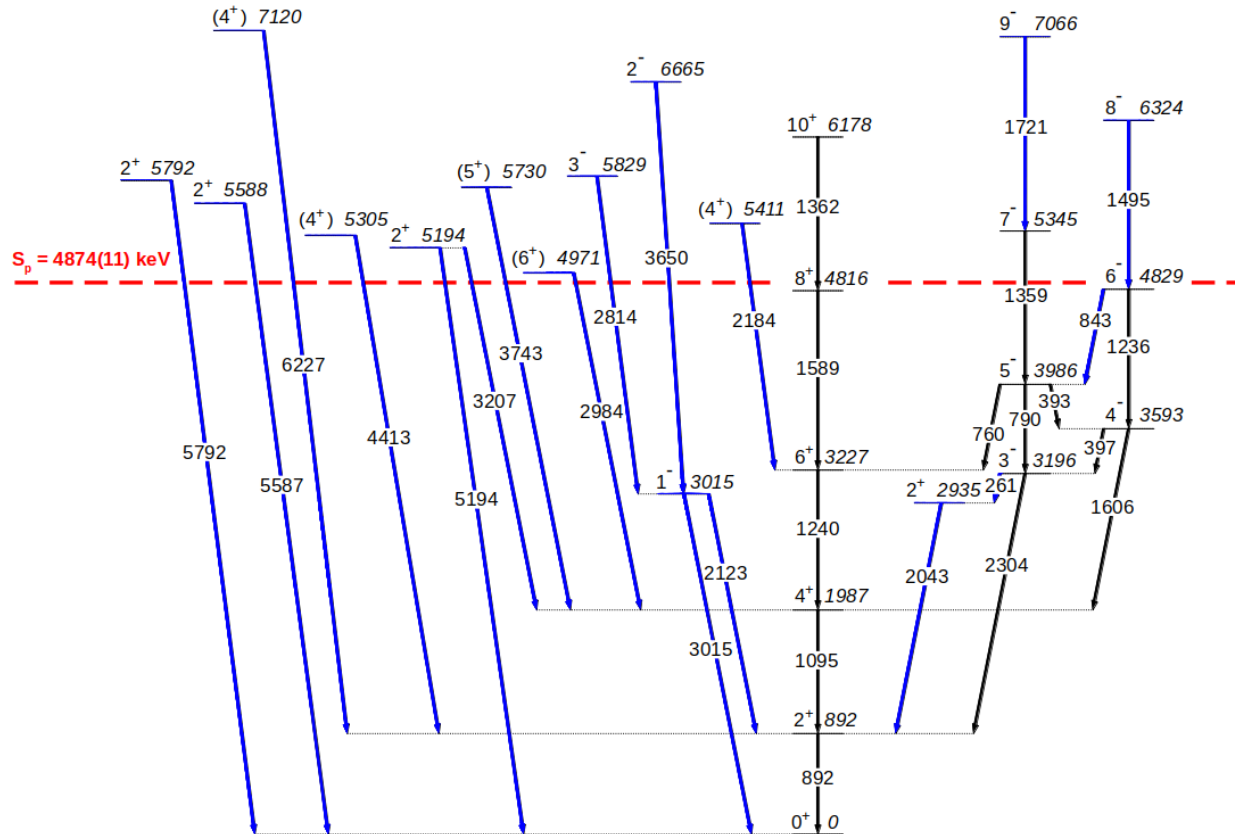
# Results – Resonant States



# Results – Resonant States



# Results – Partial Level Scheme



# Results – Reaction Rate

$E_x$ (keV)	$E_\gamma$ (keV)	$E_r$ (keV)	$J_i \rightarrow J_f$	$C^2S_{SM}$	$\Gamma_p$ (eV)	$\Gamma_\gamma$ (eV)	$\omega\gamma$ (eV)
4971(6)	2984(6)	97(13)	$(6^+) \rightarrow 4_1^+$	0.02	$2.70 \times 10^{-25}$	$9.51 \times 10^{-2}$	$2.19^{+3.12}_{-1.29} \times 10^{-25}$
5194(1)	3207(3)	320(11)	$2^+ \rightarrow 4_1^+$	0.19	$1.58 \times 10^{-7}$	$3.49 \times 10^{-1}$	$4.94^{+7.03}_{-2.90} \times 10^{-8}$
	5194(1)		$2^+ \rightarrow 0_1^+$				
5305(5)	4413(5)	431(12)	$(4^+) \rightarrow 2_1^+$	0.003	$5.69 \times 10^{-7}$	$4.81 \times 10^{-2}$	$3.20^{+4.56}_{-1.88} \times 10^{-7}$
5411(1)	2184(1)	537(11)	$(4^+) \rightarrow 6_1^+$	0.26	$1.72 \times 10^{-3}$	$4.98 \times 10^{-1}$	$9.64^{+13.67}_{-5.66} \times 10^{-4}$
5588(2)	5587(2)	714(11)	$2^+ \rightarrow 0_1^+$	0.11	$4.13 \times 10^{-2}$	$7.22 \times 10^{-1}$	$1.22^{+1.64}_{-0.71} \times 10^{-2}$
5730(6)	3743(6)	856(13)	$(5^+) \rightarrow 4_1^+$	0.007	$2.55 \times 10^{-2}$	$9.21 \times 10^{-2}$	$1.37^{+1.56}_{-0.76} \times 10^{-2}$
5792(2)	5792(2)	918(11)	$2^+ \rightarrow 0_1^+$	0.01	$8.27 \times 10^{-2}$	$8.75 \times 10^{-1}$	$2.36^{+3.07}_{-1.35} \times 10^{-2}$
5829(6)	2814(6)	955(13)	$(3^-) \rightarrow 1_1^-$	0.001	$2.83 \times 10^{-2}$	$3.16 \times 10^{-1}$	$1.14^{+1.49}_{-0.65} \times 10^{-2}$
6665(5)	3650(5)	1791(12)	$(2^-) \rightarrow 1_1^-$	0.0001	$6.44 \times 10^{-2}$	$3.69 \times 10^{-1}$	$1.71^{+2.09}_{-0.96} \times 10^{-2}$
7120(7)	6227(7)	2246(13)	$(4^+) \rightarrow 2_1^+$	0.0001	$2.52 \times 10^0$	$8.12 \times 10^{-1}$	$3.46^{+2.26}_{-1.45} \times 10^{-1}$

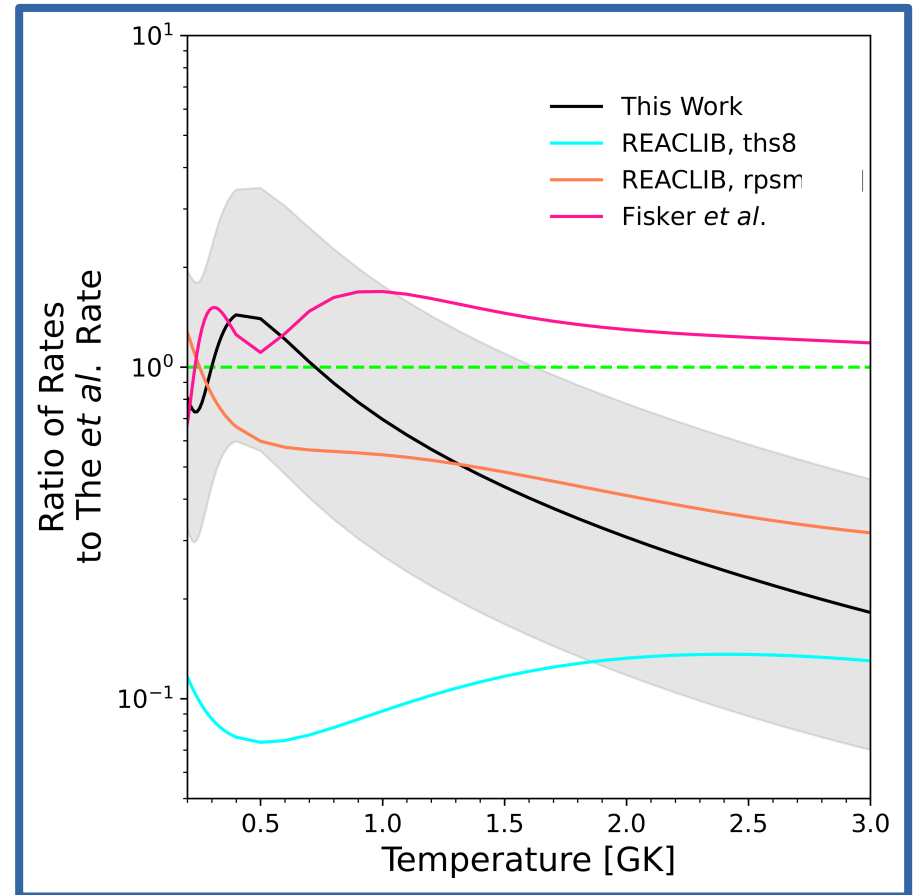
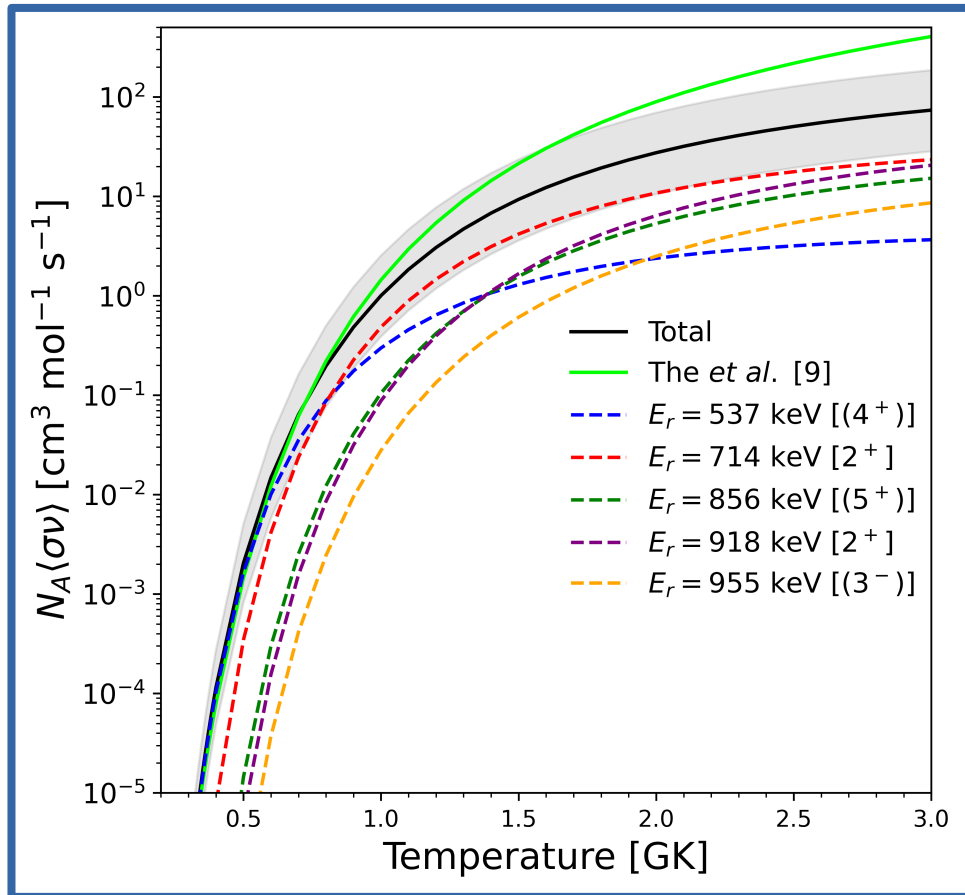
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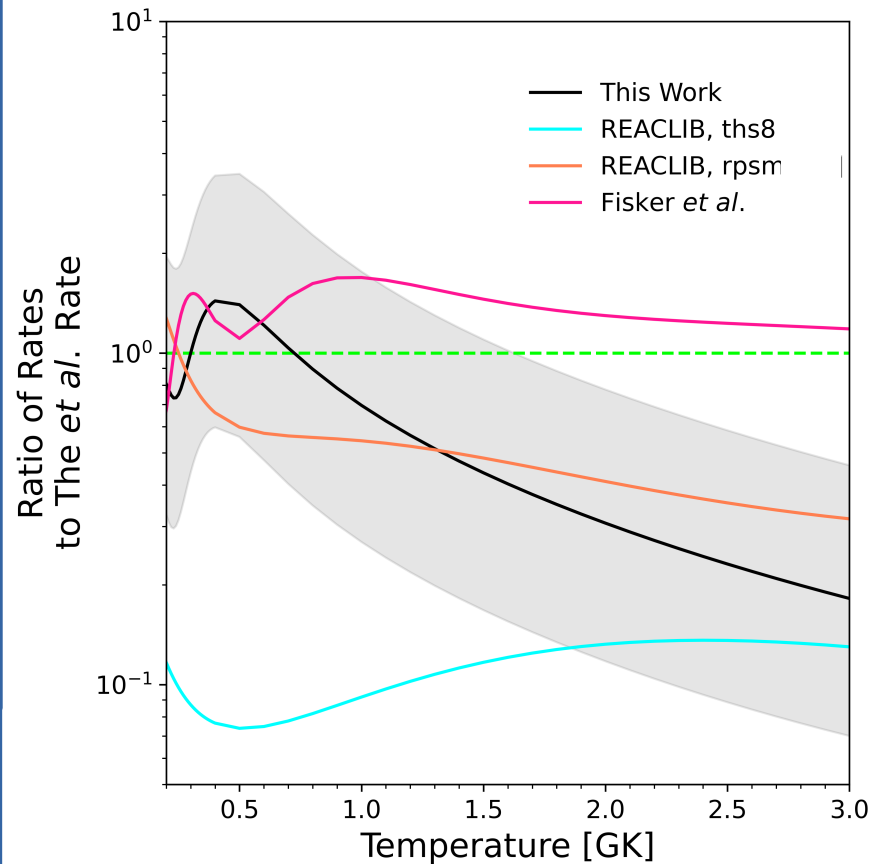
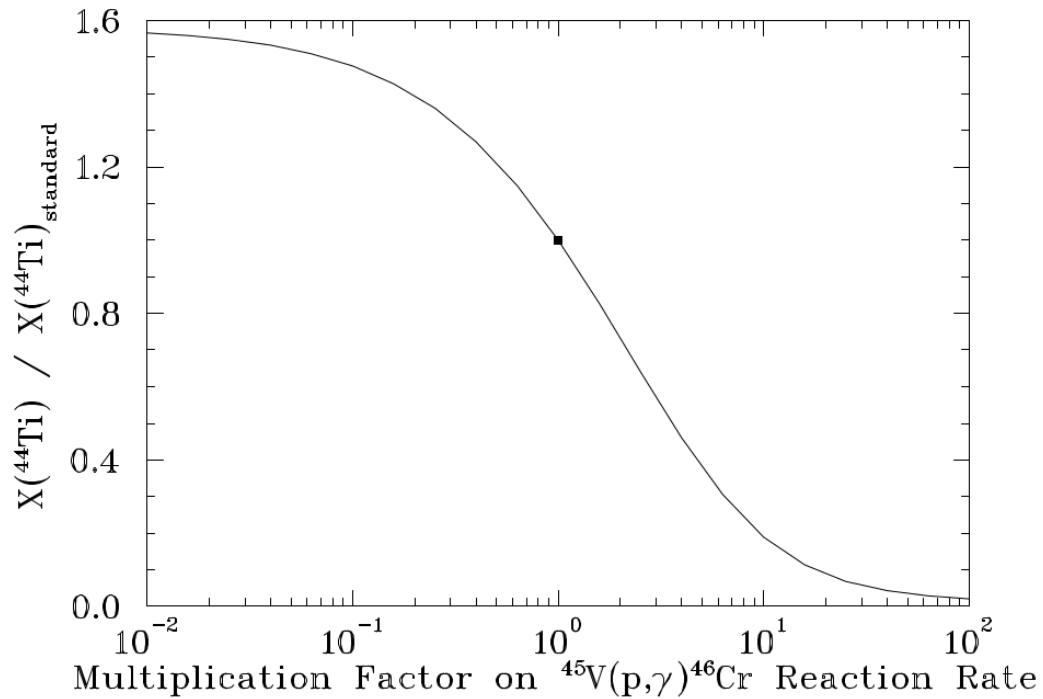
$$(\omega\gamma)_i = \left( \frac{2J_R + 1}{(2j_0 + 1)(2j_1 + 1)} \right) \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma}$$

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

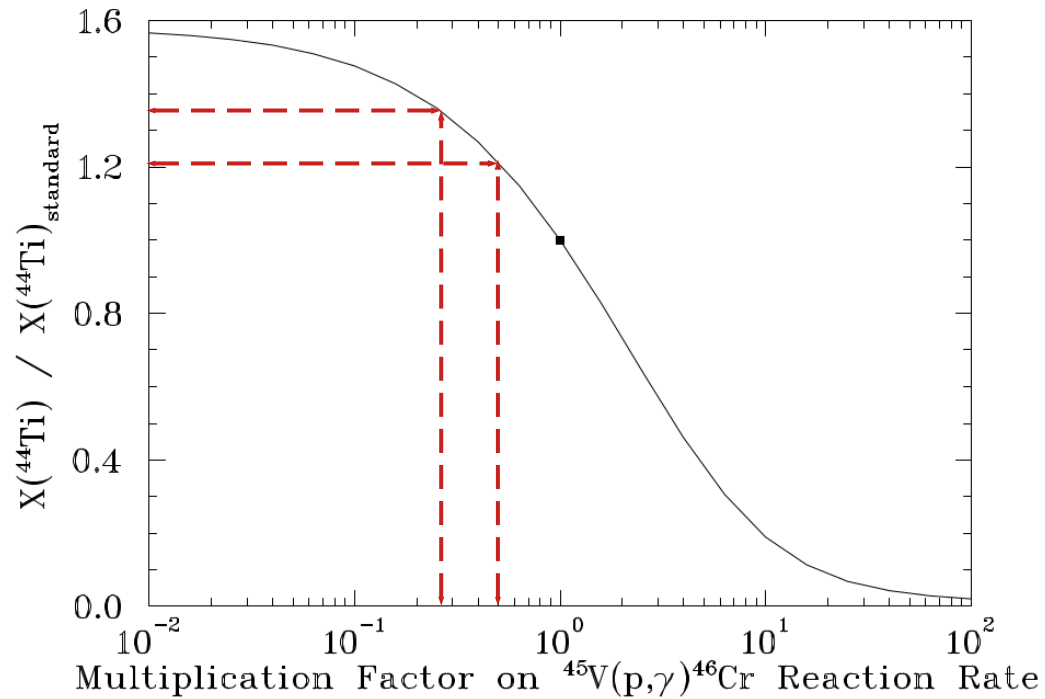
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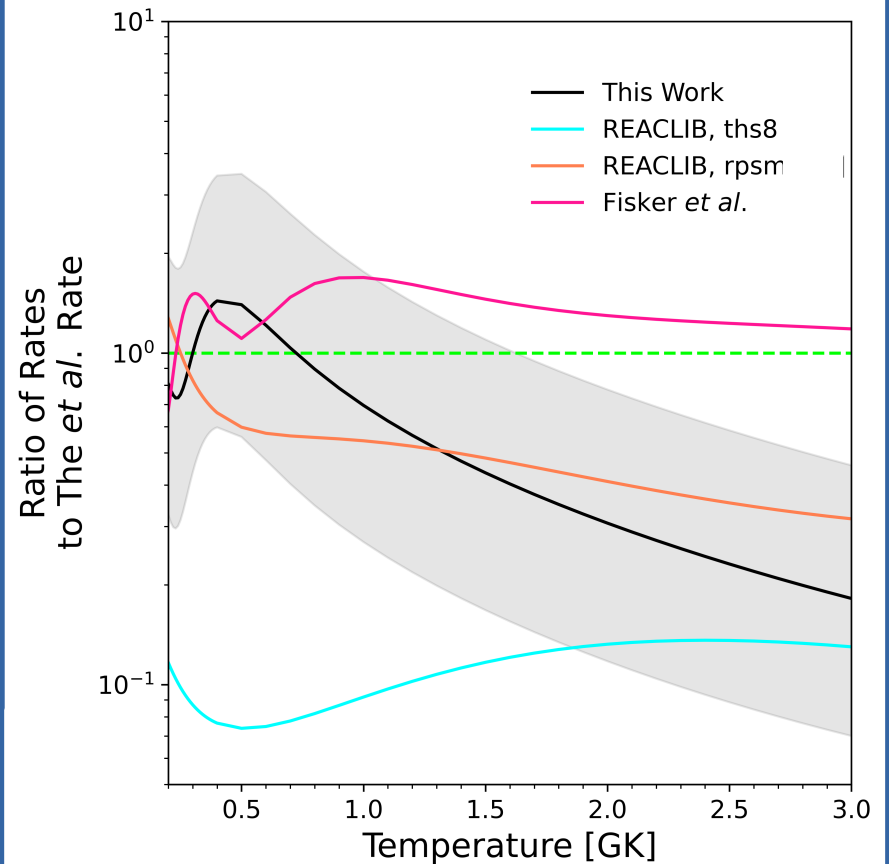
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- **~25 – 50%** of The *et al.* rate  $\rightarrow$  **~20 – 35%** increase in  $^{44}\text{Ti}$



# Summary and Future Work

- $^{45}\text{V}(p,\gamma)^{46}\text{Cr}$  reaction rate is key to the **destruction of  $^{44}\text{Ti}$**  during the  $\alpha$ -rich freeze-out of **CCSN**
- First identification of **18  $\gamma$  rays**, leading to observation of **12 proton-unbound states in  $^{46}\text{Cr}$**  (more sub- $S_p$  states to be verified)
- New rate is  **$\sim 25 - 50\%$**  of previously known rate  $\rightarrow$   **$\sim 20 - 35\%$  more  $^{44}\text{Ti}$**  in ejecta
- Transfer reaction to get  $\text{C}^2\text{S}$
- Mass measurement of  $^{46}\text{Cr}$  (L. Canete *et al.* proposal at JYFL)
- Analyse sub- $S_p$  states

# Acknowledgments

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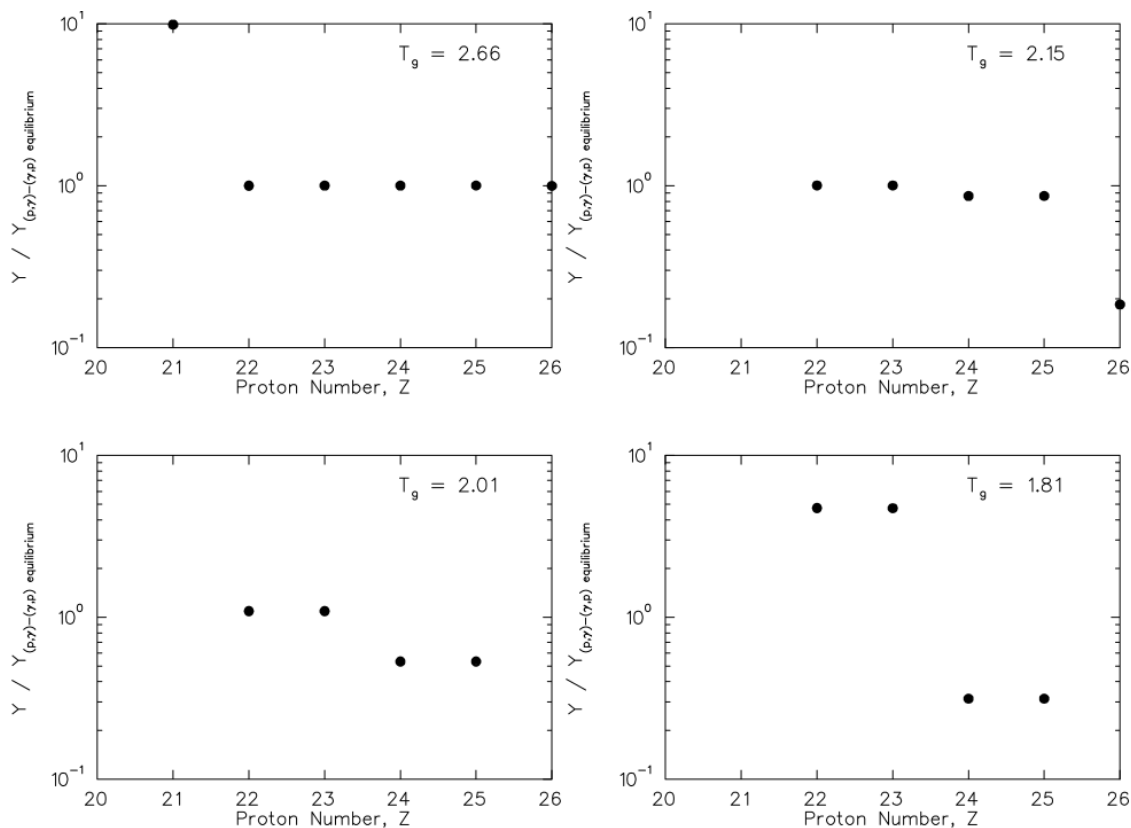


FIG. 13.—Evolution of the  $(p, \gamma)$ – $(\gamma, p)$  equilibrium for the  $N = 22$  isotones as the temperature falls, with the standard  $^{45}\text{V}(p, \gamma)^{46}\text{Cr}$  rate. The  $^{44}\text{Ti}$  and  $^{45}\text{V}$  pair ( $Z = 22$  and  $23$ ) increasingly depart from equilibrium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

TABLE 5  
ORDER OF IMPORTANCE OF  
REACTIONS PRODUCING  
 $^{44}\text{Ti}$  AT  $\eta = 0^a$

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

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

TABLE 4  
ORDER OF IMPORTANCE OF REACTIONS PRODUCING  $^{44}\text{Ti}$  AT  $\eta = 0$

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

# PACE4 Calculations

On  $^{12}\text{C}$

## 1. Yields of residual nuclei

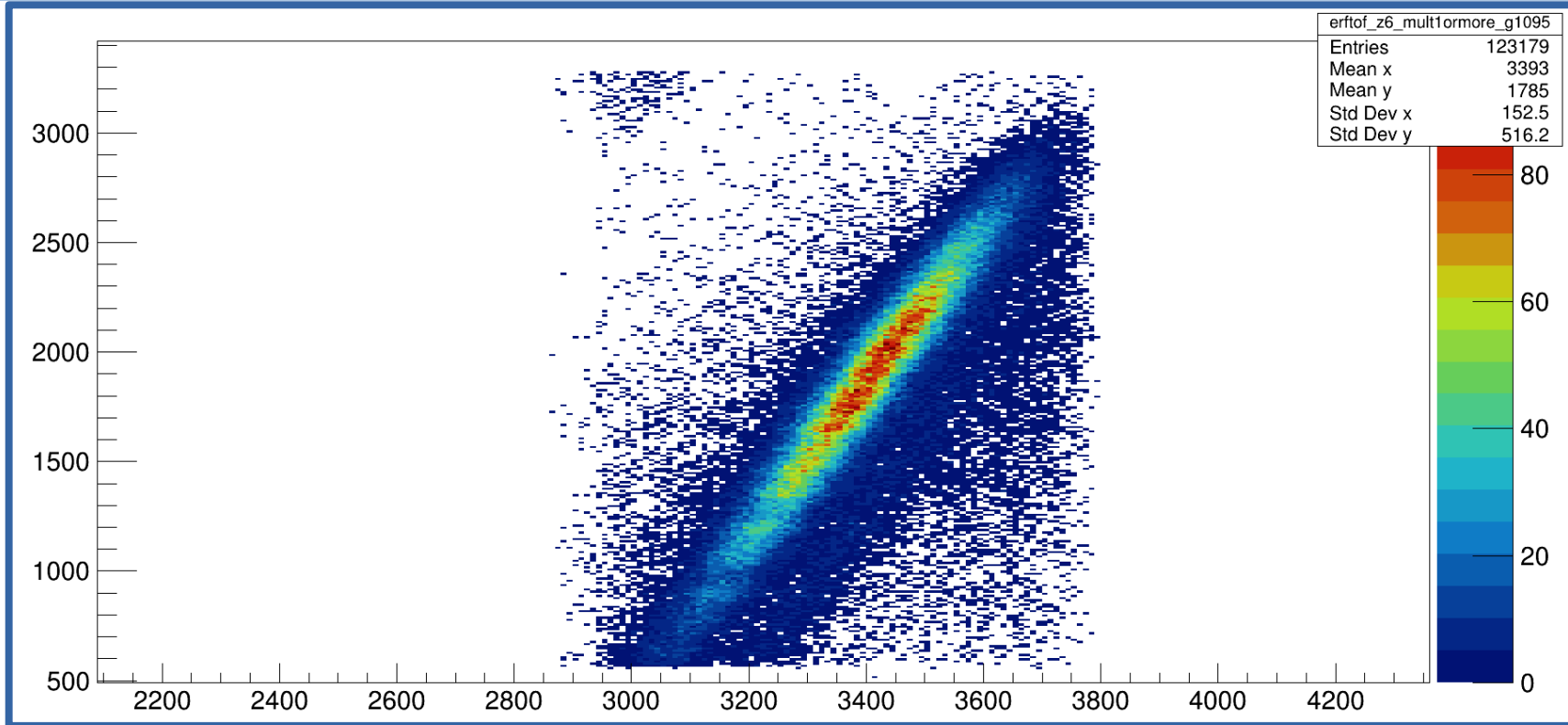
Z	N	A	events	percent	x-section(mb)
24	23	47 Cr	63	0.063%	0.595
23	24	47 V	380	0.38%	3.59
24	22	46 Cr	25	0.025%	0.236
23	23	46 V	18520	18.5%	175
22	24	46 Ti	28646	28.6%	270
23	22	45 V	10	0.01%	0.0944
22	23	45 Ti	16937	16.9%	160
21	24	45 Sc	5540	5.54%	52.3
22	22	44 Ti	1193	1.19%	11.3
22	21	43 Ti	364	0.364%	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
<b>TOTAL</b>			<b>99999</b>	<b>100</b>	<b>944.208</b>

On  $^{16}\text{O}$

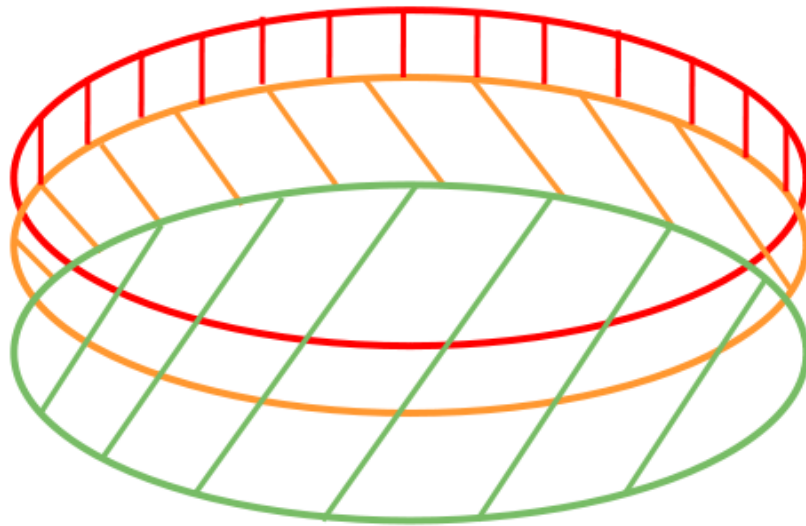
## 1. Yields of residual nuclei

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
<b>TOTAL</b>			<b>99999</b>	<b>100</b>	<b>919.564</b>


# TOF Dependence on Recoil Energy




# X-RFTOF Gates





 - 46Cr xrftof cut

 - 46V xrftof cut

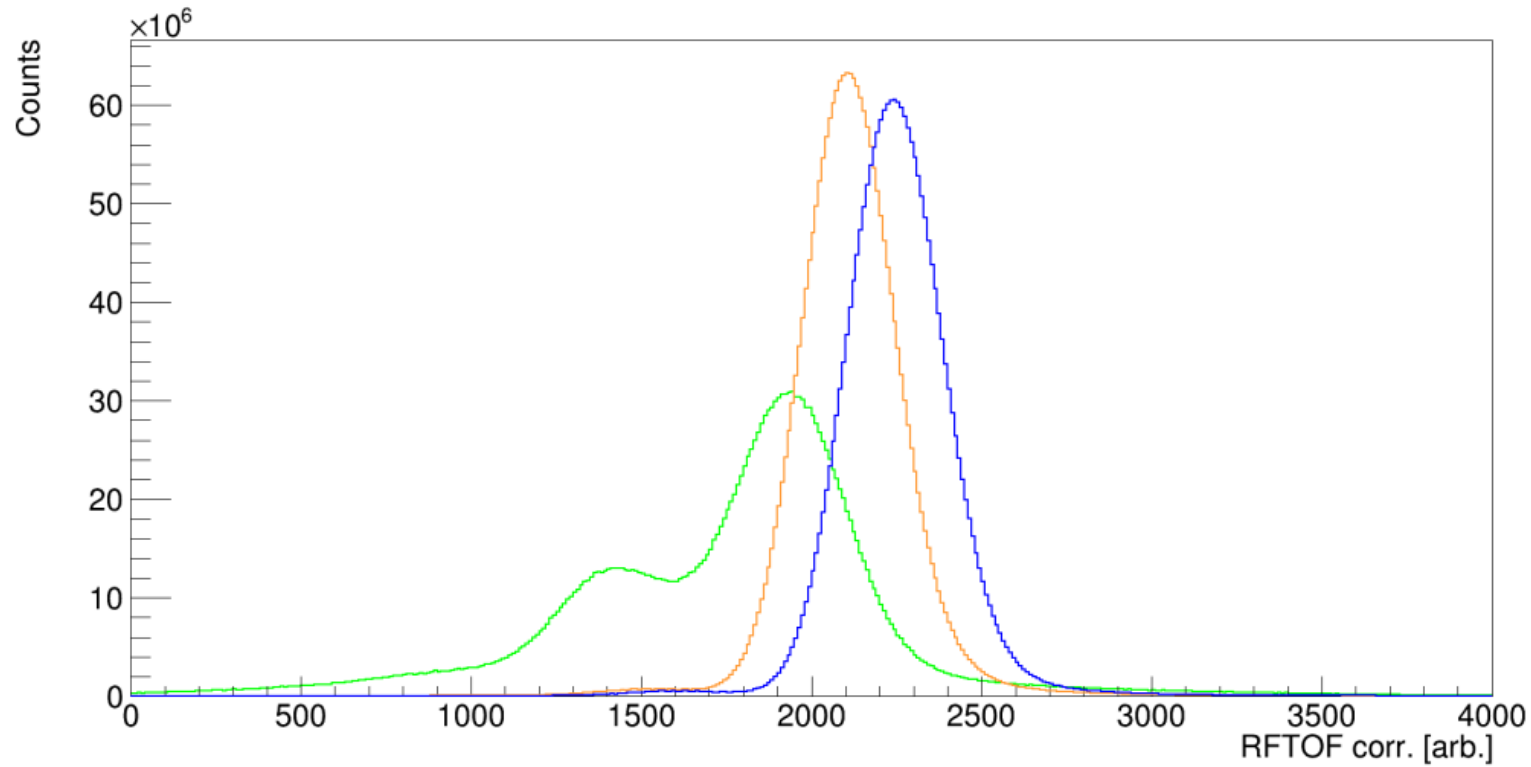
 - 46Ti xrftof cut

 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





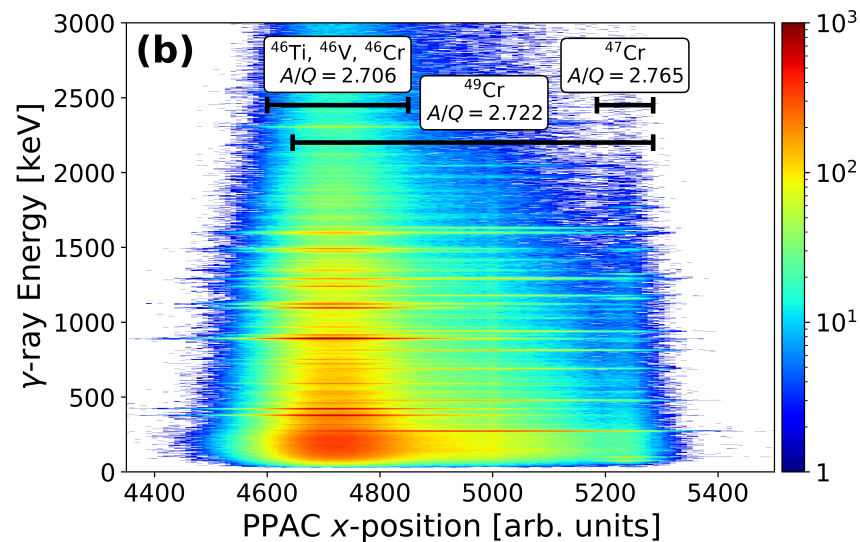
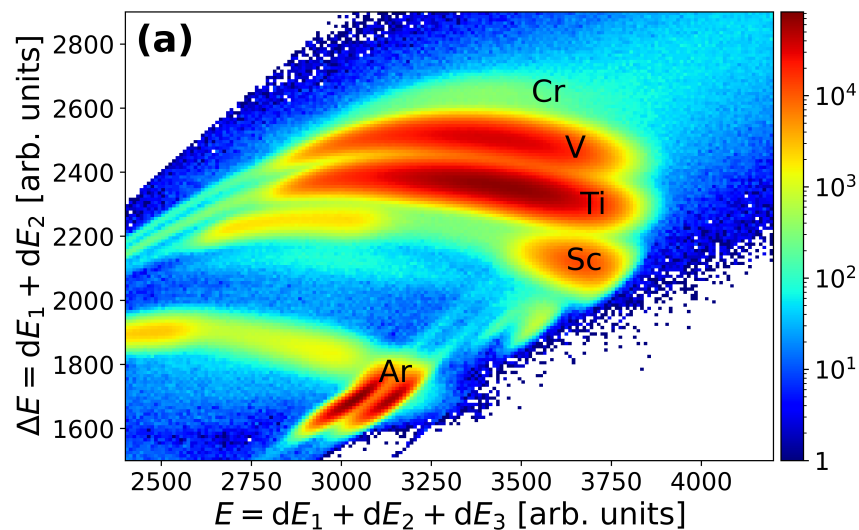
# Z and A/Q Gate

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

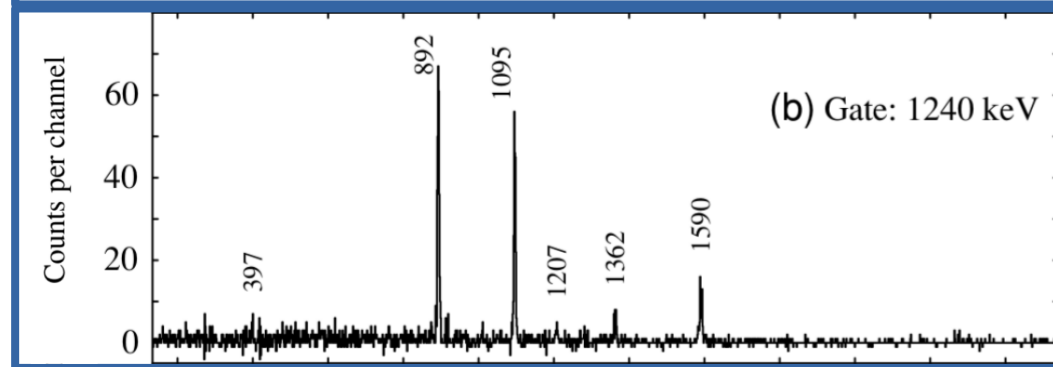
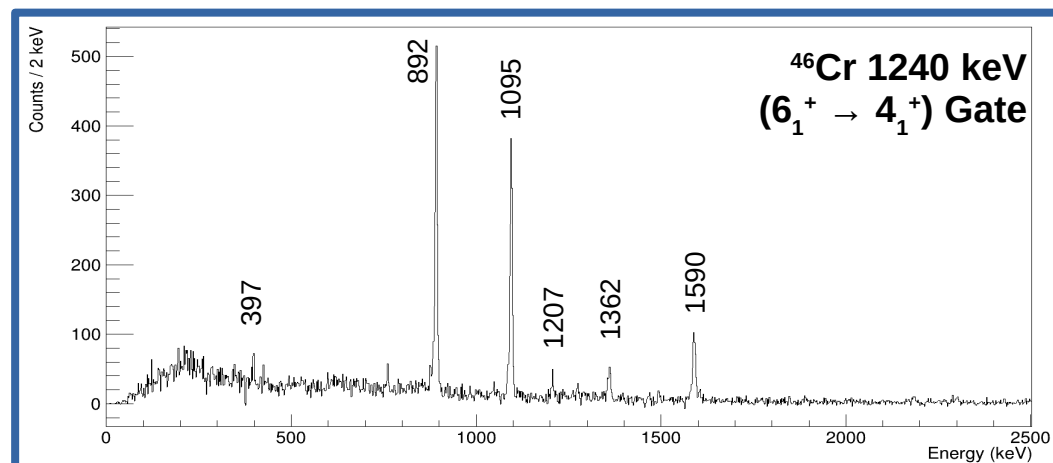
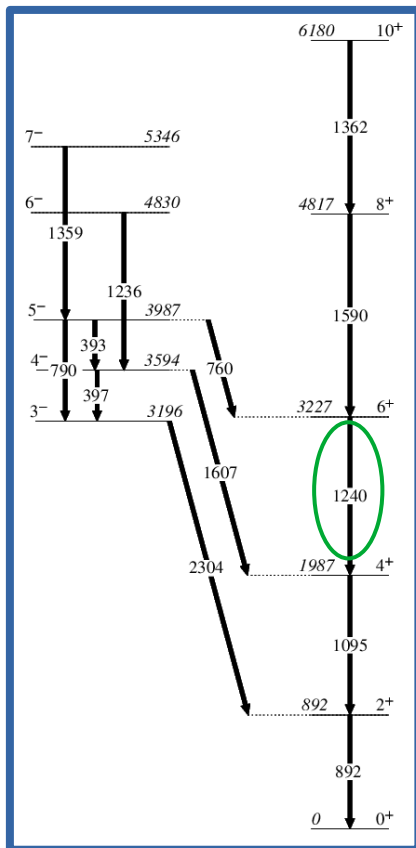
$$|\mathbf{F}| = Q|\mathbf{E} + \mathbf{v} \times \mathbf{B}| = \frac{A|\mathbf{v}|^2}{\rho}$$

$$B\rho = \frac{Av}{Q}$$

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

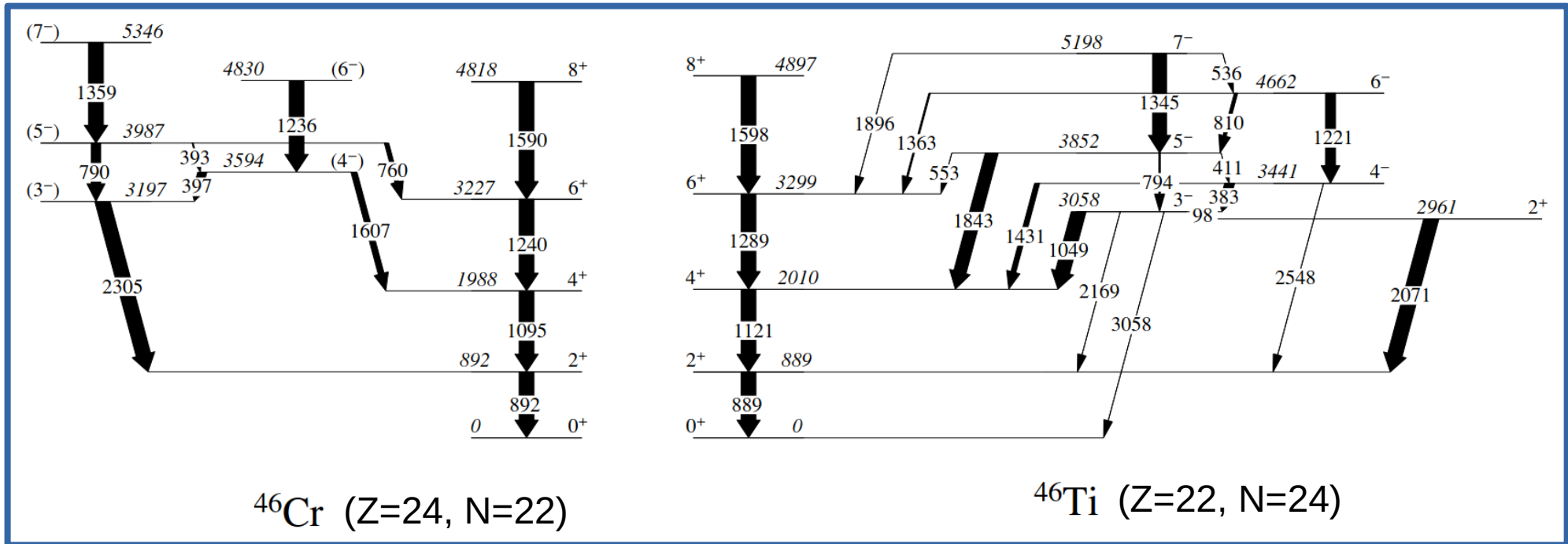


# Results – Previous Studies Comparison



# Mirror Nucleus Comparison

$T = 1, A = 46$  Mirror Pair



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