# Possible Insight to the Explosion Mechanism of Core Collapse Supernovae Through $\gamma$-ray Spectroscopy of $^{46}Cr$

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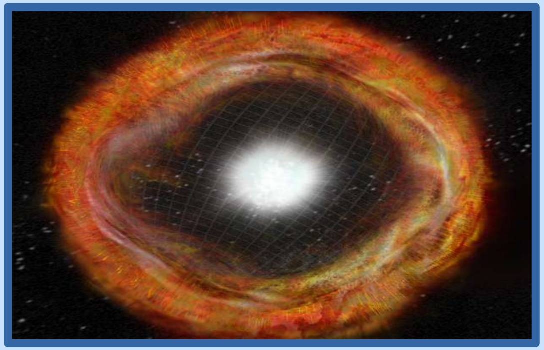
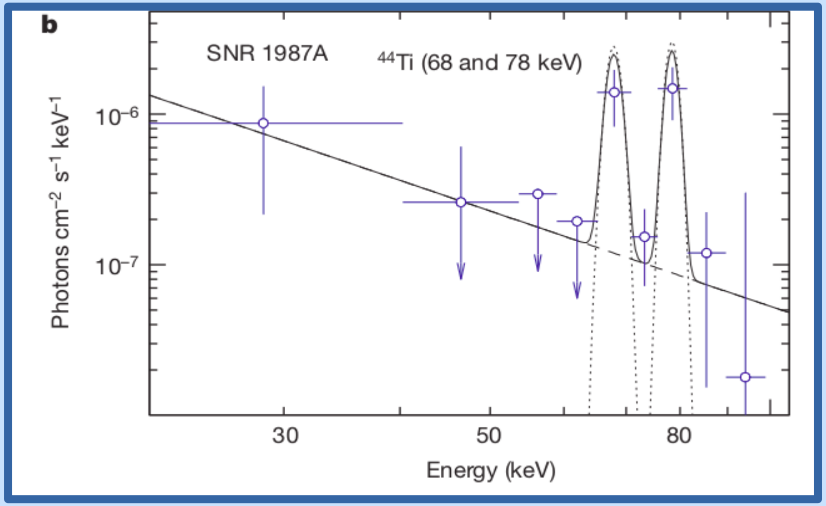
# Motivation and Astrophysical Background

- Uncertainty in explosion mechanism of core collapse supernovae (CCSN)
- New insight – observing abundances of $^{44}$Ti cosmic $\gamma$ rays ($t_{1/2}$ = 60 yr) – INTEGRAL
- Mass cut point of the star can be found – key hydrodynamic property of supernovae
- Road block! – uncertainty in nuclear reactions that destroy $^{44}$Ti – most notably $^{45}$V($p$,$\gamma$)$^{46}$Cr



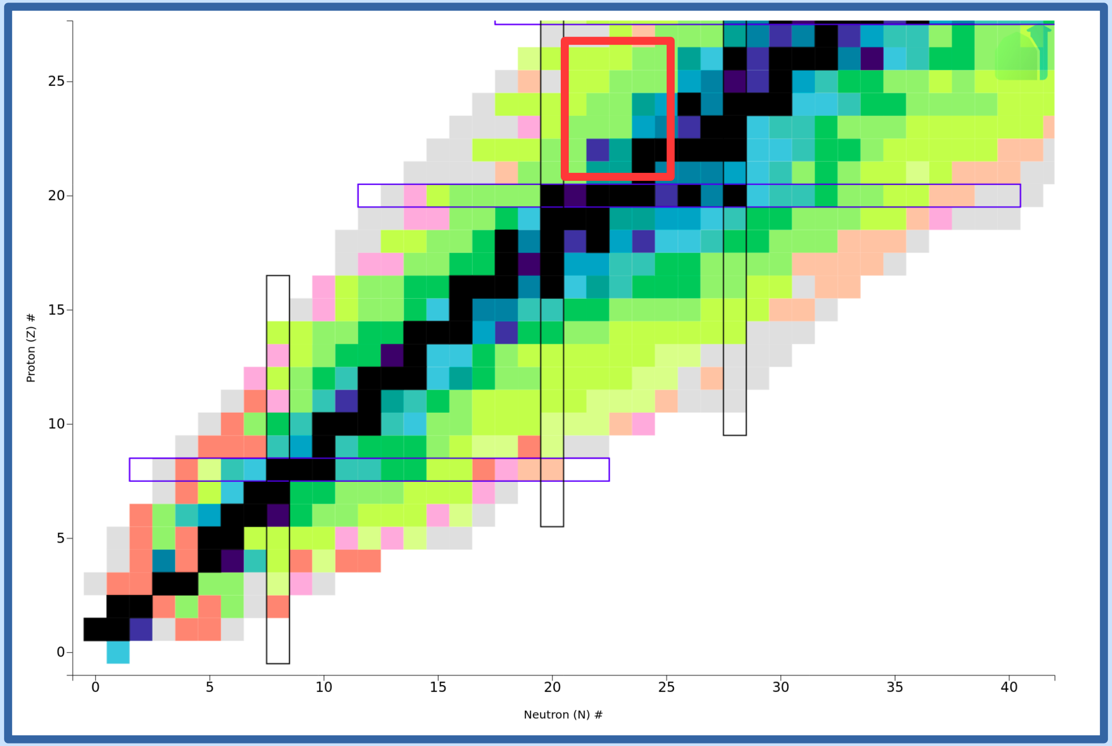
Bill Saxton (NRAO/AUI/NSF)




SA Grebenev et al. Nature 490(7420) (2012), p.373–375.

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

- Shock wave breaks nuclei into free nucleons and α particles
- T ↓ – Reassemble back into nuclei
- Cluster of nuclei around $f_{7/2}$ shell in equilibrium




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

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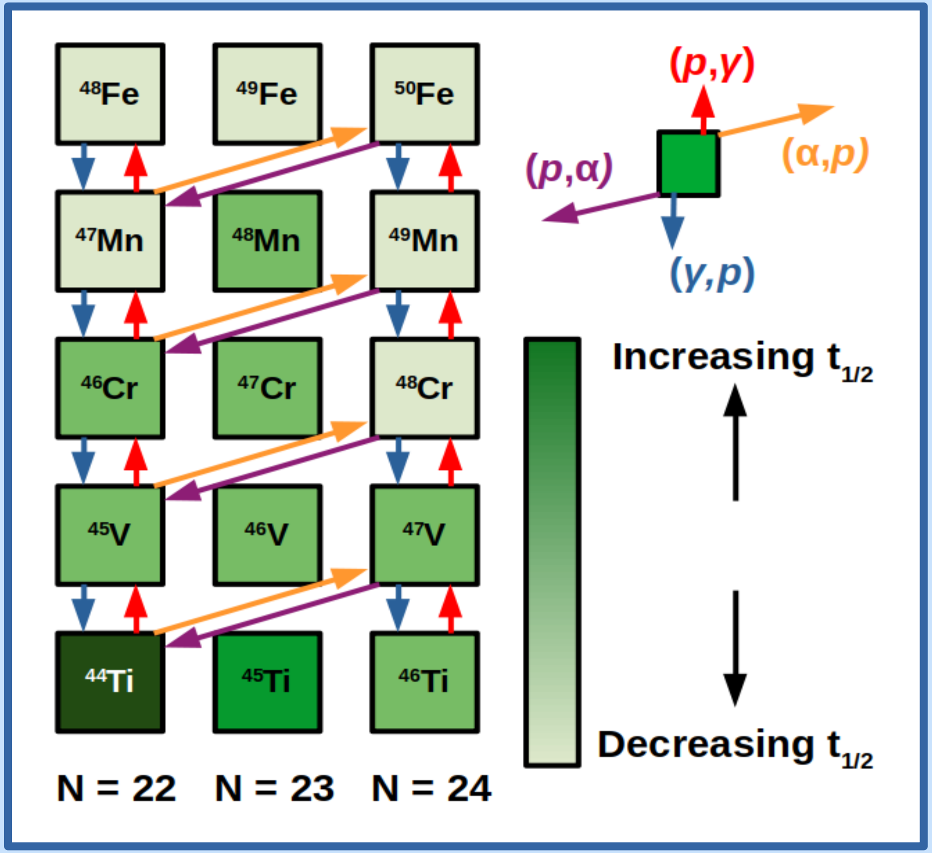

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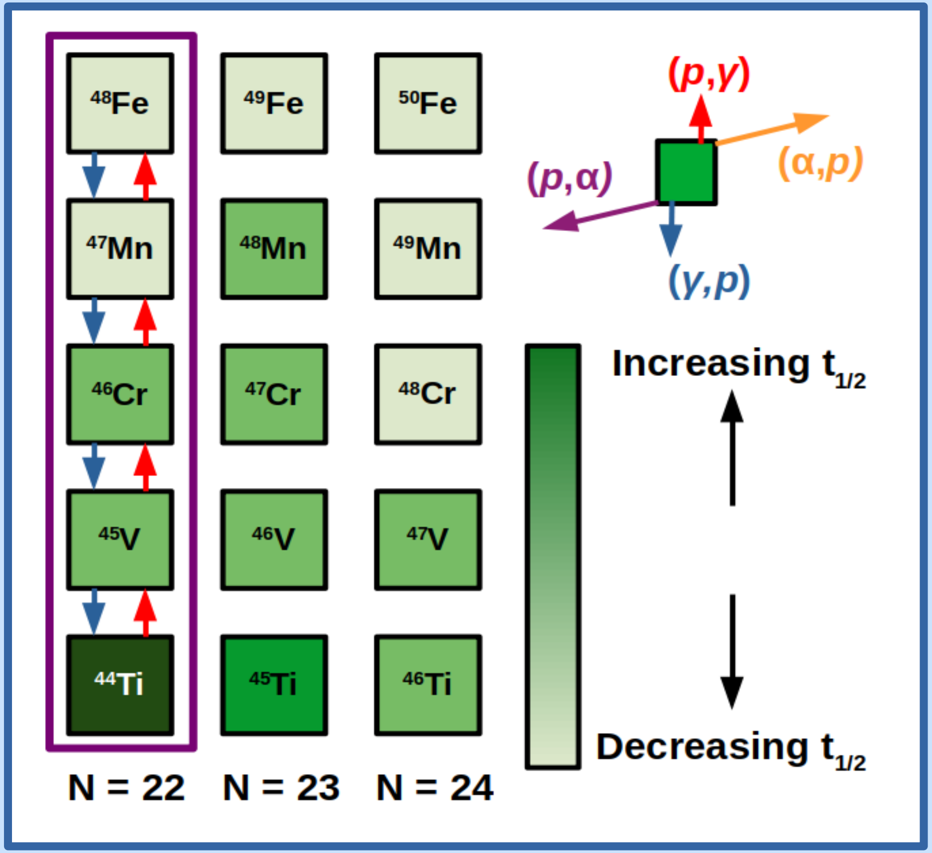

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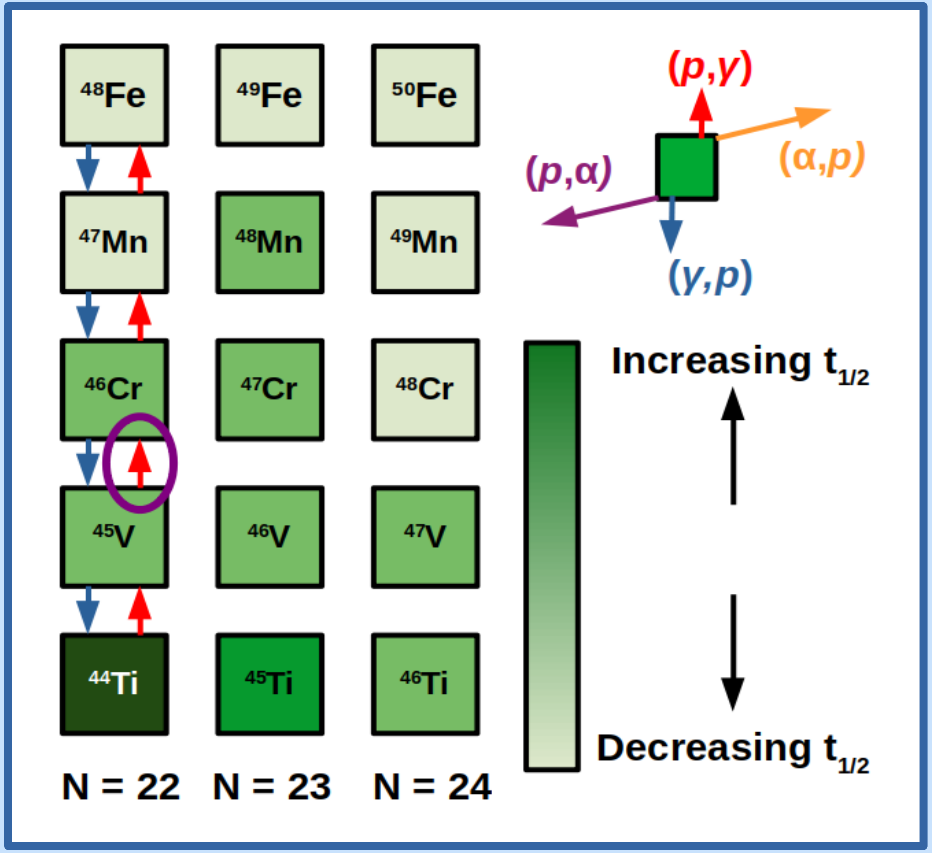


[1] G. Magkotsios et al. The Astrophysical Journal Supplement Series 191.1 (2010), p. 66.

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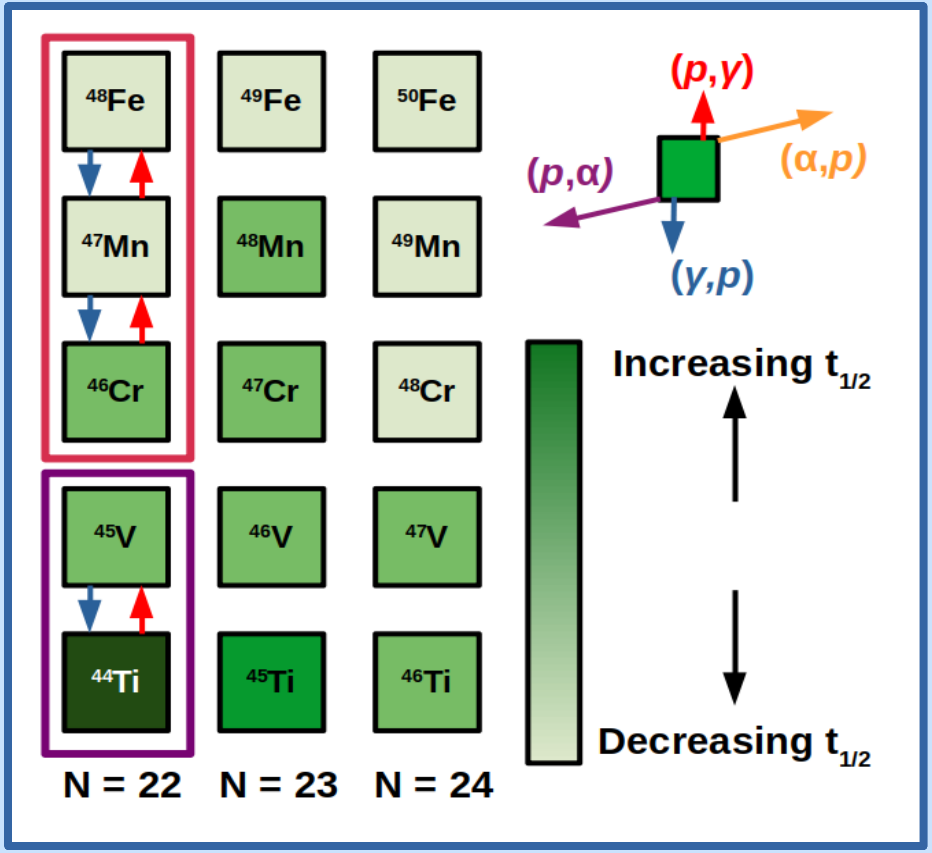
- $^{44}Ti$ and $^{45}V$ cut off from the rest of N=22 isotone chain – abundance determined at freeze out




[1] G. Magkotsios et al. The Astrophysical Journal Supplement Series 191.1 (2010), p. 66.

# Finding the Reaction Rate

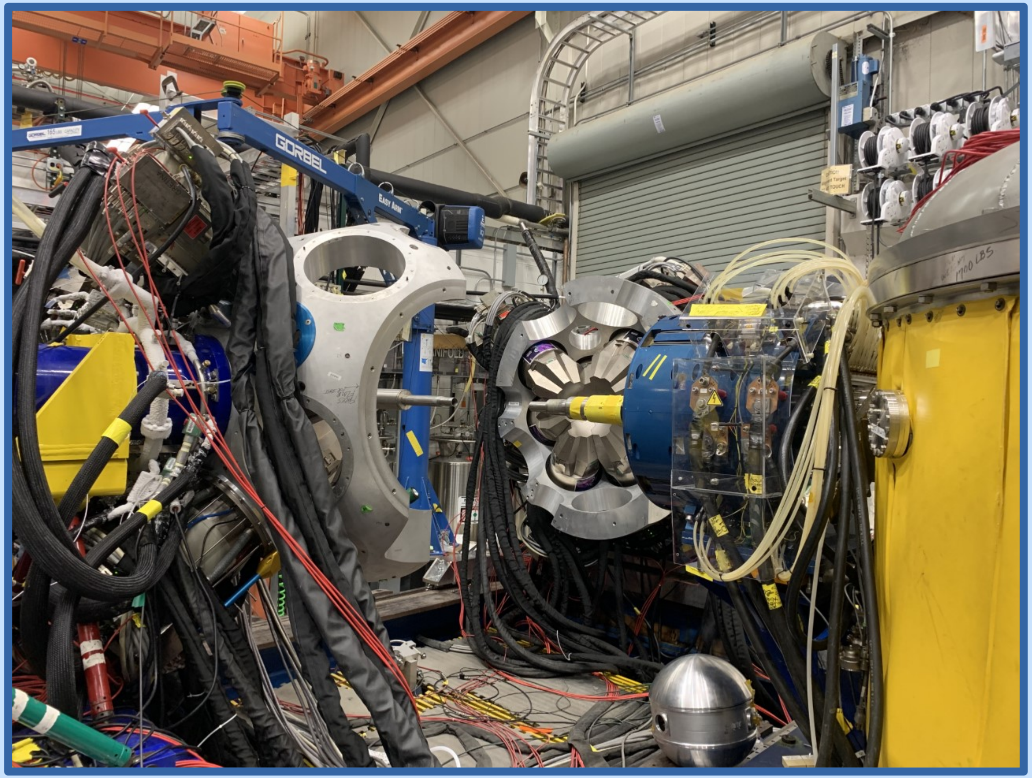
- Reaction governed by low-spin resonant states above proton separation energy ($S_p$ = 4882(22) keV)
- Performing γ-ray spectroscopy of $^{46}$Cr – identifying proton-unbound resonant states
- Use resonant energies and spins to place constraints on $^{45}$V(*p*,*γ*)$^{46}$Cr stellar reaction rate in CCSN

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

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

# 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

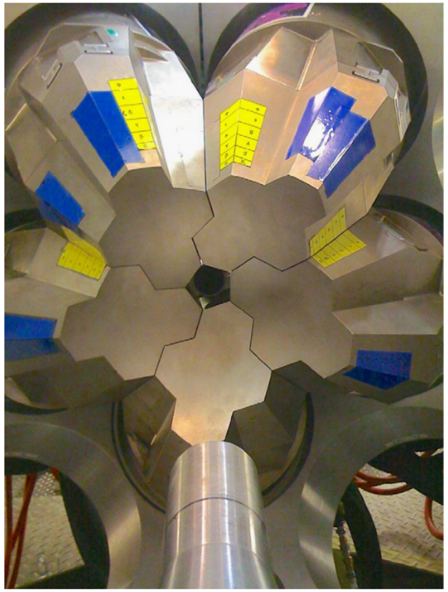
- Can't measure directly – $^{45}V$ $t_{1/2}$ ~ 500 ms
- Fusion-evaporation reaction – $^{12}C(^{36}Ar,2n)^{46}Cr$
- Other channels dominate this reaction – *p*-rich side of stability
- Contamination from oxygen on target – significant production of $^{49}Cr$

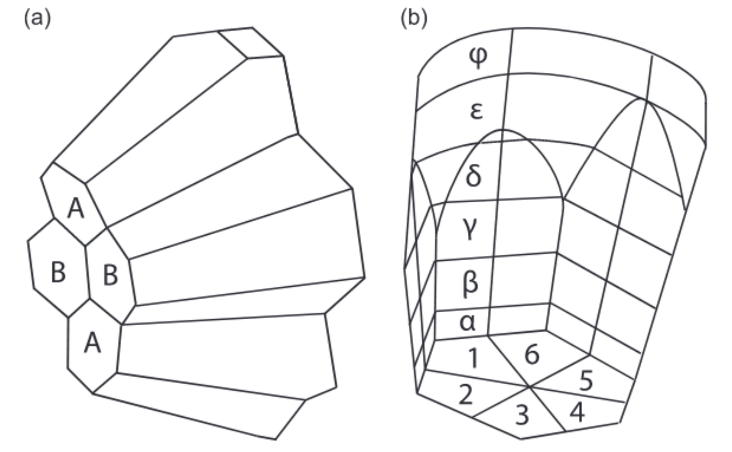
| Channel | Mode | Yield (%) |
|---|---|---|
| $^{46}Ti$ | 2*p* | 28.6 |
| $^{46}V$ | *pn* | 18.5 |
| $^{45}Ti$ | 2*pn* | 16.9 |
| $^{43}Sc$ | *αp* | 16.4 |
| $^{40}Ca$ | 2*α* | 9.02 |
| ⋮ | ⋮ | ⋮ |
| **$^{46}Cr$** | **2*n*** | **0.025** |

Calculations provided by PACE4

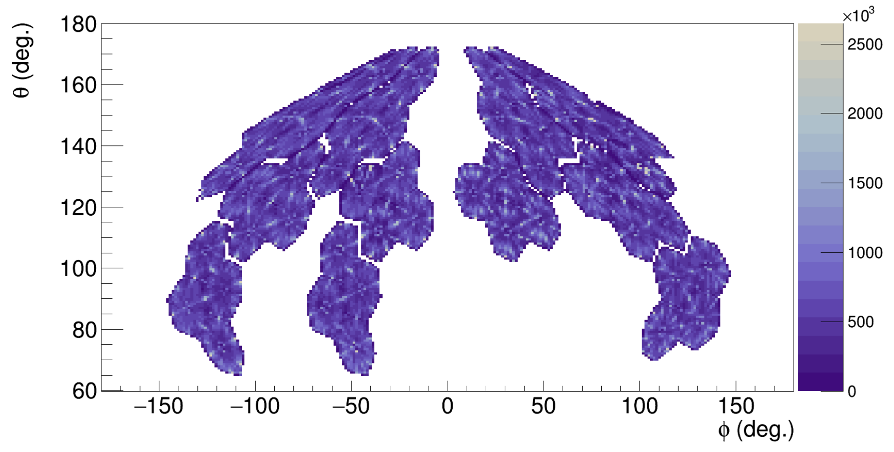
# GRETINA

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



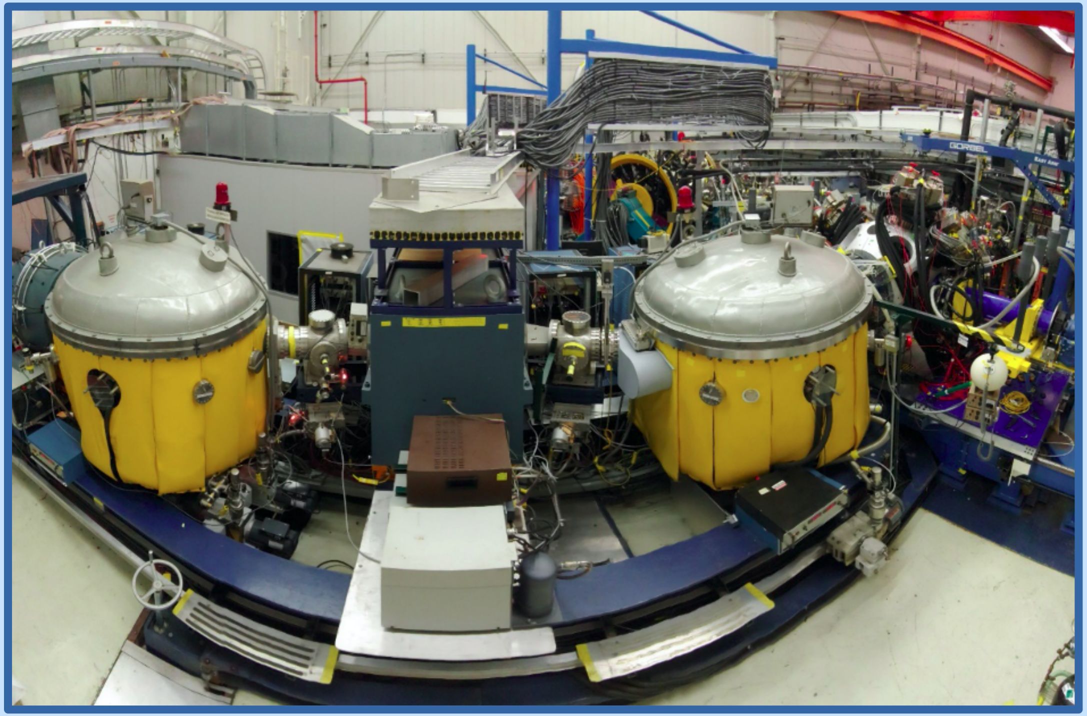



S. Paschalis et al. Nuclear Instruments and Methods in Physics Research Section A 709 (2013), p.44-55.



# FMA

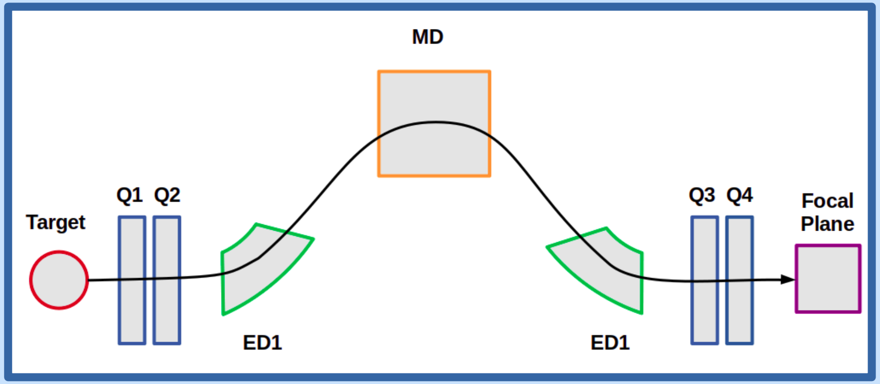
- Separates recoils by mass/charge (A/Q) at the focal plane
- Ionisation chamber – identify recoil isotopes by their Z

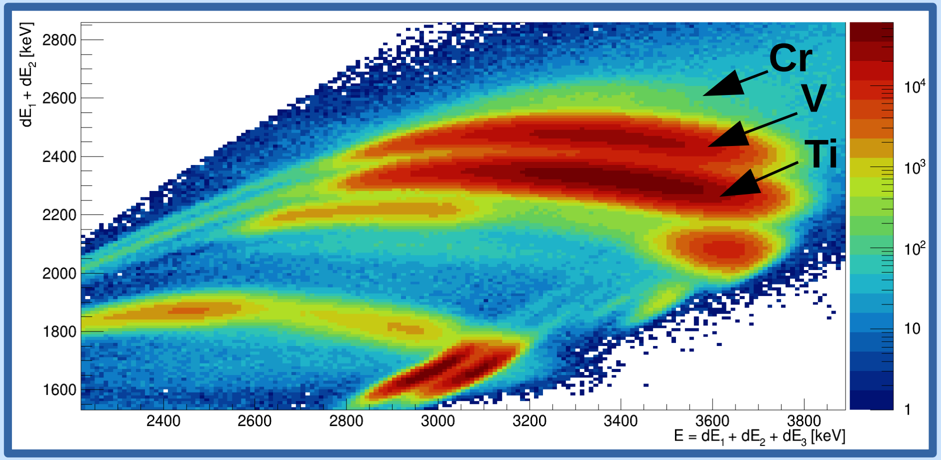


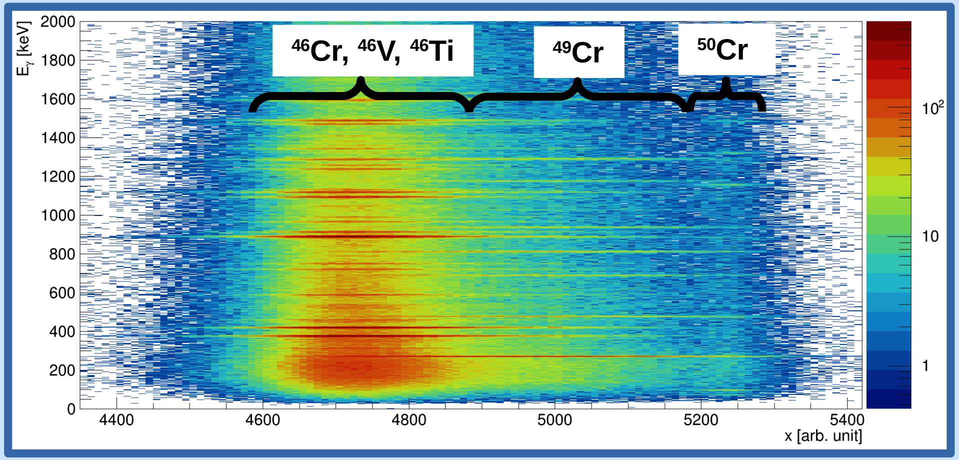
https://www.anl.gov/phy/fragment-mass-analyzer

# Z and A/Q Gate

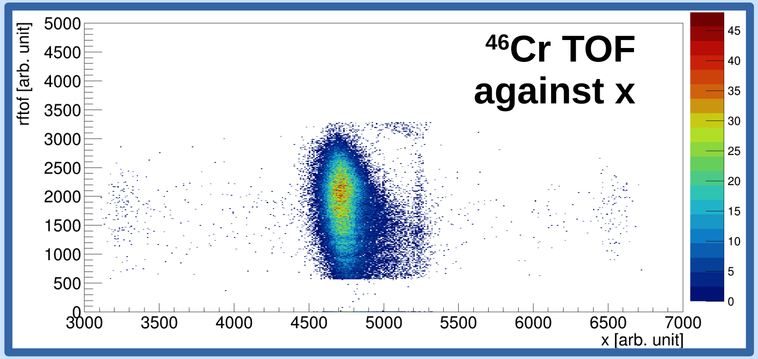
$$-\left\langle \frac{dE}{dx} \right\rangle \approx \frac{4\pi e^4}{m_e} \frac{\boxed{Z_p^2}}{\nu^2} \left( N_A \rho \frac{Z_t}{M_t} \right) \ln \left( \frac{2 m_e \nu^2}{I} \right)$$



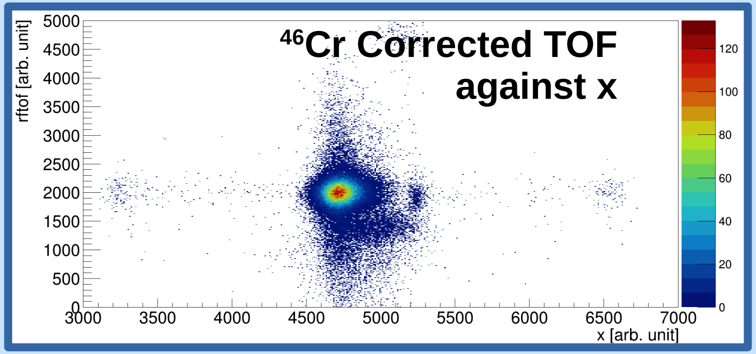



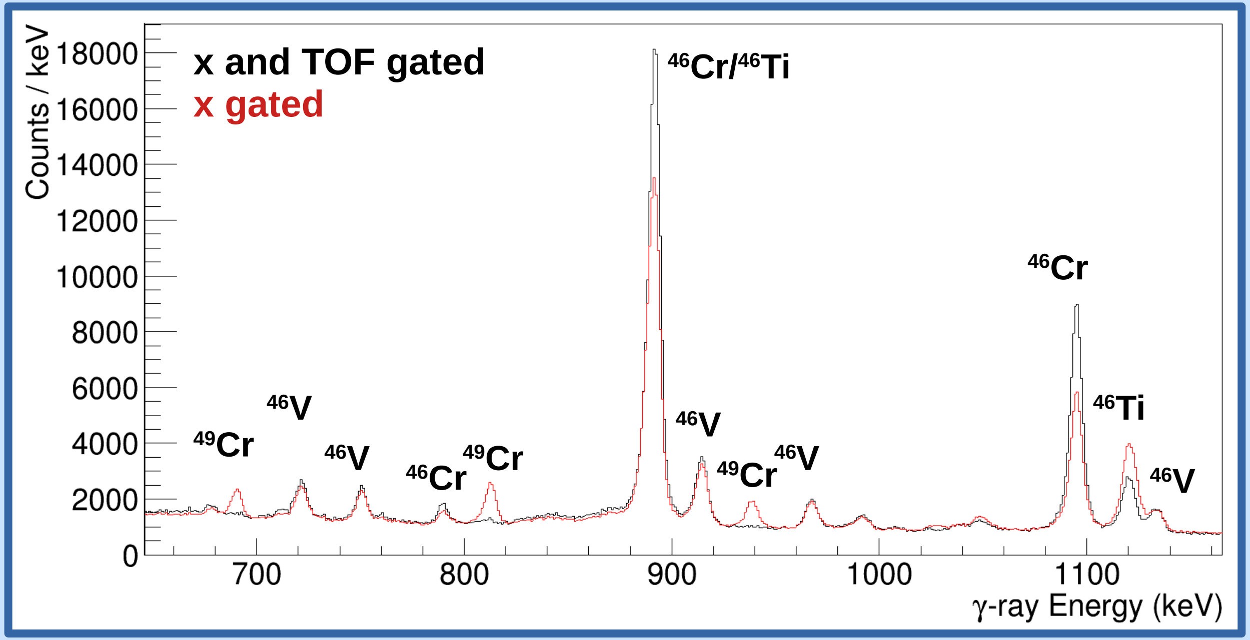



# TOF Gate




Correction for recoil energy

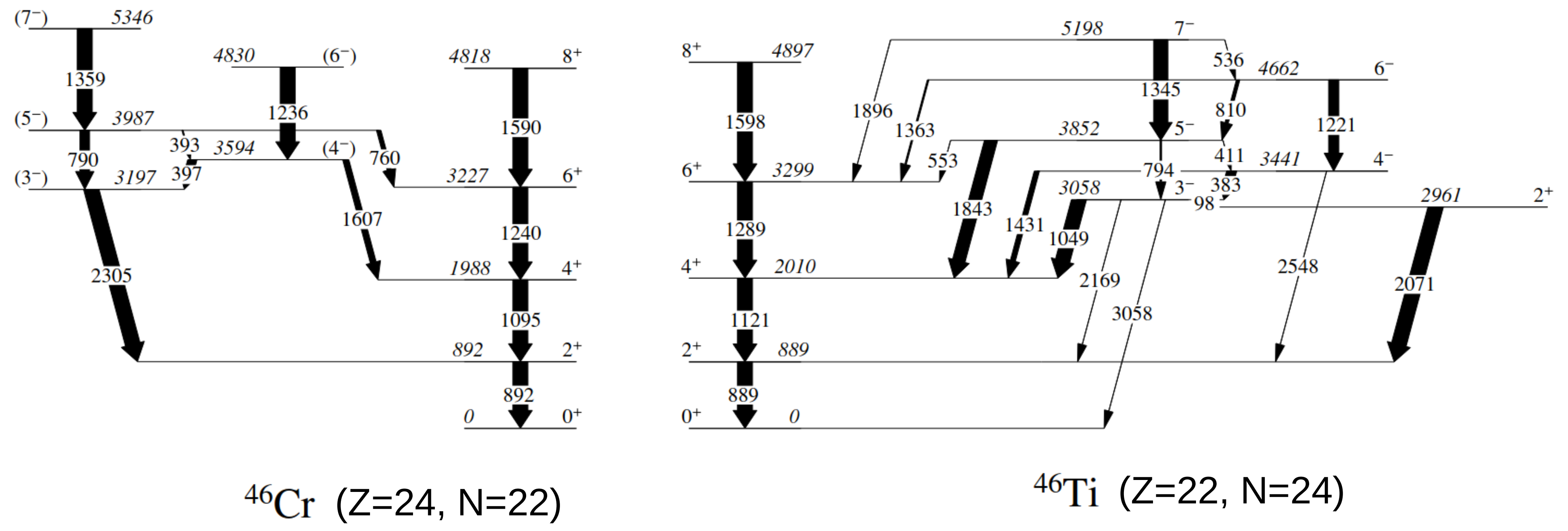



| $E_\gamma$ (keV) | % reduced using x and TOF |
|---|---|
| 1120 ($^{46}$Ti) | 69(2) |
| 424 ($^{46}$V) | 40.5(4) |

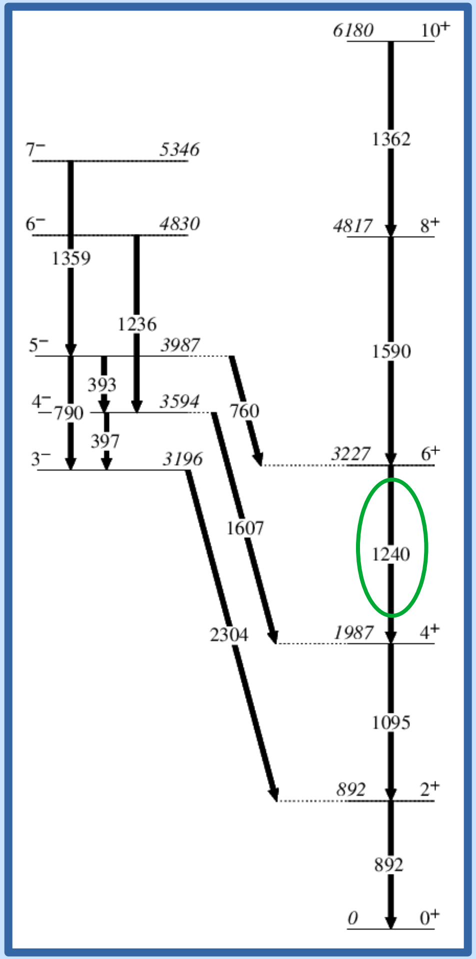
# Mirror Nucleus Comparison

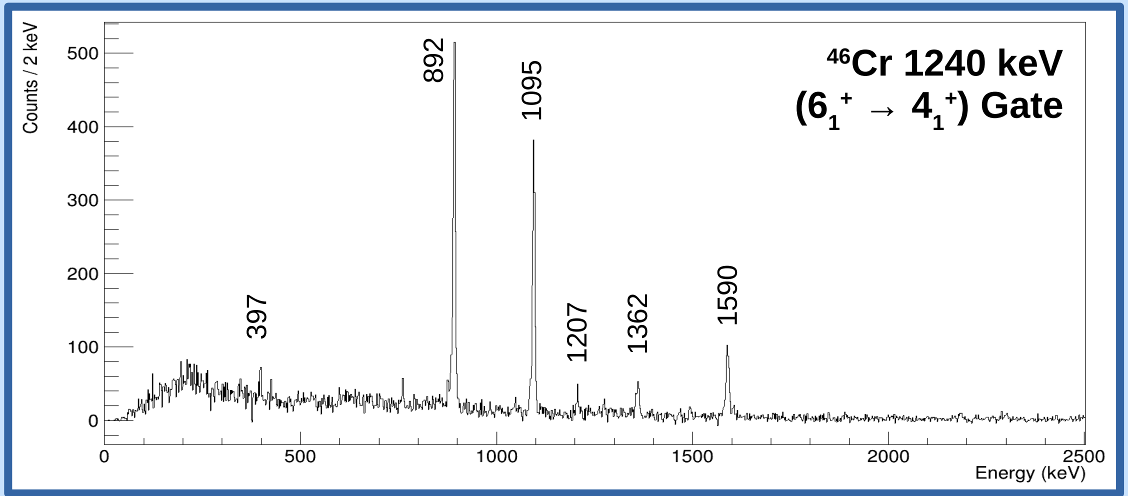
## T = 1, A = 46 Mirror Pair

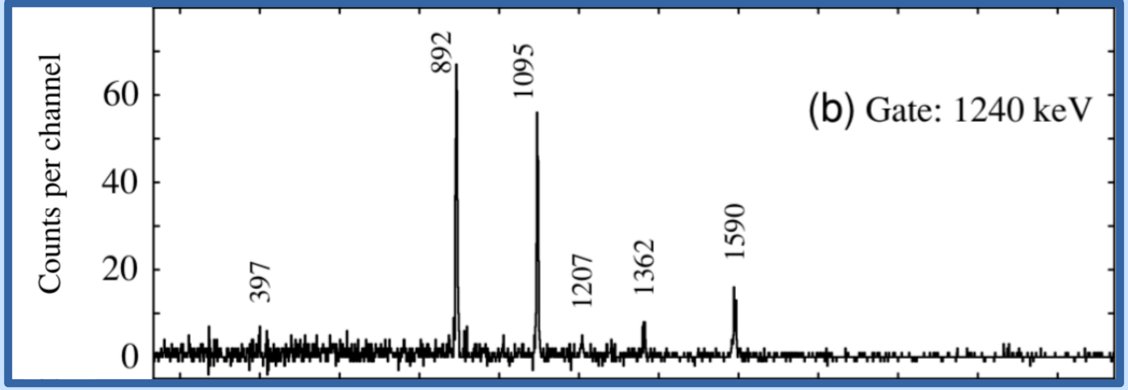



Garrett, P. E., et al. PRC 75.1 (2007): 014307.

# Results – Previous Studies Comparison

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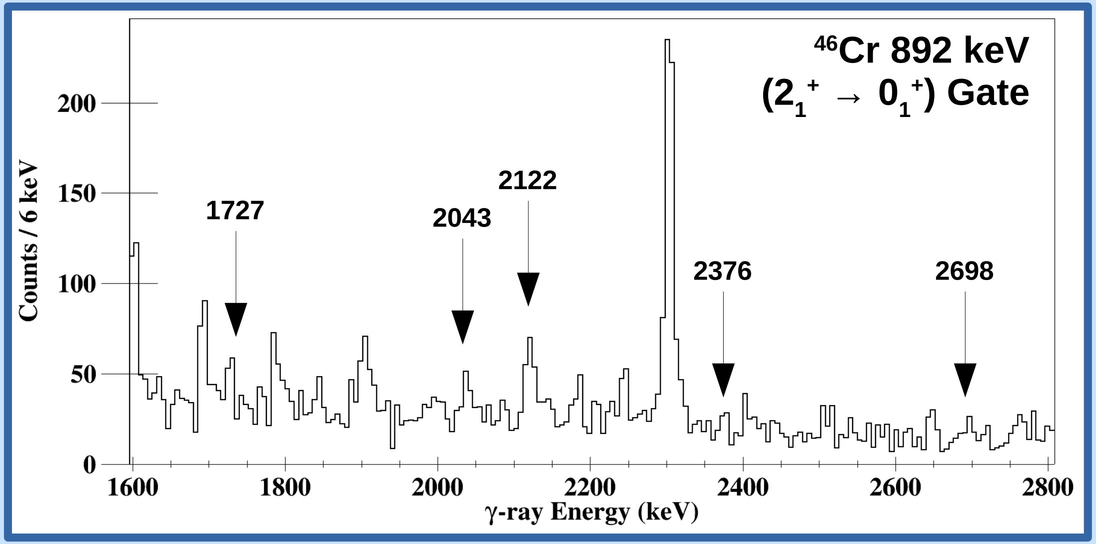
# Results – Resonance States




| $E_x$ (keV) | $J^\pi$ | $E_\gamma$ (keV) | Mirror $E_x$ (keV) |
|---|---|---|---|
| 892.24(5) | $2^+$ | 892.24(5) | 889 |
| 1987.4(1) | $4^+$ | 1095.1(1) | 2010 |
| 2619(1) | $0^+$ | 1727(1) * | 2611 |
| 2935(2) | $2^+$ | 2043(3) * | 2962 |
| 3014.1(5) | $1^-$ | 2121.8(5) * | 3168 |
| 3196.0(3) | $3^-$ | 259(2) | 3058 |
| | | 2303.7(3) | |
| 3227.0(2) | $6^+$ | 1239.6(2) | 3299 |
| 3268(3) | | 2376(3) * | 3212 |
| 3298.3(8) | $2^+$ | 2405(1) | 3236 |
| | | 3299(1) | |
| 3494.4(5) | $3^-$ | 1507.0(5) | 3569 |
| 3590(2) | $0^+$ | 2698(2) * | 3572 |
| 3593.0(4) | $4^-$ | 397.2(4) | 3441 |
| | | 1605.5(6) | |
| 5195(2) | $2^+$ | 5195(2) | 5079 |
| 5305(5) | $2^+$ | 4413(5) | 5363 |
| 5327(8) | $3^-$ | 2313(8) | 5530 |
| 5588(2) | $2^+$ | 5587(2) | 5465 |
| 5792(2) | $2^+$ | 5792(2) | 5872 |
| 5826(8) | $4^+$ | 2812(8) | 5994 |
| 6326(6) | $4^+$ | 5434(5) | 6344 |
| 6587(3) | $2^+$ | 6587(3) | 6629 |
| 6614(9) | $3^-$ | 3600(9) | 6458 |
| 7111(6) | $4^+$ | 6219(6) | 7104 |

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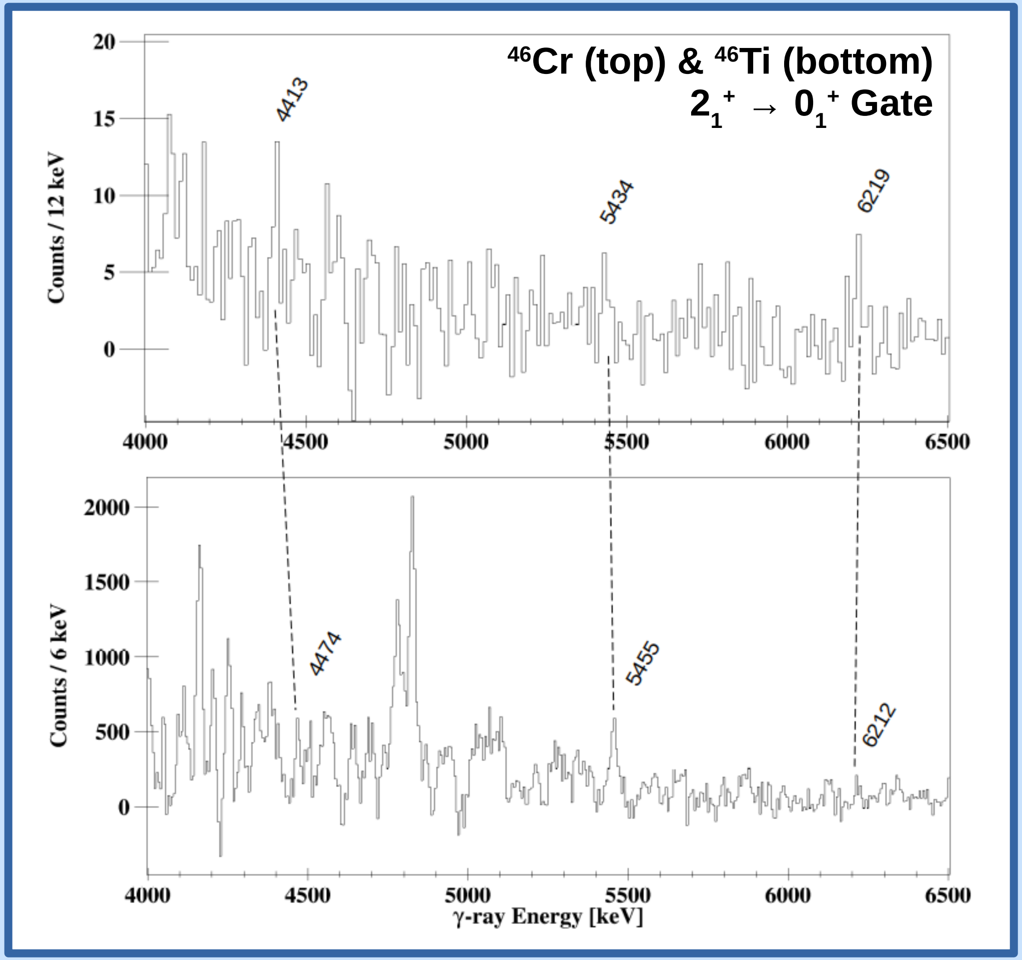


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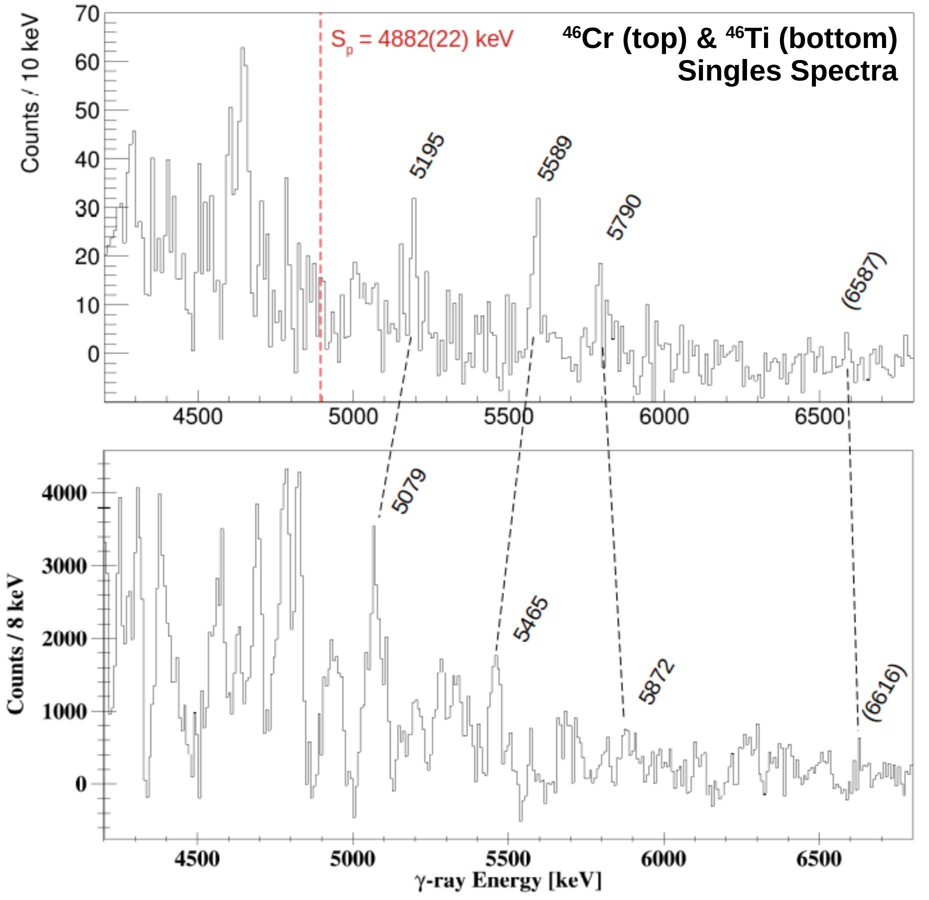


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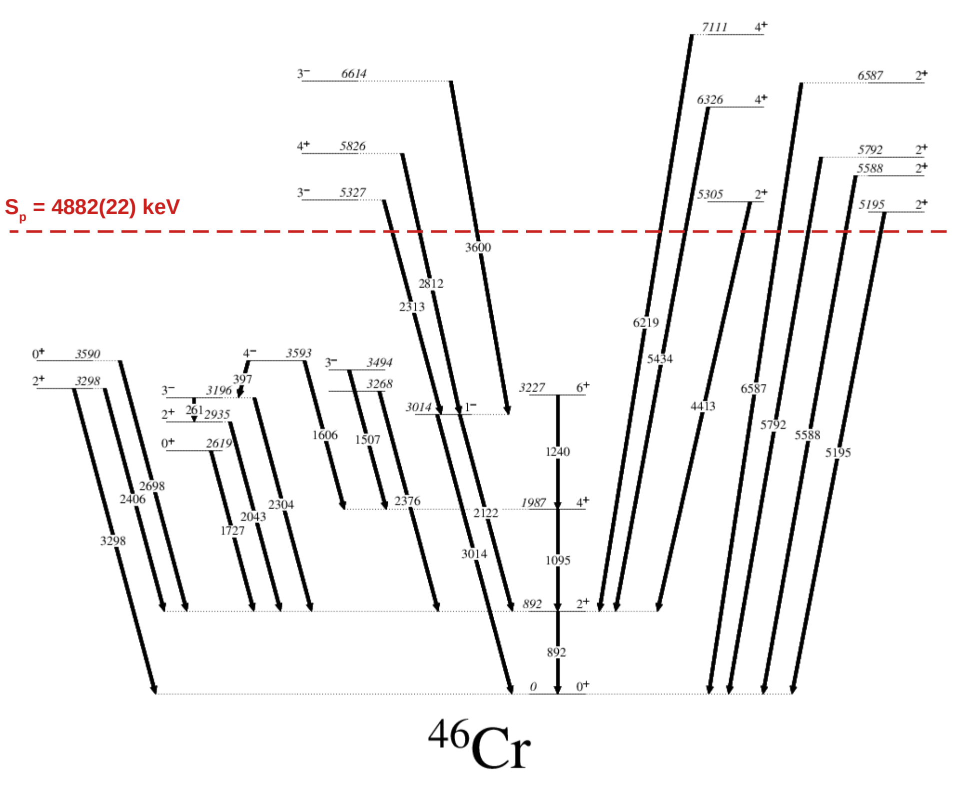
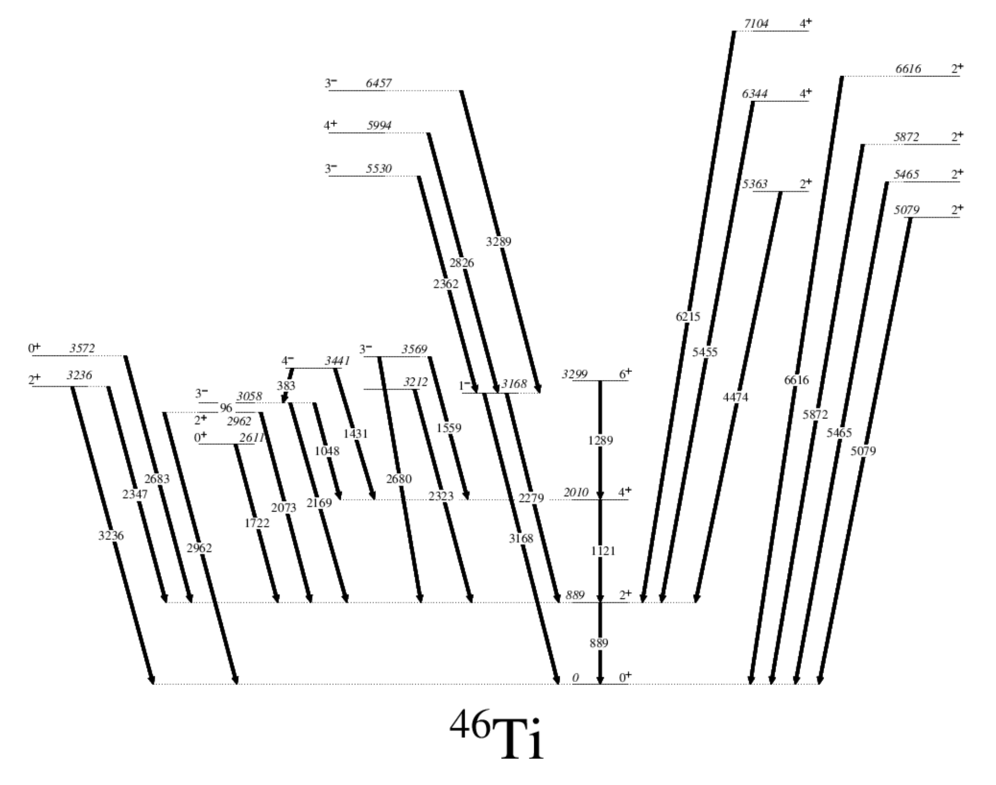
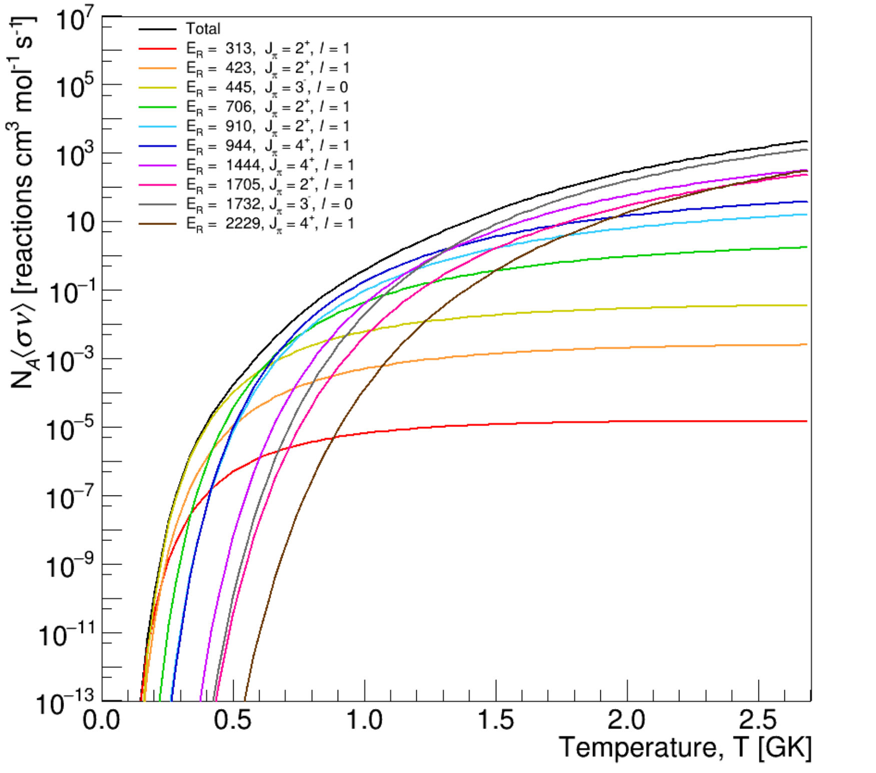
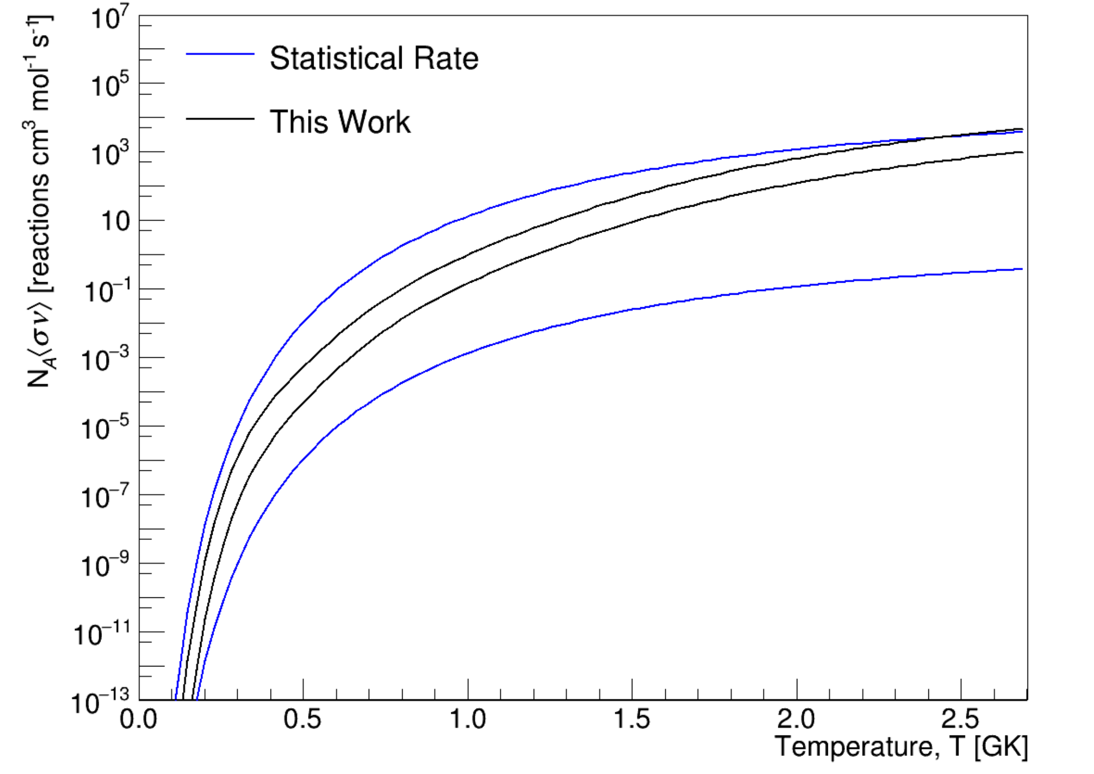
# Results – Partial Level Scheme



# Results – Reaction Rate



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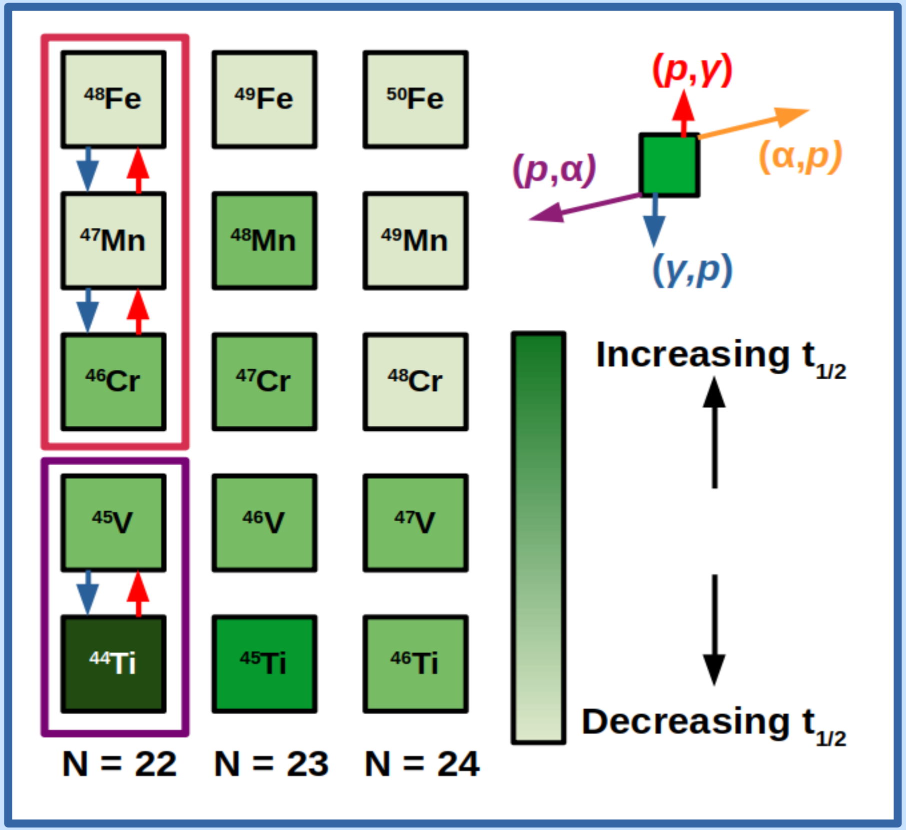


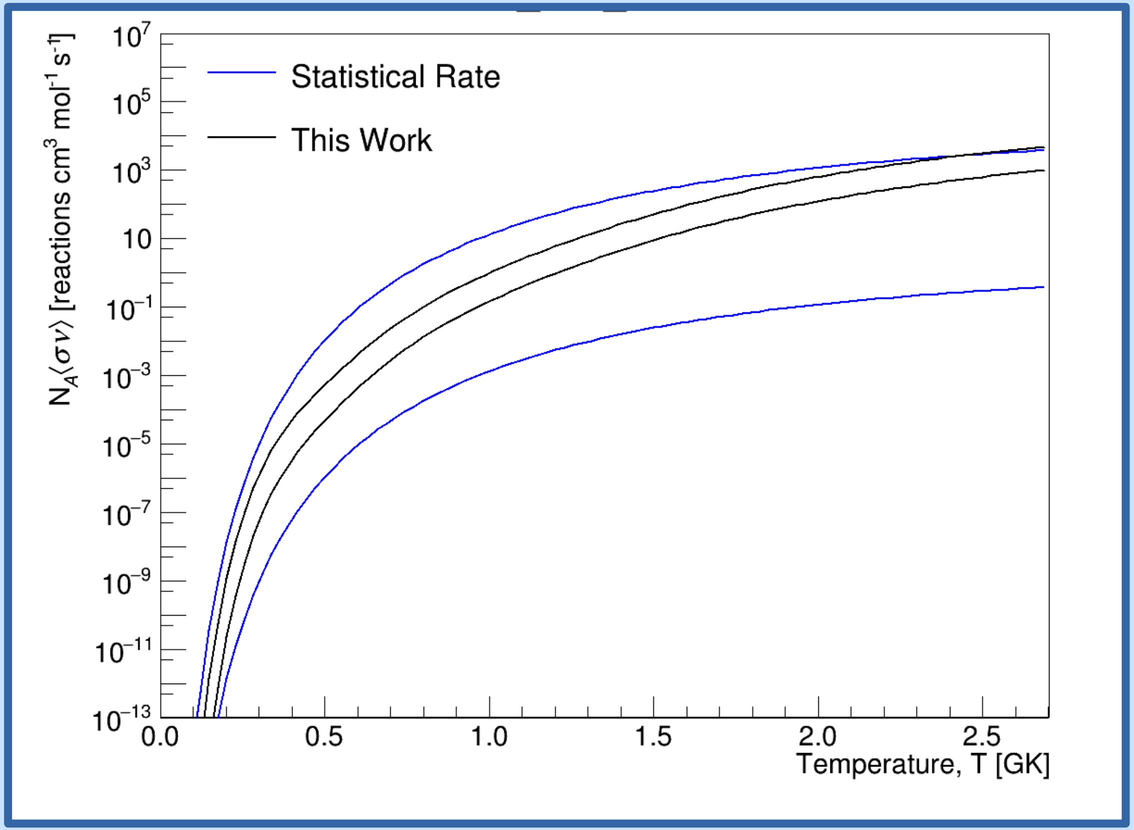

# Summary and Future Work

- $^{45}V(p,\gamma)^{46}Cr$ reaction rate is key to the destruction of $^{44}Ti$ during the α-rich freeze-out of CCSN
- First identification of 17 γ-rays, leading to observation of 10 proton-unbound states in $^{46}Cr$
- Towards upper limit of previously known rate – more $^{44}Ti$ flows out of $^{44}Ti$-$^{45}V$ cluster

- Finalise reaction rate; compare resonance states to shell model calculations
- Transfer reaction to get $C^2S$, mass measurement of $^{46}Cr$

# Acknowledgments

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

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[3]Argonne National Laboratory, Argonne, Illinios 60439, USA

[4]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

[5]Universitat Politècnica De Catalunya, 08034 Barcelona, Spain

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[7]Louisiana State University, Baton Rouge, Louisiana 70803, USA

[8]Brookhaven National Laboratory, National Nuclear Data Center, New York 11973, USA

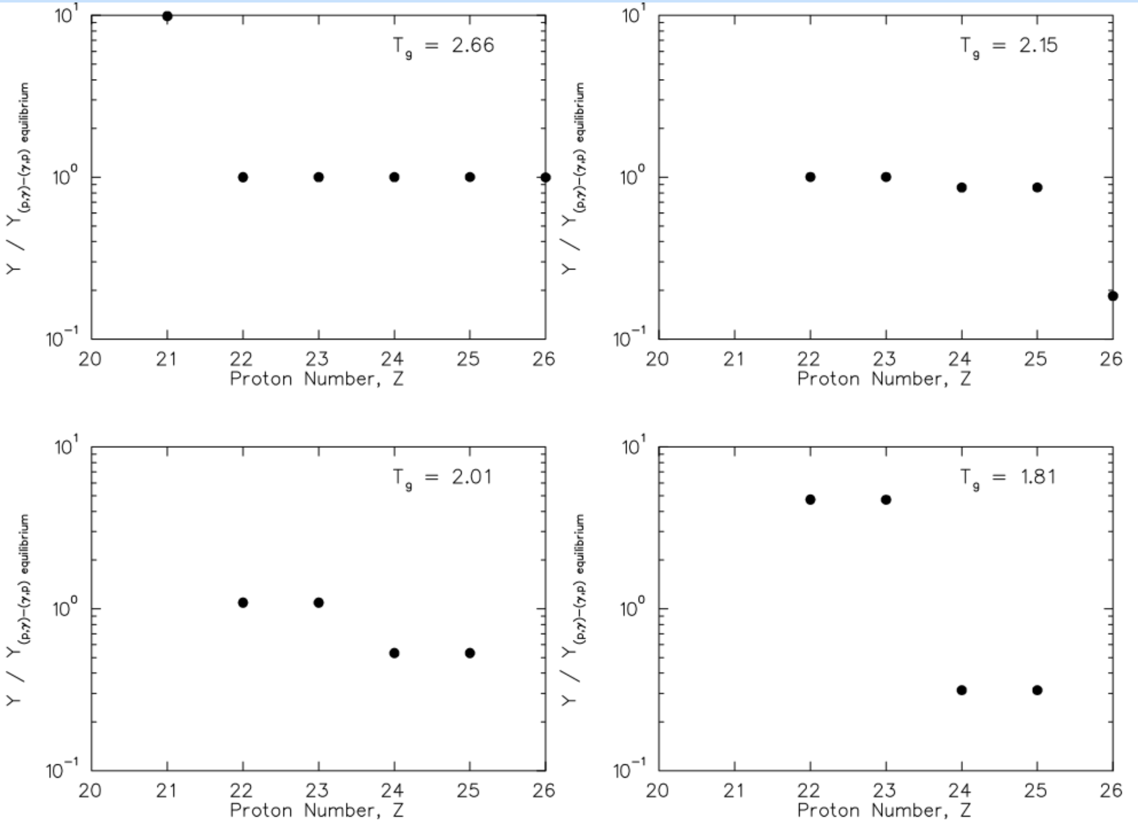



FIG. 13.—Evolution of the $(p, \gamma)$–$(\gamma, p)$ equilibrium for the $N = 22$ isotones as the temperature falls, with the standard $^{45}V(p, \gamma)^{46}Cr$ rate. The $^{44}Ti$ and $^{45}V$ pair ($Z = 22$ and 23) increasingly depart from equilibrium with the $^{46}Cr$ and $^{47}Mn$ pair ($Z = 24$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

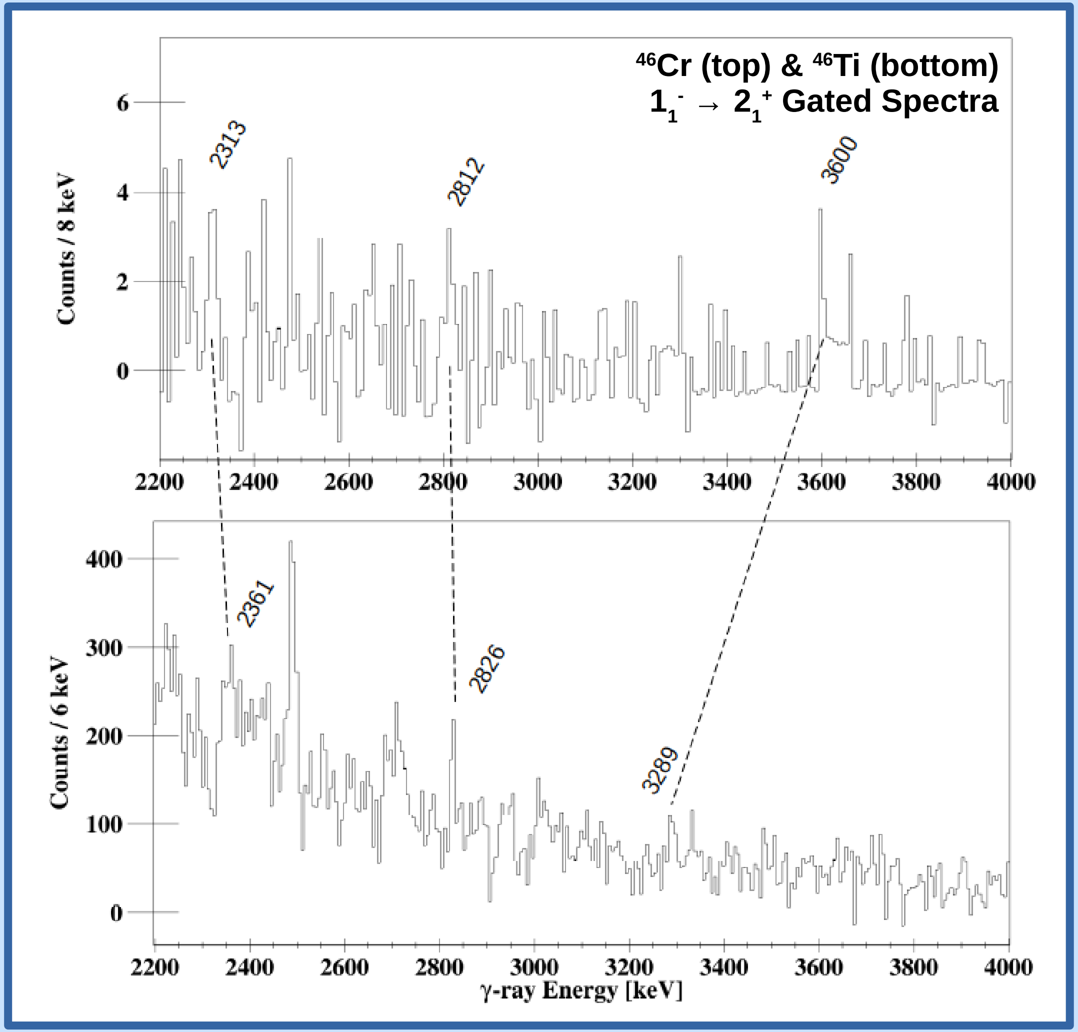

Clayton, D.D., Jin, L. and Meyer, B.S., 1998. Nuclear reactions governing the nucleosynthesis of 44Ti. The Astrophysical Journal, 504(1), p.500.

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 |

Clayton, D.D., Jin, L. and Meyer, B.S., 1998. Nuclear reactions governing the nucleosynthesis of 44Ti. The Astrophysical Journal, 504(1), p.500.




| $E_x$ (keV) | $J^\pi$ | $E_\gamma$ (keV) | Mirror $E_x$ (keV) |
|---|---|---|---|
| 892.24(5) | $2^+$ | 892.24(5) | 889 |
| 1987.4(1) | $4^+$ | 1095.1(1) | 2010 |
| 2619(1) | $0^+$ | 1727(1) | 2611 |
| 2935(2) | $2^+$ | 2043(3) | 2962 |
| 3014.1(5) | $1^-$ | 2121.8(5) | 3168 |
| 3196.0(3) | $3^-$ | 259(2) | 3058 |
| | | 2303.7(3) | |
| 3227.0(2) | $6^+$ | 1239.6(2) | 3299 |
| 3268(3) | | 2376(3) | 3212 |
| 3298.3(8) | $2^+$ | 2405(1) | 3236 |
| | | 3299(1) | |
| 3494.4(5) | $3^-$ | 1507.0(5) | 3569 |
| 3590(2) | $0^+$ | 2698(2) | 3572 |
| 3593.0(4) | $4^-$ | 397.2(4) | 3441 |
| | | 1605.5(6) | |
| 5195(2) | $2^+$ | 5195(2) | 5079 |
| 5305(5) | $2^+$ | 4413(5) | 5363 |
| 5327(8) | $3^-$ | 2313(8) * | 5530 |
| 5588(2) | $2^+$ | 5587(2) | 5465 |
| 5792(2) | $2^+$ | 5792(2) | 5872 |
| 5826(8) | $4^+$ | 2812(8) * | 5994 |
| 6326(6) | $4^+$ | 5434(5) | 6344 |
| 6587(3) | $2^+$ | 6587(3) | 6629 |
| 6614(9) | $3^-$ | 3600(9) * | 6458 |
| 7111(6) | $4^+$ | 6219(6) | 7104 |

# PACE4 Calculations

## On $^{12}C$

**1. Yields of residual nuclei**

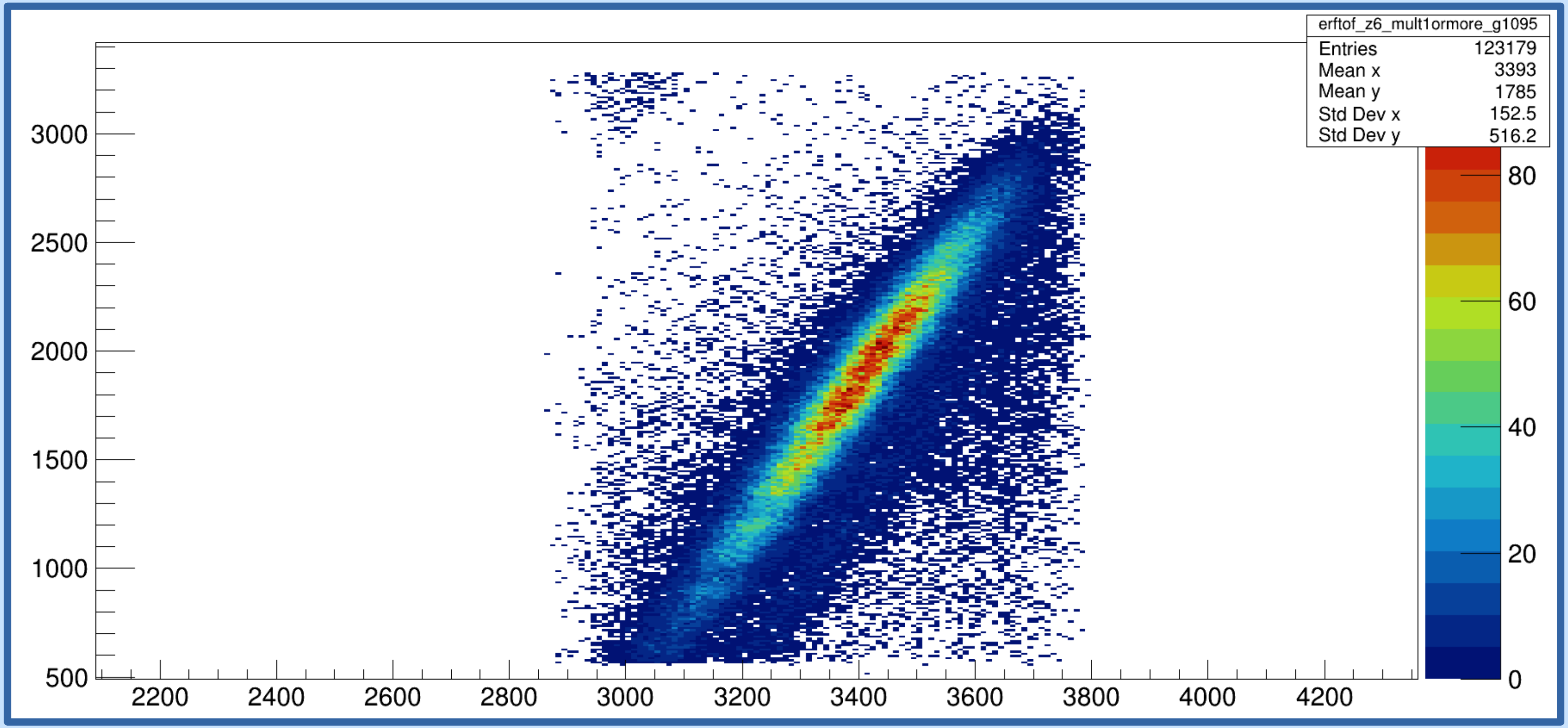
| Z | N | A | events | percent | x-section(mb) |
|---|---|---|---|---|---|
| 24 | 23 | **47 Cr** | 63 | 0.063% | 0.595 |
| 23 | 24 | **47 V** | 380 | 0.38% | 3.59 |
| 24 | 22 | **46 Cr** | 25 | 0.025% | 0.236 |
| 23 | 23 | **46 V** | 18520 | 18.5% | 175 |
| 22 | 24 | **46 Ti** | 28646 | 28.6% | 270 |
| 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 $^{16}O$

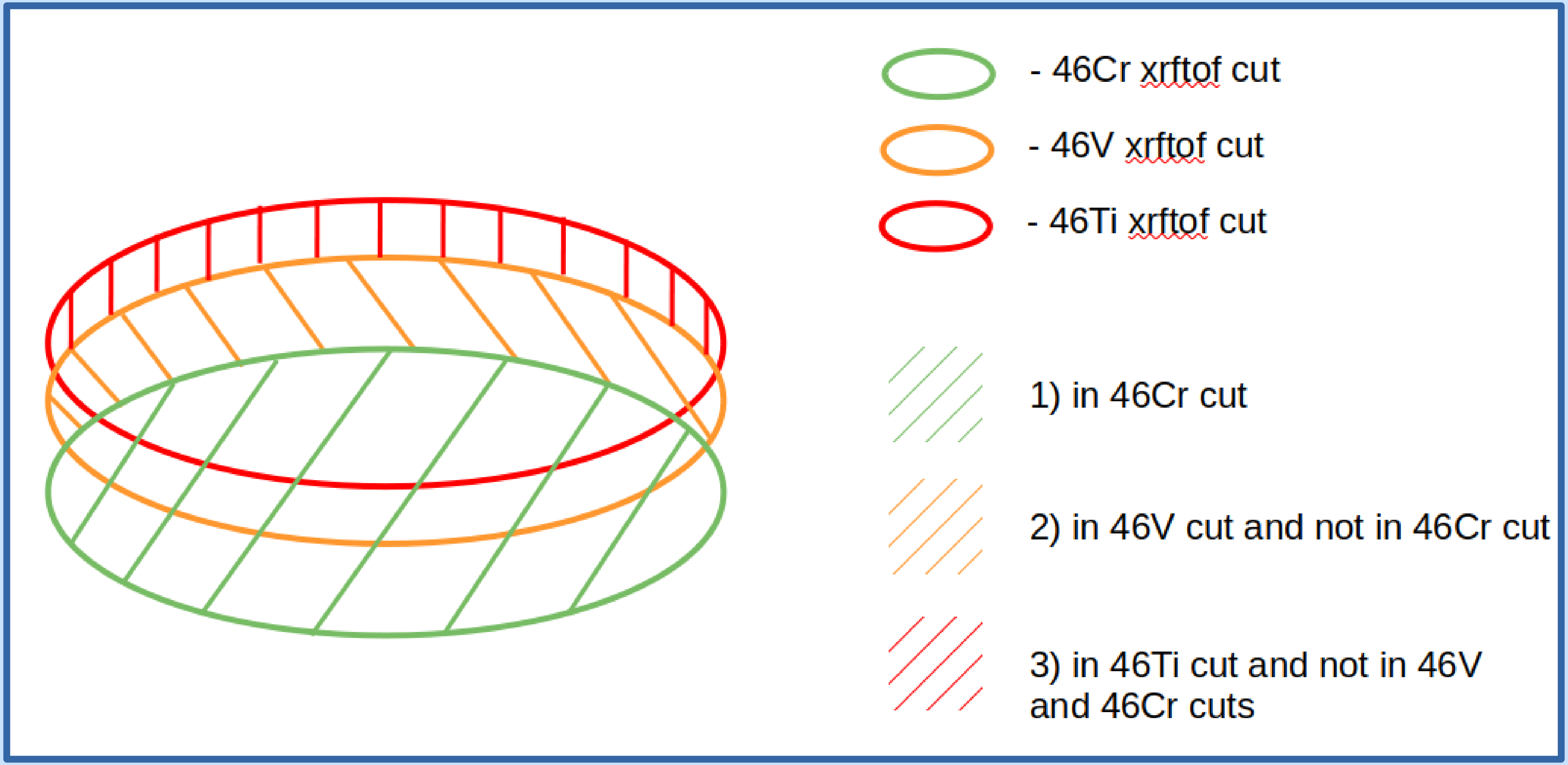
**1. Yields of residual nuclei**

| 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

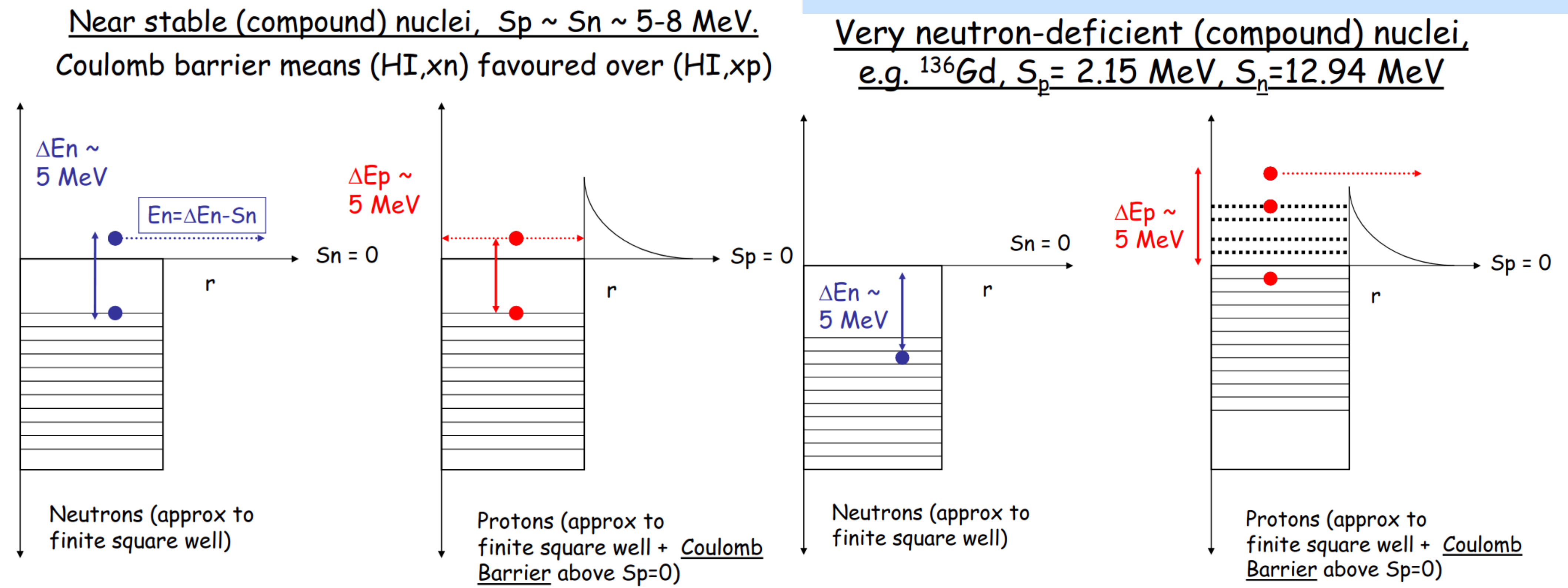


# X-RFTOF Gates



# Decay Channels

- Why neutron-deficient compound nuclei emit neutron over protons in fusion-evaporation




Nuclear structure studies of high-spin states with large arrays, Regan 2016