Key Experimental Probes of Energy Generation in X-ray Bursts – Spectroscopy of ^{49}Mn

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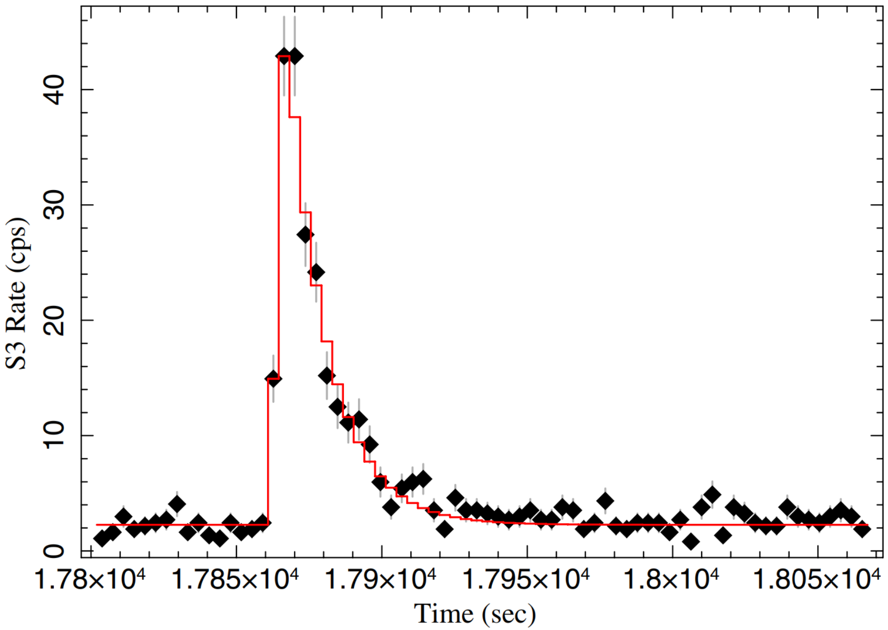
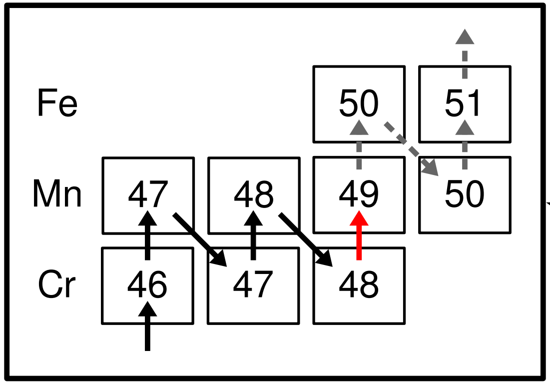
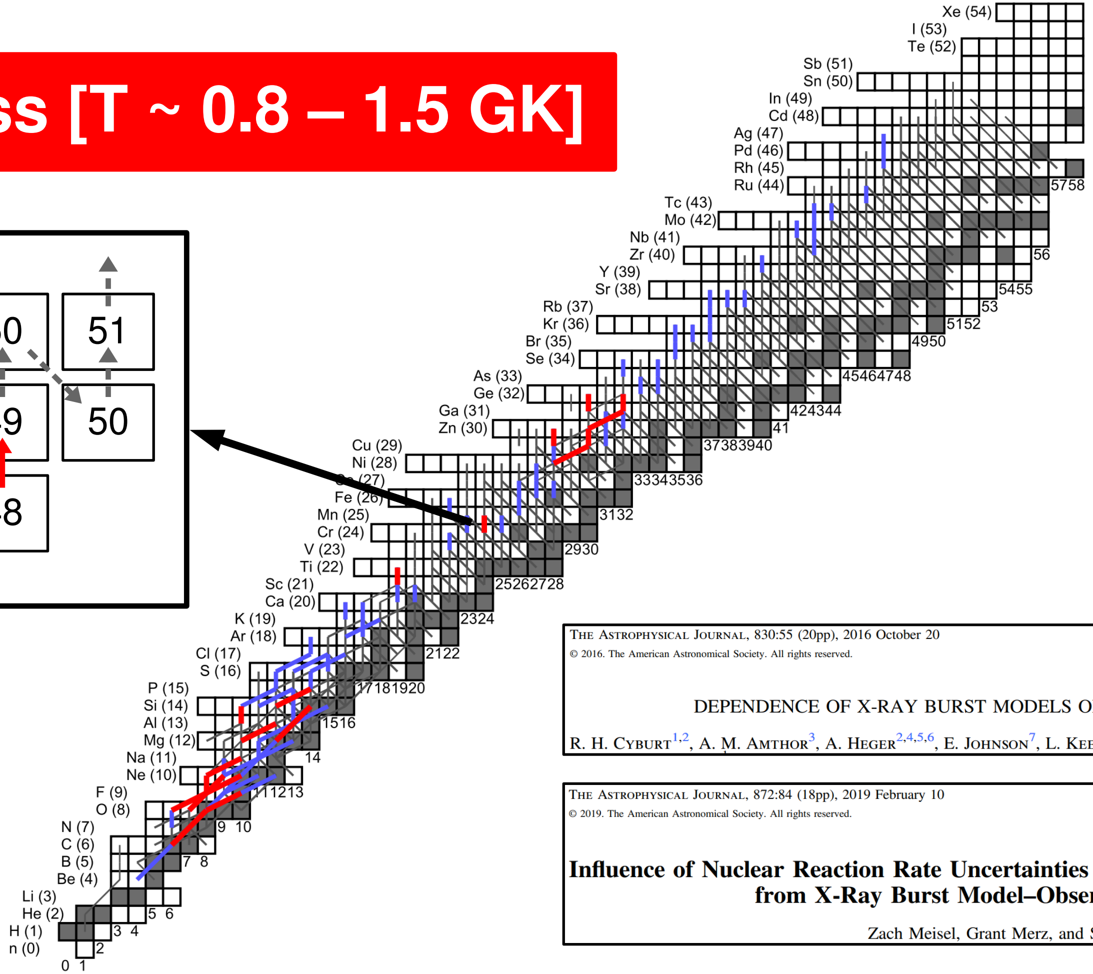
ECR Workshop 2025



Type-I X-ray Burst Nucleosynthesis

The *rp* process [T ~ 0.8 – 1.5 GK]





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DEPENDENCE OF X-RAY BURST MODELS ON NUCLEAR REACTION RATES

R. H. Cyburt[1,2], A. M. Amthor[3], A. Heger[2,4,5,6], E. Johnson[7], L. Keek[1,2,7,9], Z. Meisel[2,8], H. Schatz[1,2,7], and K. Smith[2,10]

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Influence of Nuclear Reaction Rate Uncertainties on Neutron Star Properties Extracted from X-Ray Burst Model–Observation Comparisons

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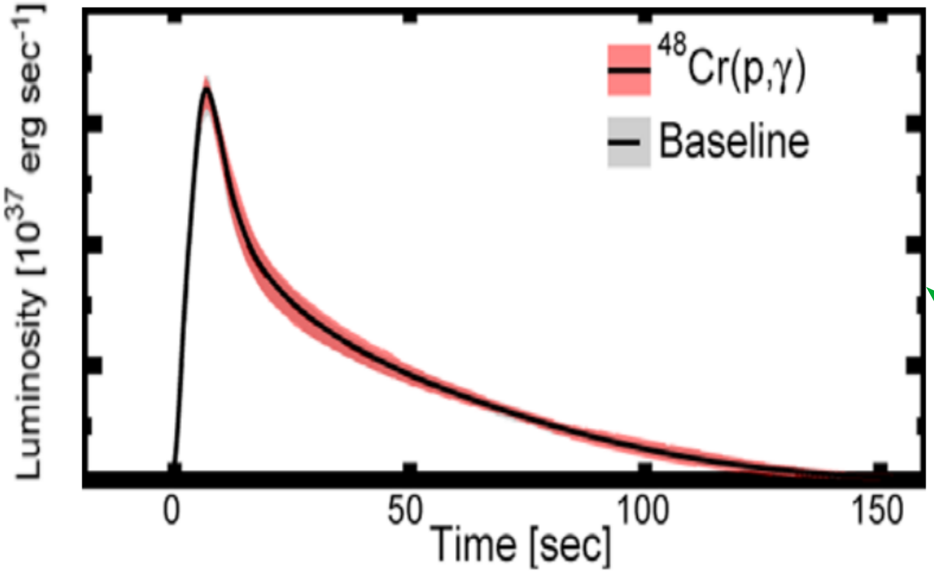

Reactions that Impact the Burst Light Curve in the Multi-zone X-ray Burst Model

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	^{15}O(α, γ)^{19}Ne	D	16	1
2	^{56}Ni(α, p)^{59}Cu	U	6.4	1
3	^{59}Cu(p, γ)^{60}Zn	D	5.1	1
4	^{61}Ga(p, γ)^{62}Ge	D	3.7	1
5	^{22}Mg(α, p)^{25}Al	D	2.3	1
6	^{14}O(α, p)^{17}F	D	5.8	1
7	^{23}Al(p, γ)^{24}Si	D	4.6	1
8	^{18}Ne(α, p)^{21}Na	U	1.8	1
9	^{63}Ga(p, γ)^{64}Ge	D	1.4	2
10	^{19}F(p, α)^{16}O	U	1.3	2
11	^{12}C(α, γ)^{16}O	U	2.1	2
12	^{26}Si(α, p)^{29}P	U	1.8	2
13	^{17}F(α, p)^{20}Ne	U	3.5	2
14	^{24}Mg(α, γ)^{28}Si	U	1.2	2
15	^{57}Cu(p, γ)^{58}Zn	D	1.3	2
16	^{60}Zn(α, p)^{63}Ga	U	1.1	2
17	^{17}F(p, γ)^{18}Ne	U	1.7	2
18	^{40}Sc(p, γ)^{41}Ti	D	1.1	2
19	^{48}Cr(p, γ)^{49}Mn	D	1.2	2

Variation of 1,931 reactions

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Indirect Measurements

Ideally we would measure the (p,γ) reaction directly,
but this usually is not feasible

↓

Instead, measure indirectly

↙ ↓ ↘

Excitation Energies, E_{ex}

Spin and Parity, J^{π}

Spectroscopic Factors, C^2S

Indirect Measurements

$$N_A \langle \sigma \nu \rangle = \frac{1.54 \times 10^{11}}{(\mu T_9)^{3/2}} \sum_i \exp\left[\frac{-11.605 E_{\mathrm{res},i}}{T_9}\right] \cdot (\omega\gamma)_i$$

These are the required ingredients to compute the reaction rate

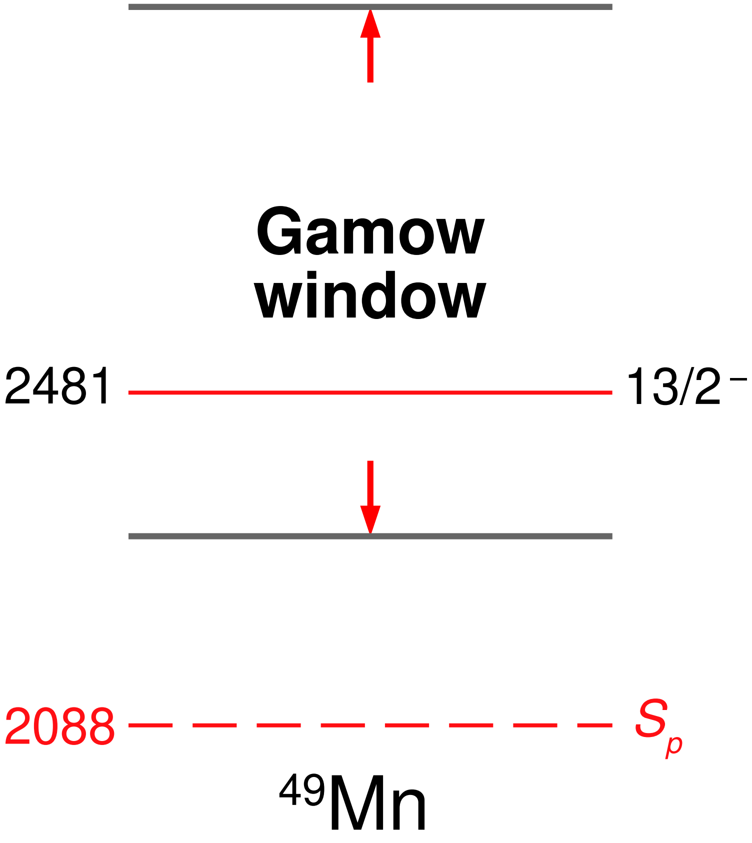
$$E_{\mathrm{res}} = E_{\mathrm{ex}} - S_p$$

$$\omega\gamma \simeq \omega\Gamma_p = \frac{2\hbar^2}{\mu R^2} \cdot \frac{2J_{\mathrm{res}}+1}{(2j_p+1)(2j_X+1)} \cdot P_\ell \cdot C^2 S \cdot \theta_p^2$$

Structural Information of ^{49}Mn

^{24}Mg(^{28}Si,*pn*) – C.D. O'Leary *et al.*, PRL **79** (1997), 4349

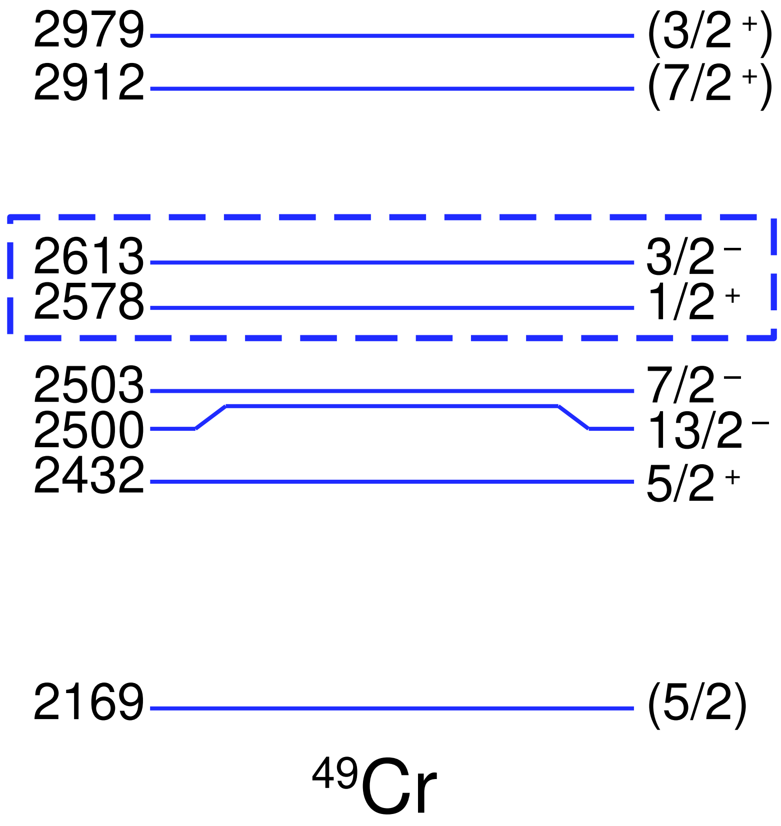
No low-ℓ transfers known in the astrophysically relevant region above S_p = 2088(8) keV



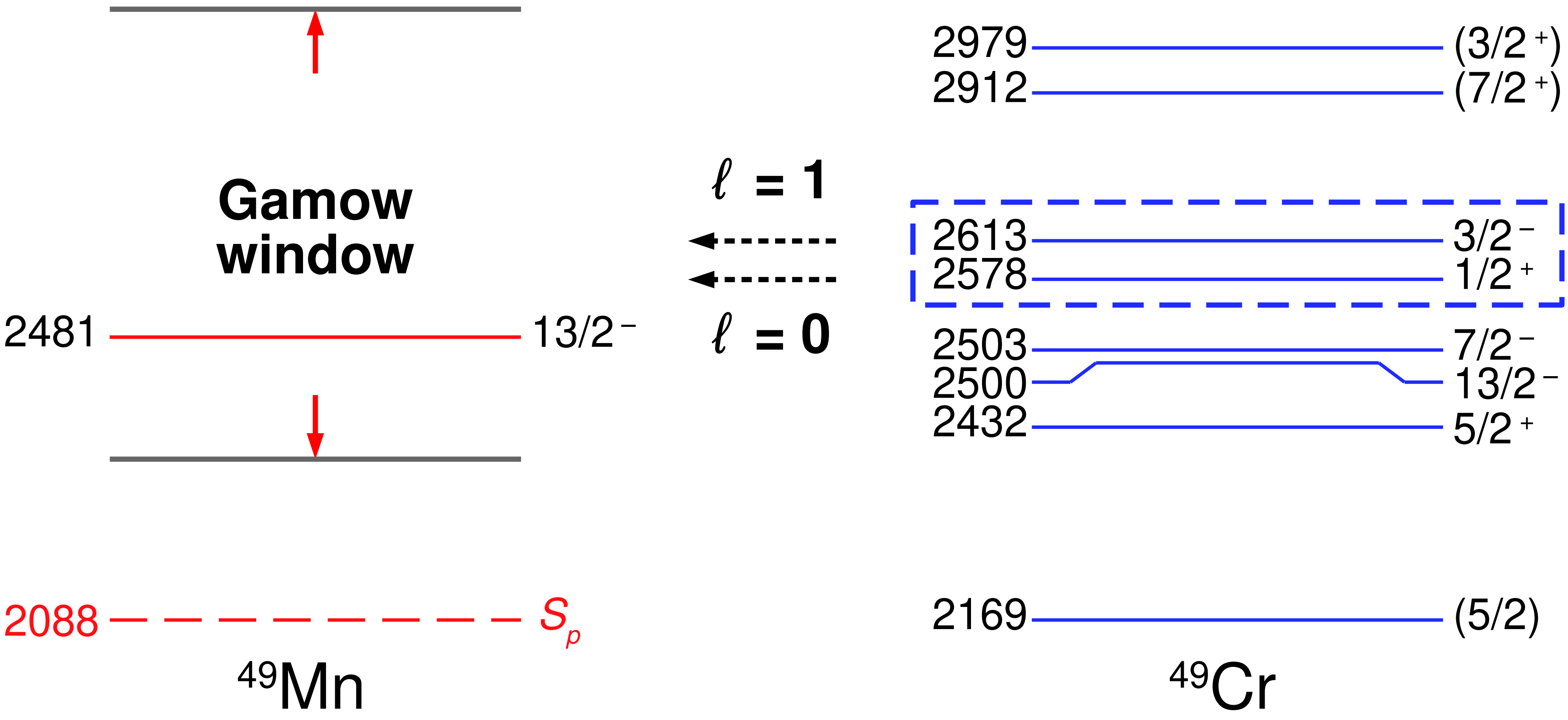
Structural Information of ^{49}Mn

^{46}Ti(α,n) – F. Brandolini *et al.*, PRC **73** (2006), 024313

An evaluation of the mirror nucleus, ^{49}Cr, shows **two low-ℓ transfers** are known in the region: an $\ell = 0$ and an $\ell = 1$

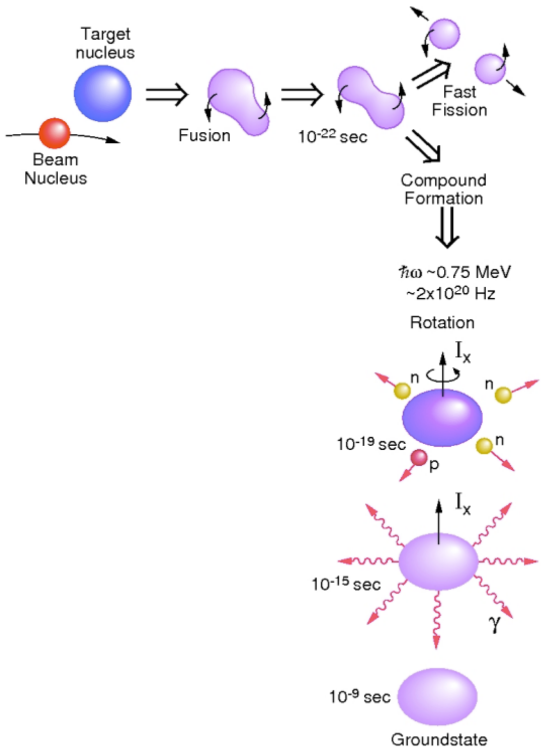


Structural Information of ^{49}Mn



Fusion-evaporation Reactions

Combinations of stable beam and target may be used to produce ***p*-rich nuclei** via **fusion-evaporation** reactions



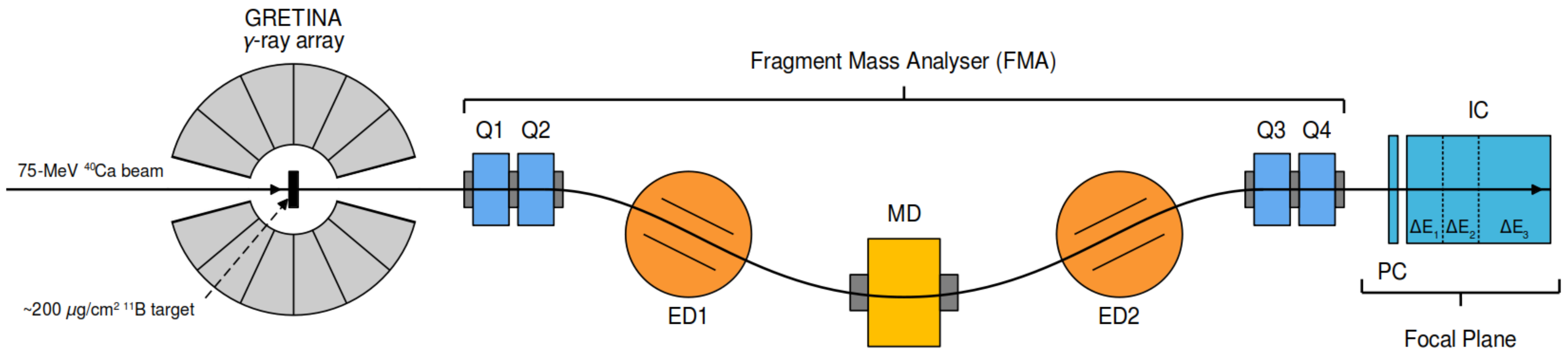
Techniques in ***γ*-ray spectroscopy** allow for the precise measurements of **resonance energies**

Challenging as **high-spin states** are **preferentially populated** and the ***n*-evaporation** channel is usually **weak**

The ^{11}B(^{40}Ca,2*n*) Reaction @ ANL

A 75-MeV, ~13-pnA ^{40}Ca beam was used to bombard a ~200-μg/cm^2 ^{11}B target, populating states in ^{49}Mn via ^{11}B(^{40}Ca,2*n*) and ^{49}Cr via ^{11}B(^{40}Ca,*pn*)

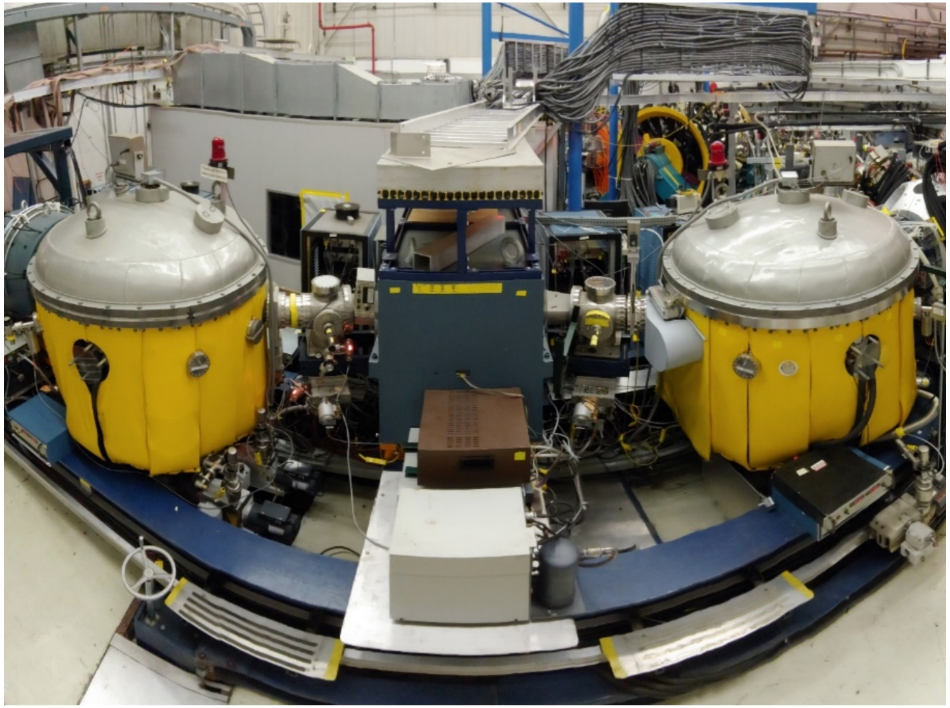
Aim: separate and select upon ^{49}Mn nuclei, and look to the coincident γ rays



The ^{11}B(^{40}Ca,2*n*) Reaction @ ANL

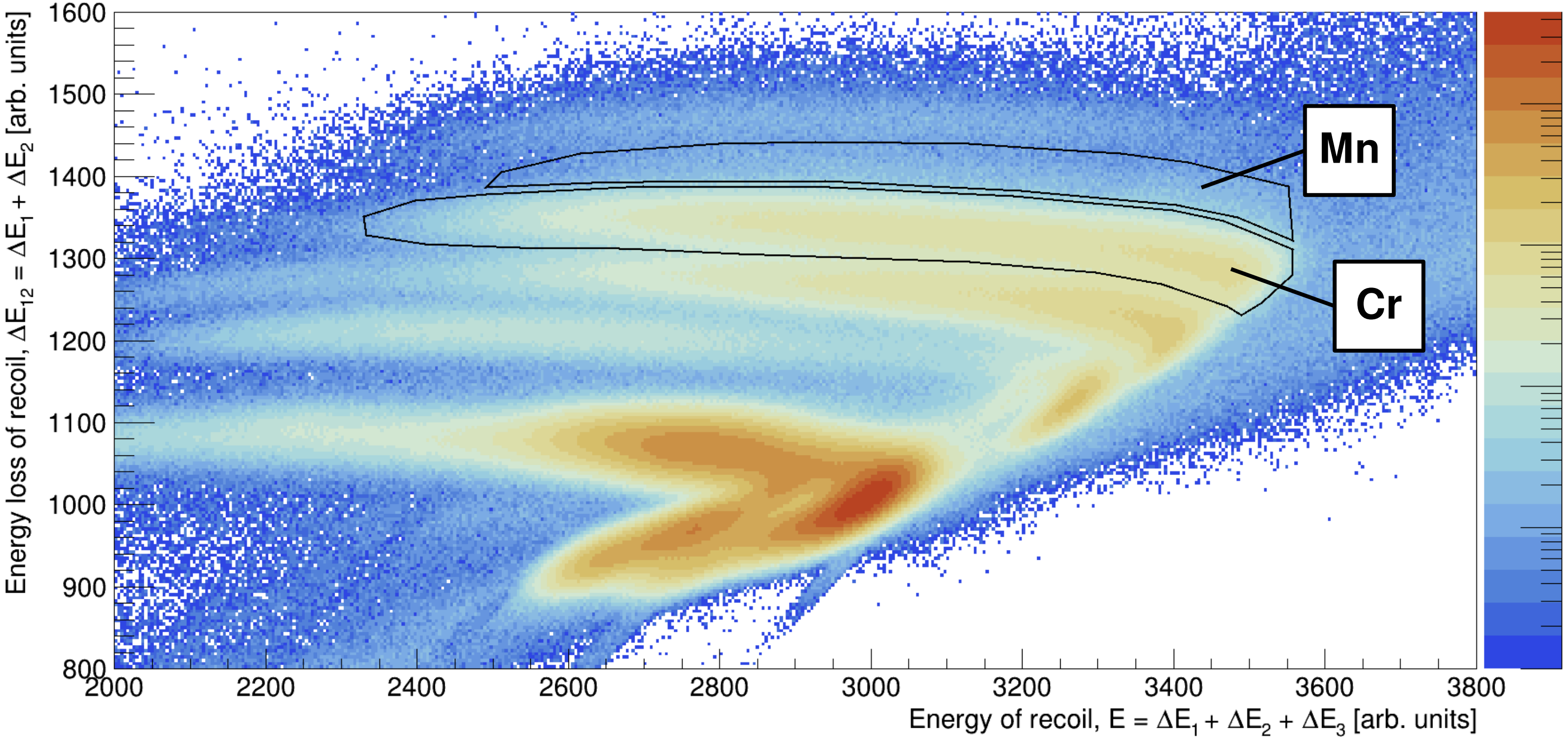
GRETINA

Fragment Mass Analyser



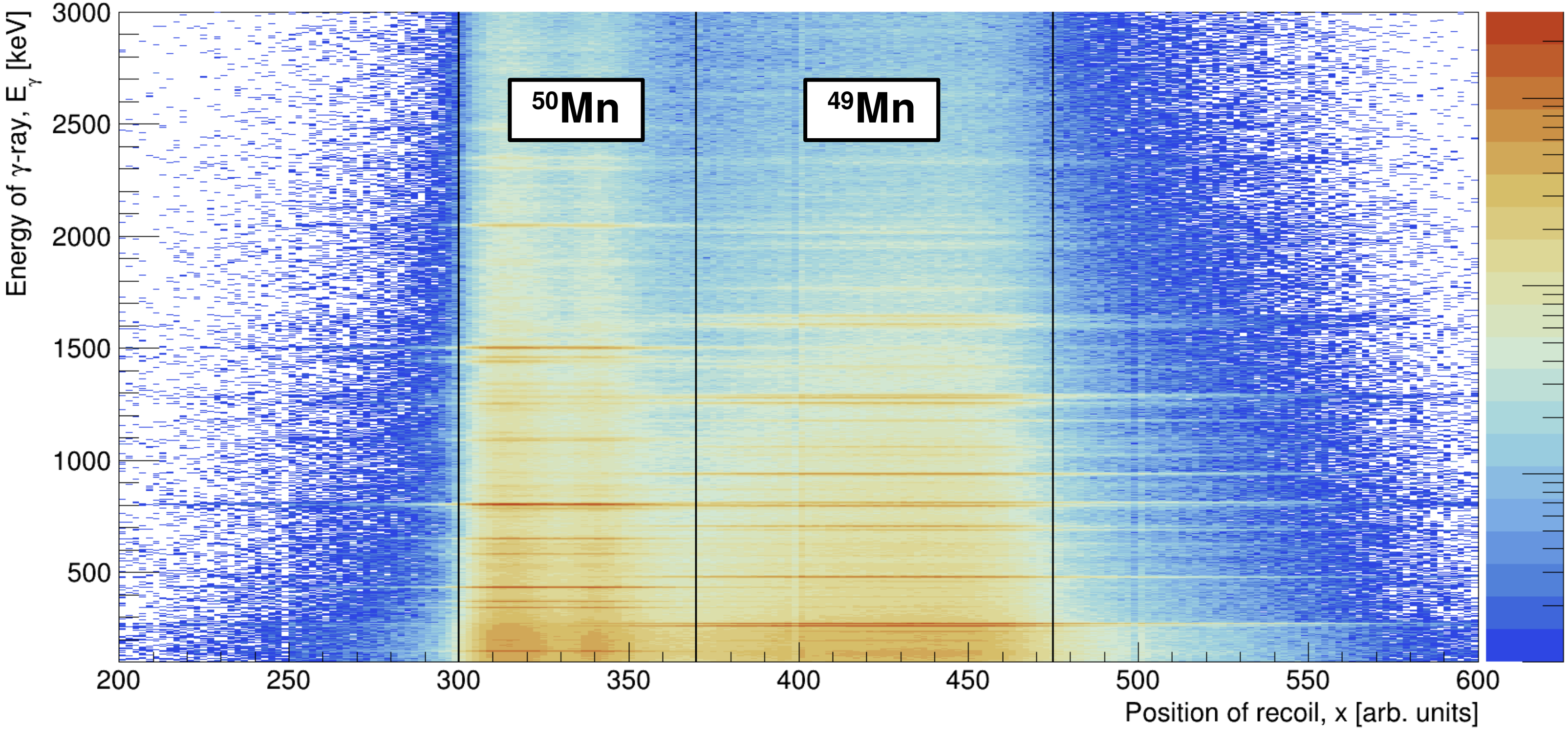
Recoil Selection of $^{11}B(^{40}Ca,2n)$

Ionisation Chamber allows for separation of $Z = 25$ (Mn) nuclei

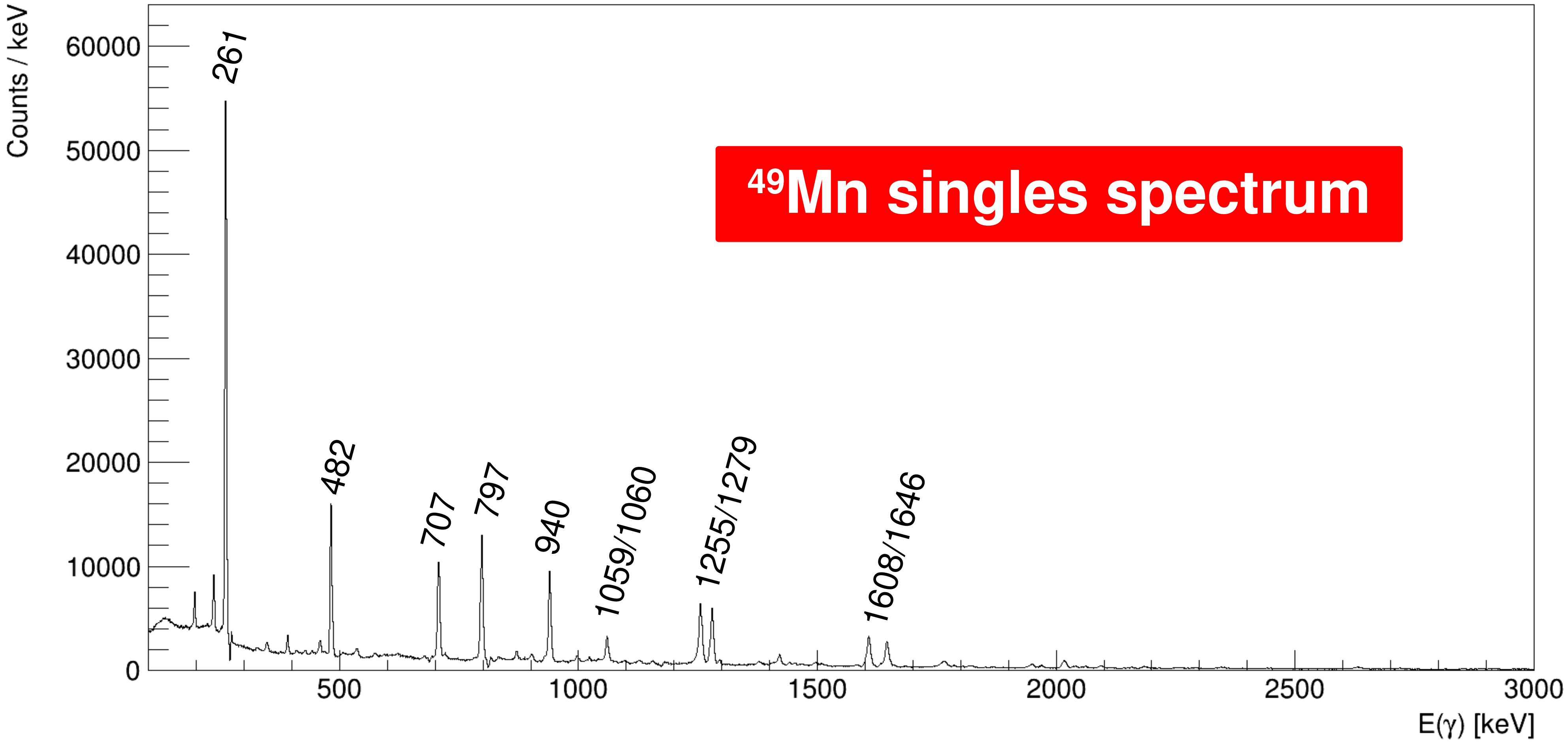


Recoil Selection of $^{11}B(^{40}Ca,2n)$

Proportional Counter allows for separation of *A* = 49 nuclei



Gamma-ray Spectroscopy Study of ^{49}Mn



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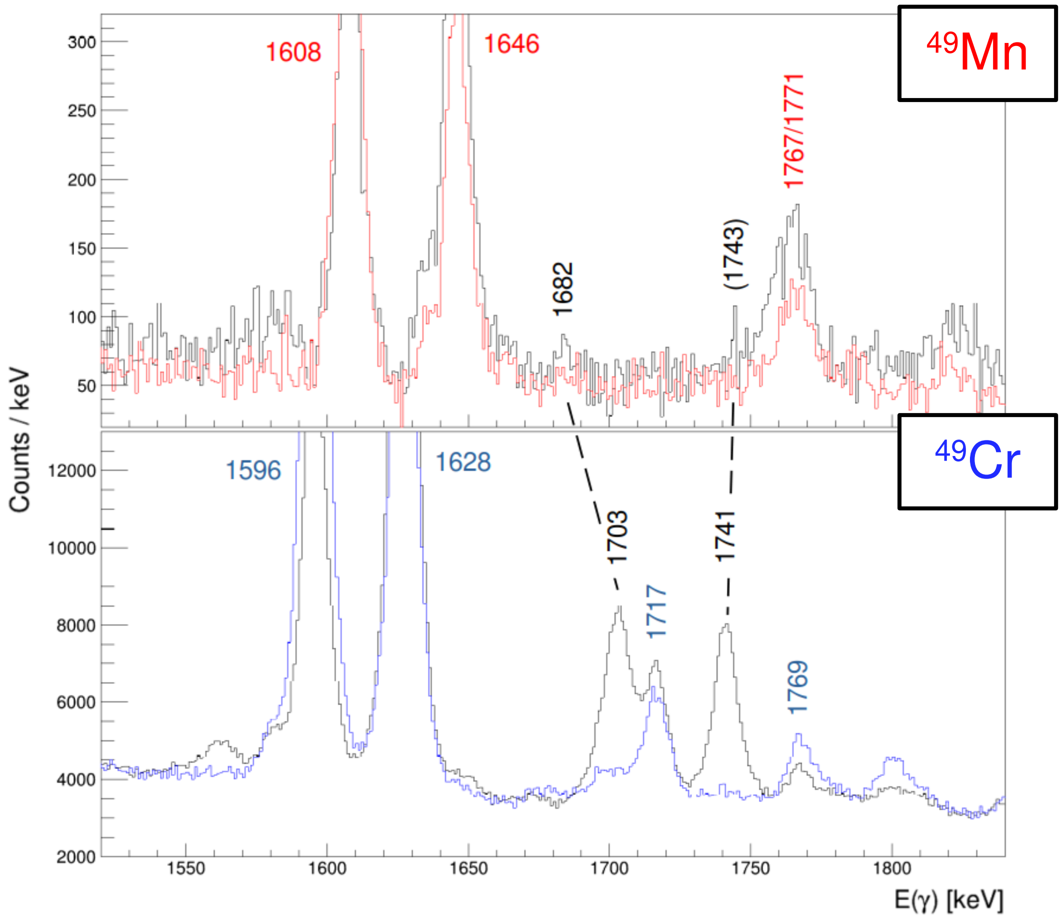
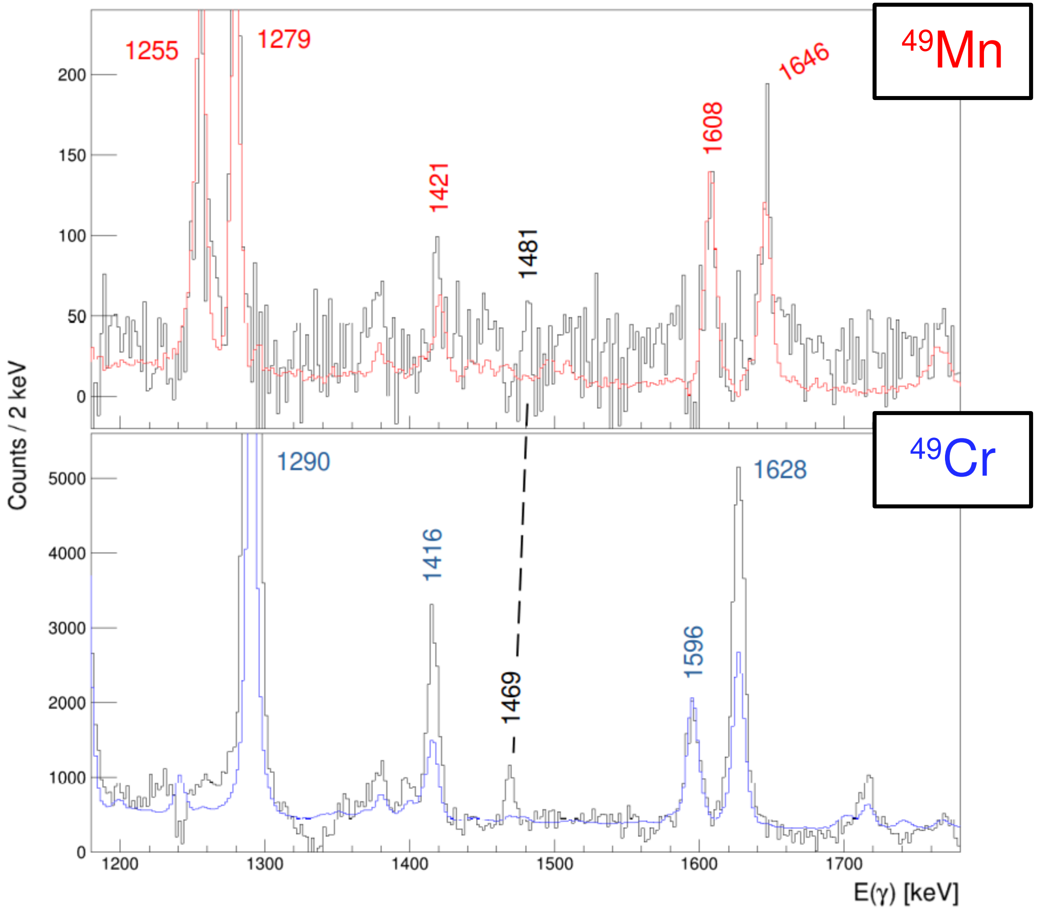


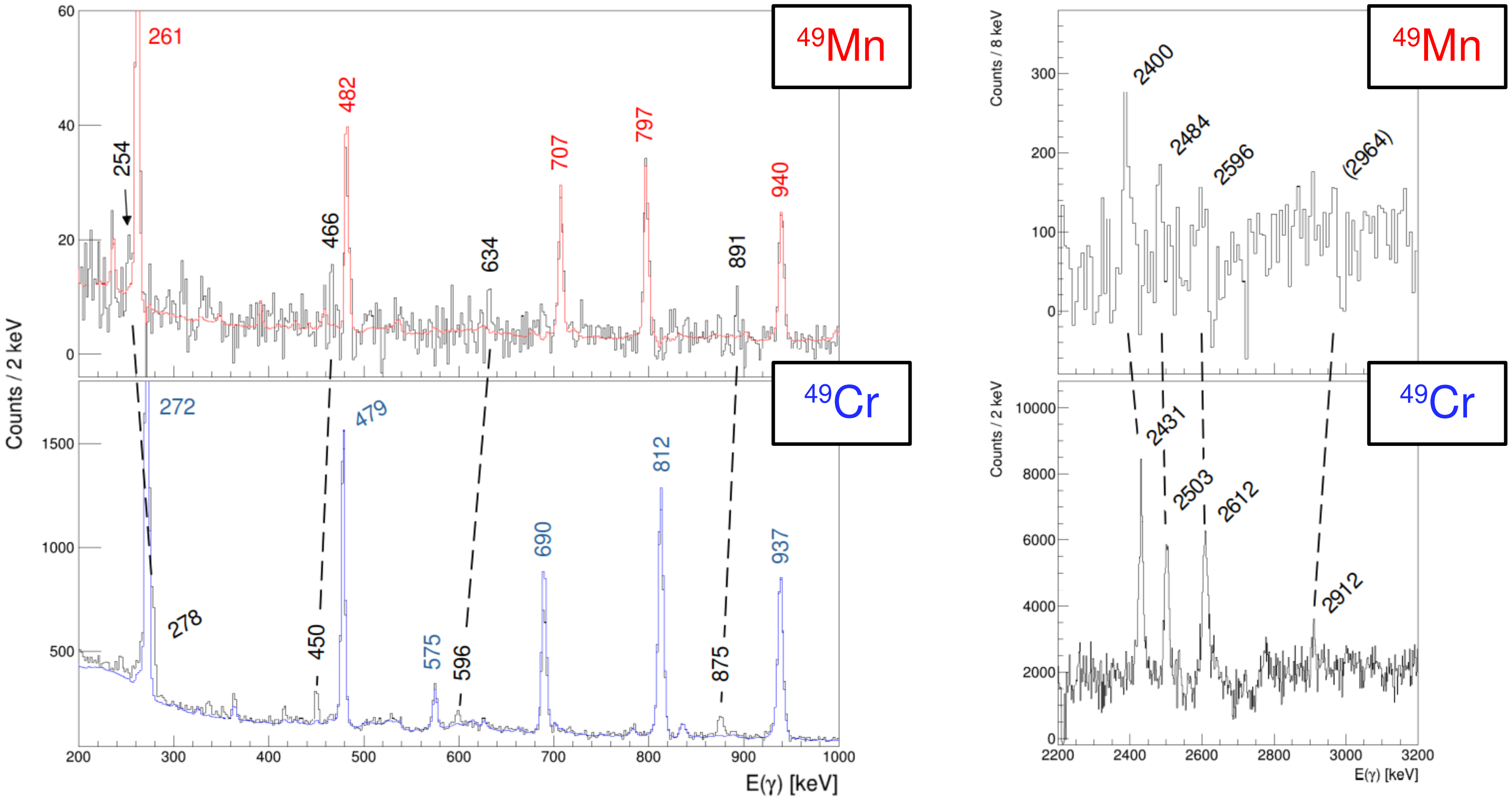
Comparison of **low-** ($N_\gamma = 1$) and **high-** ($N_\gamma \geq 4$) **multiplicity singles**

Gamma-ray Spectroscopy Study of ^{49}Mn

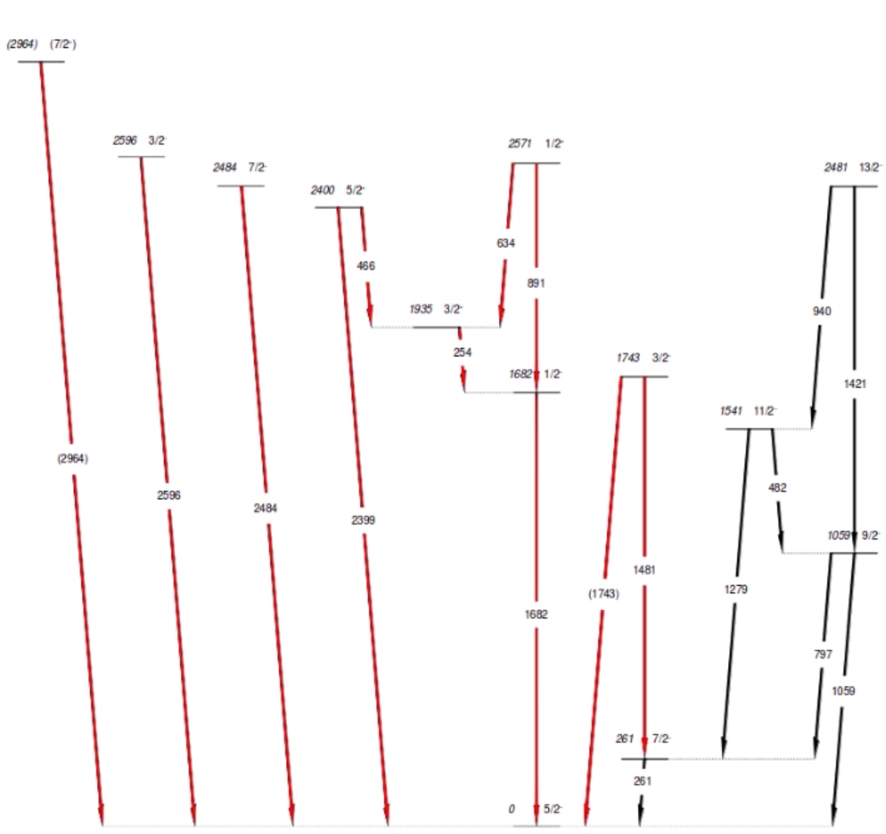


Comparison of
low- ($N_\gamma = 2$) and
high- ($N_\gamma \geq 5$)
multiplicity *γ-γ*
(gate on $7/2^- \rightarrow 5/2^-$)

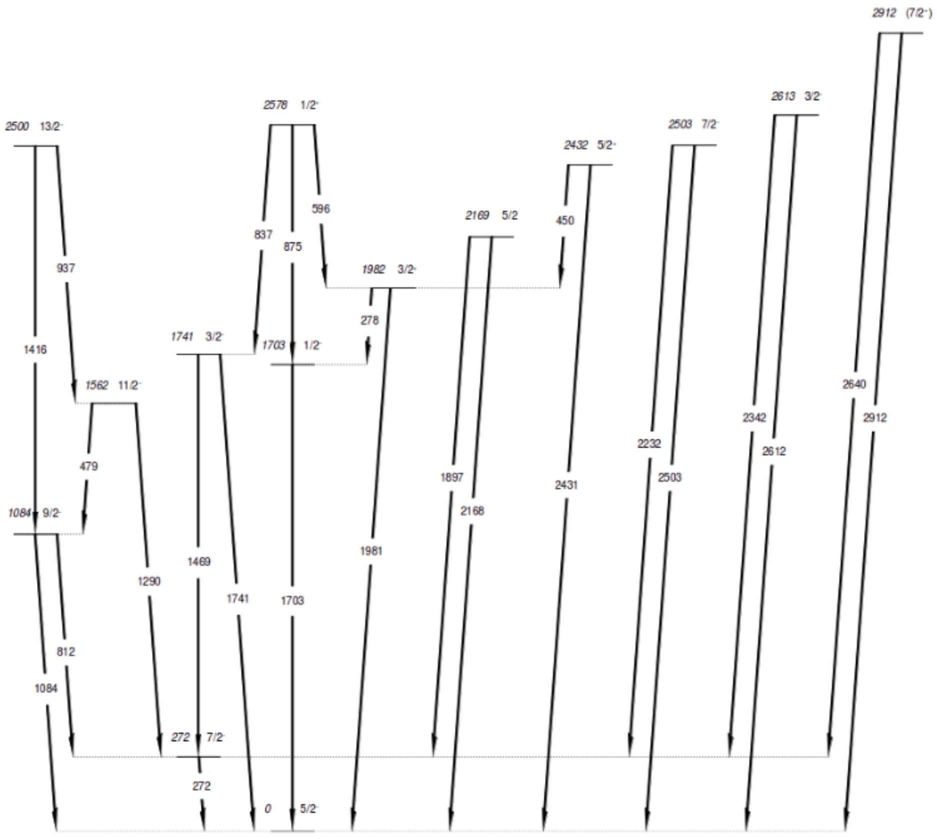
Gamma-ray Spectroscopy Study of ^{49}Mn



Partial Level Schemes of ^{49}Mn and ^{49}Cr



^{49}Mn



^{49}Cr

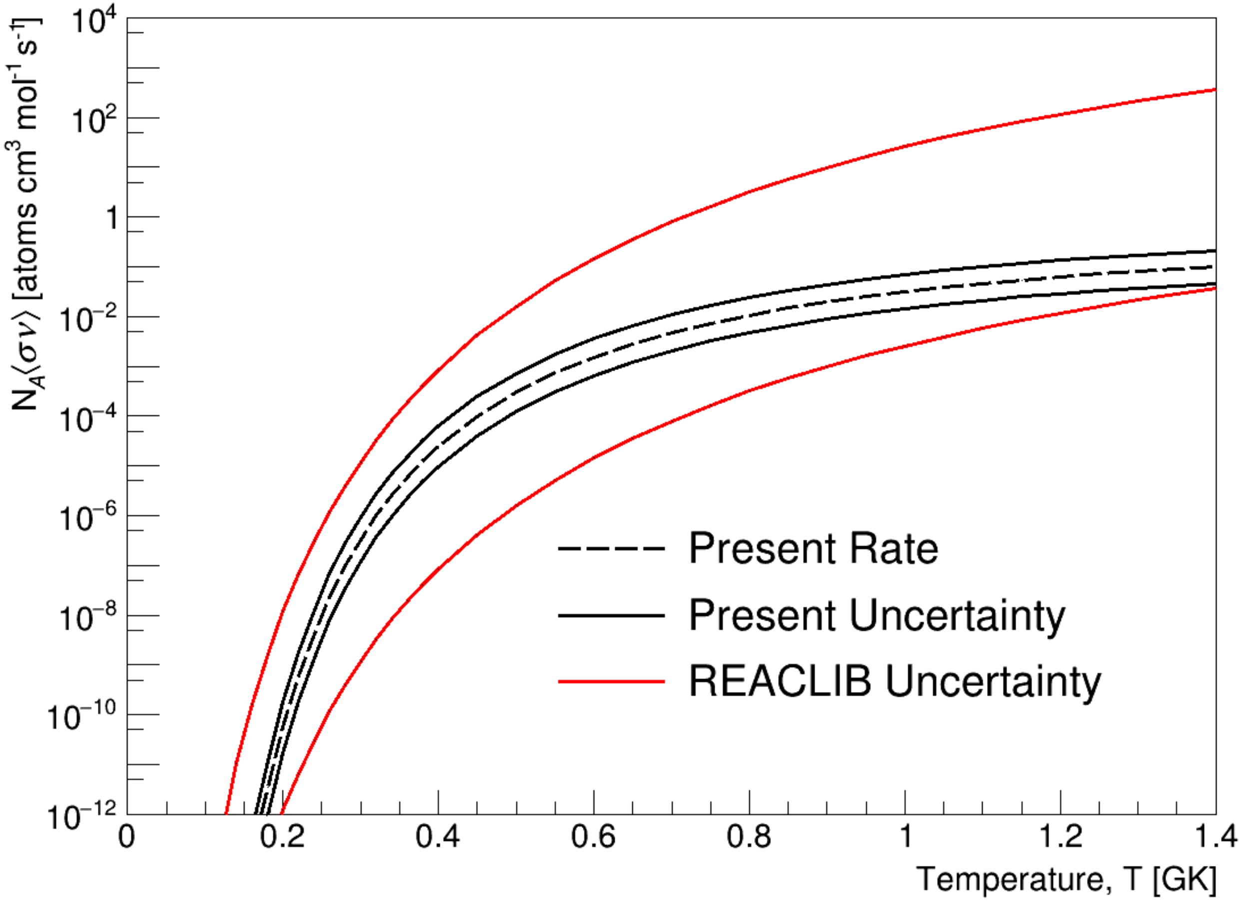
Resonances in the ^{48}Cr + *p* system

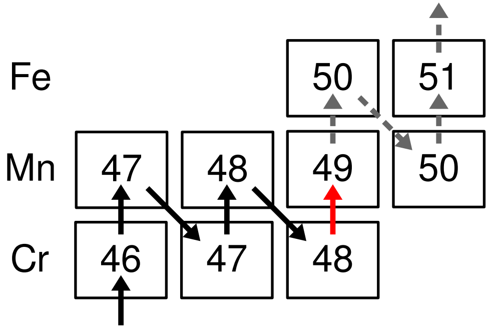
E_{ex} (keV)	E_{res} (keV)	J^π	ℓ	C^2S	Γ_p (eV)	Γ_γ (eV)	$\omega\gamma$ (eV)
2400.3(29)	312.3(85)	$5/2^+$	2	0.01	7.90×10^{-11}	6.91×10^{-4}	2.37×10^{-10}
2484.4(19)	396.4(82)	$7/2^-$	3	0.01	3.71×10^{-10}	5.70×10^{-2}	1.48×10^{-9}
2570.9(26)	482.9(84)	$1/2^+$	0	0.03	3.89×10^{-5}	5.70×10^{-4}	3.64×10^{-5}
2595.9(21)	507.9(83)	$3/2^-$	1	0.01	1.24×10^{-5}	1.01×10^{-2}	2.48×10^{-5}
(2964.4(28))	(876.4(85))	$(7/2^+)$	4	0.01	3.35×10^{-6}	8.77×10^{-4}	1.34×10^{-5}

Spectroscopic factors adopted from comparison with ^{51}Mn ^{50}Cr(^{3}He,*d*) – J.E. Kim *et al.*, PRC **23** (1981), 742

$$N_A\langle\sigma\nu\rangle = \frac{1.54 \times 10^{11}}{(\mu T_9)^{3/2}} \sum_i \exp\left[\frac{-11.605 E_{\mathrm{res},i}}{T_9}\right] \cdot (\omega\gamma)_i$$

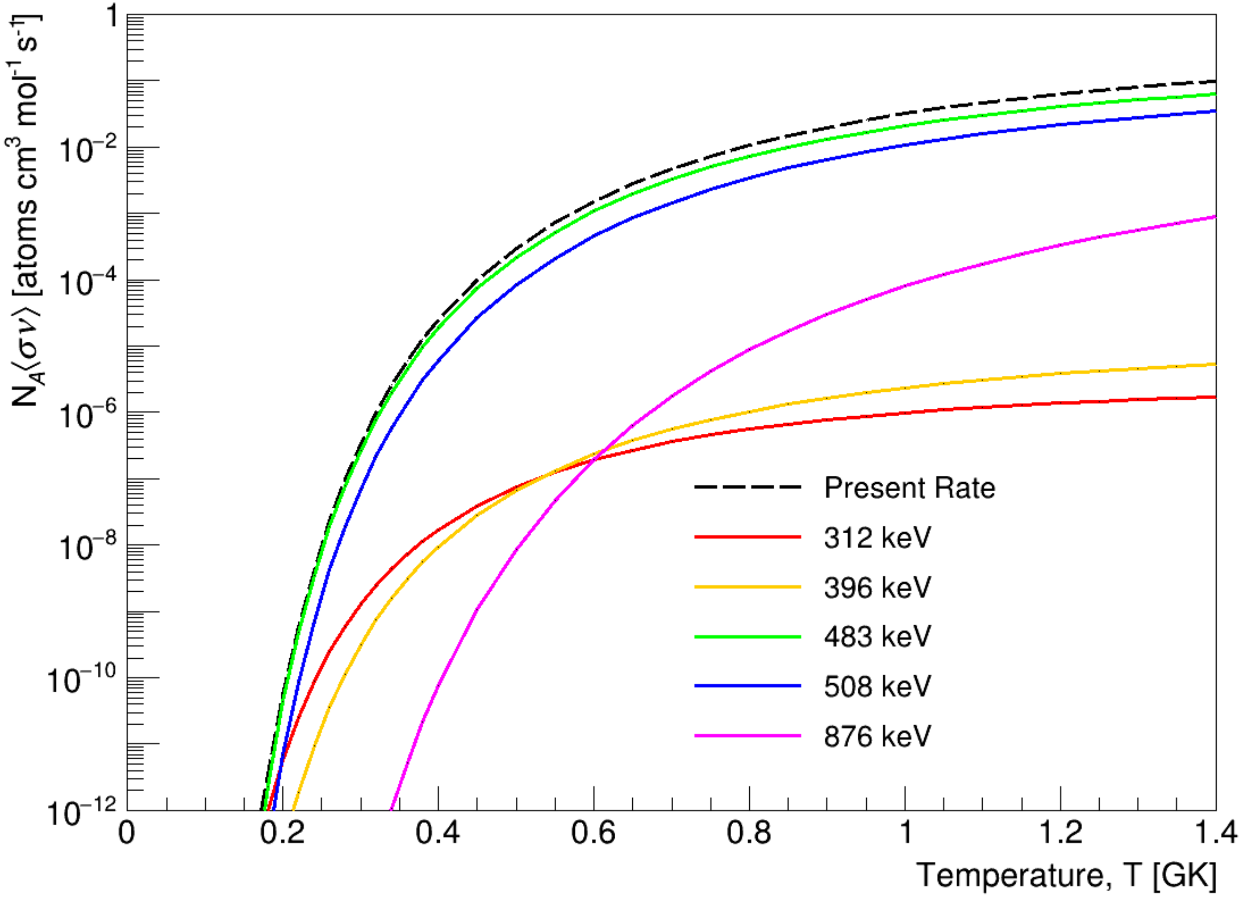
The Stellar Reaction Rate of ^{48}Cr(p,γ)

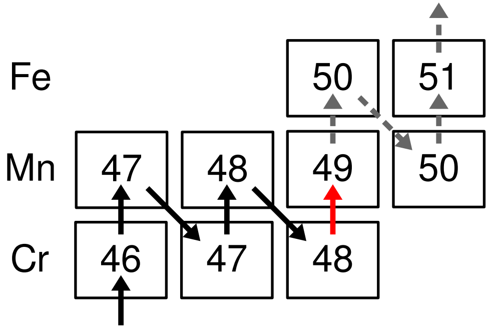




Stellar rate reduced by ~3 orders of magnitude

The Stellar Reaction Rate of $^{48}Cr(p,\gamma)$



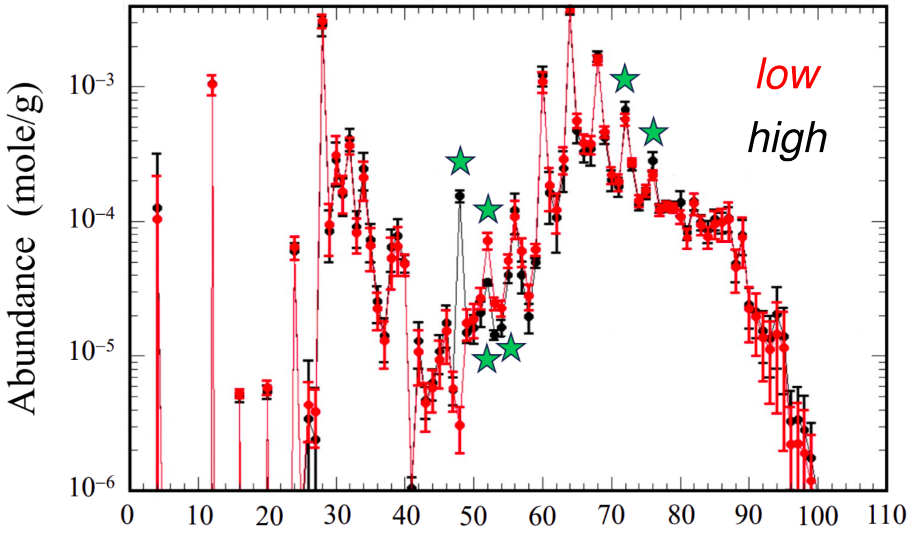


Stellar rate reduced by ~3 orders of magnitude

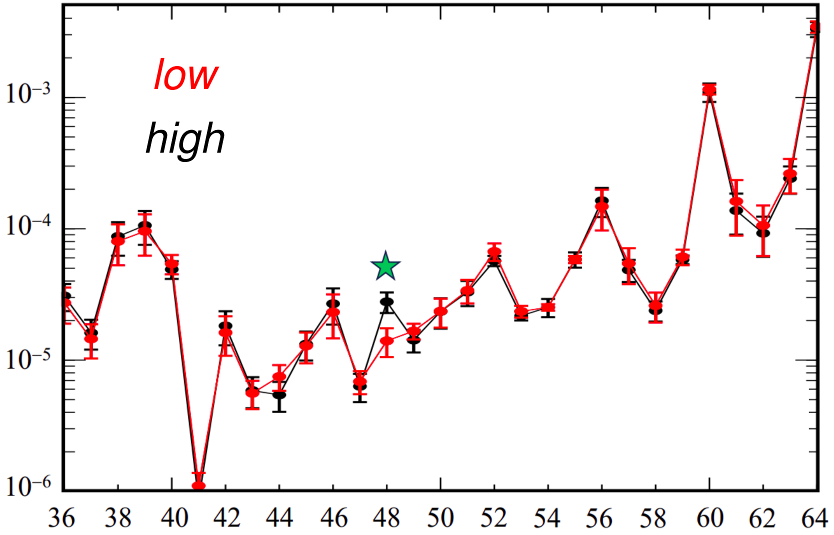
Astrophysical Implications of ^{48}Cr(p,γ)

Look to MESA stellar evolution code calculations:

PREVIOUS



PRESENT



C. O'Shea, G. Lotay, D.T. Doherty *et al.*, PLB **854** (2024), 138740

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Thank you for your attention