^{56}Fe(p,p'ɤ) Lifetime Measurements with GRETINA

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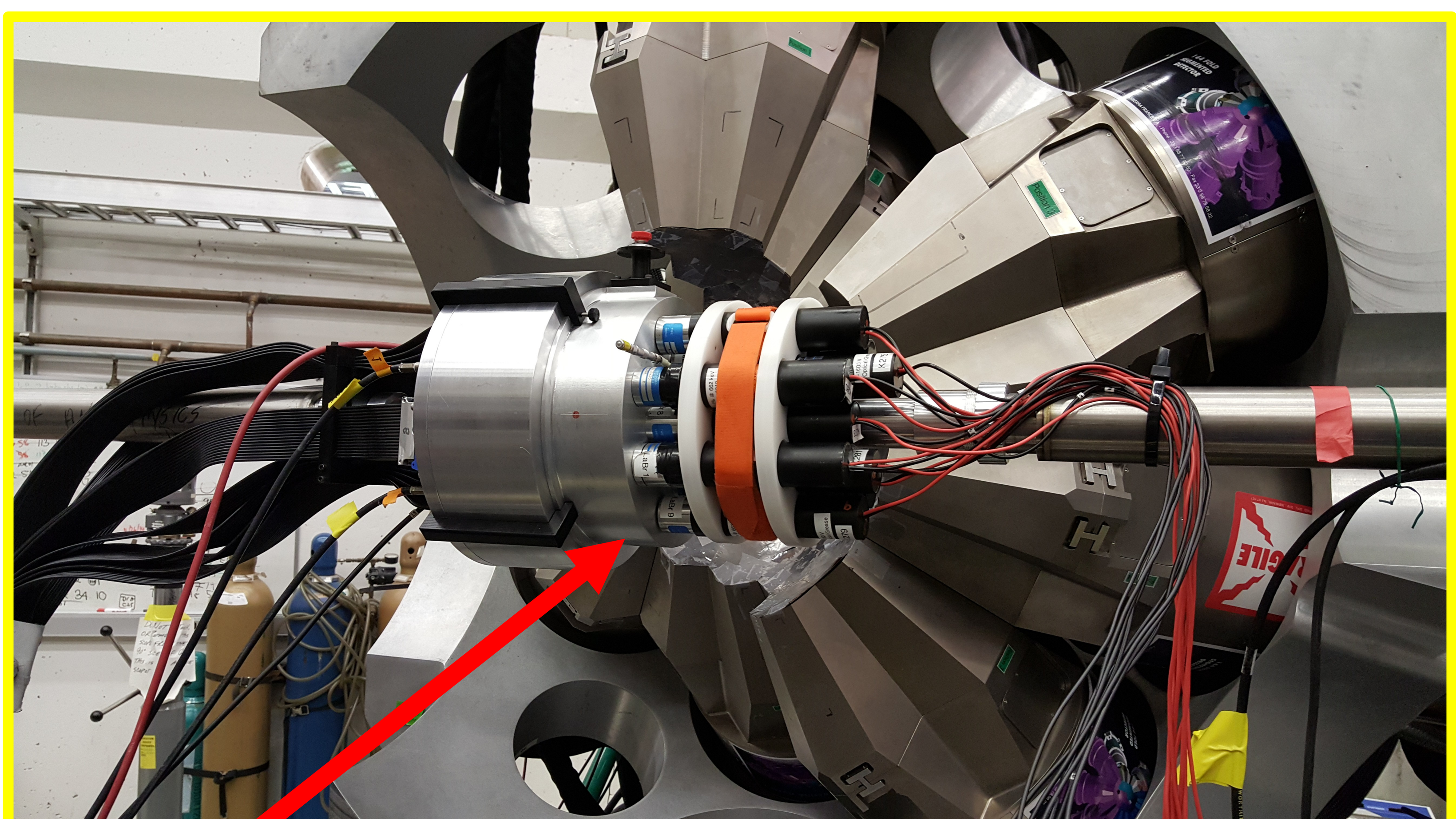
Introduction

The Gamma-Ray Tracking In-beam Nuclear Array[1] (GRETINA) is one of the world's premier ɤ-ray spectrometers. GRETINA uses electrically segmented high-purity germanium crystals to reconstruct the energy and position of each ɤ-ray interaction point with high resolution, thereby enabling the tracking of the paths of ɤ-rays emitted from nuclear reactions.

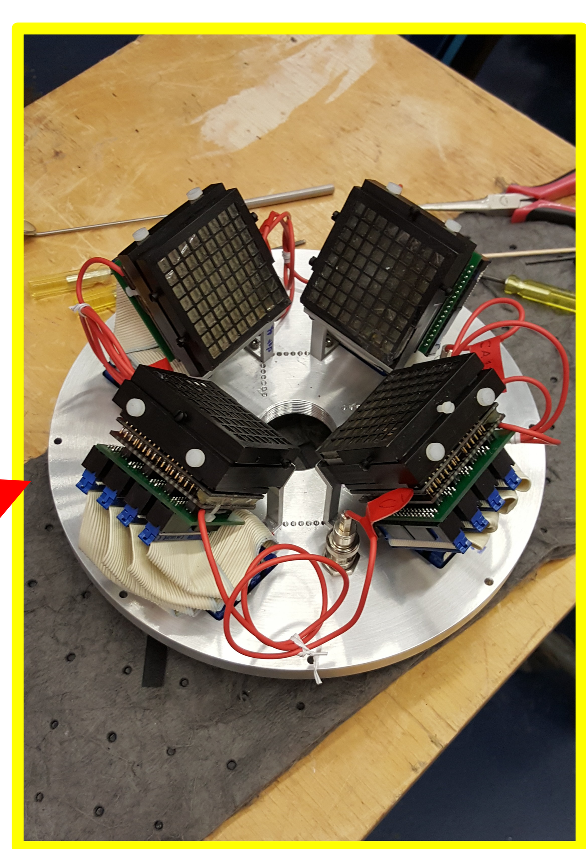
[1]S. Paschalis et al., NIM A 709, 44 (2013).



Eight Quads each containing four Germanium Crystals

Individual Crystal < 2.5keV energy resolution and < 10ns timing resolution at 1.33MeV

Phoswich Wall charged particle detector for energy, angle, and timing of outgoing protons



Experiment

The Argonne Tandem and Linear Accelerator System (ATLAS) produced pulses of 16 MeV protons every 40 ns for an average current of 750 pA on a 1 mg/cm^2 iron target enriched to 99.7% in ^{56}Fe. 80 hours of beam uptime provided a 3 kHz particle-ɤ master trigger.

The (p,p'ɤ) reaction produced excited states of ^{56}Fe up to roughly the neutron separation energy. The charged-particle detector array Phoswich Wall[2] measured the energy, timing, and angle of the forward scattering protons.

[2]D. G. Sarantites et al., NIM A 790, 42 (2015).

Recoil Doppler Shift

Nuclear stopping time is on the order of ps while most nuclear decays are on the order of fs. Therefore the nucleus emits a ɤ-ray while moving a fraction of the speed of light toward the detector. This causes a measureable doppler shift in the energy of the emitted ɤ-ray:

$$E_{\gamma,\,observed} = E_{\gamma,\,source}\,(1 + v_\Theta) \qquad \text{where} \quad v_\Theta = v\cos\Theta / c$$

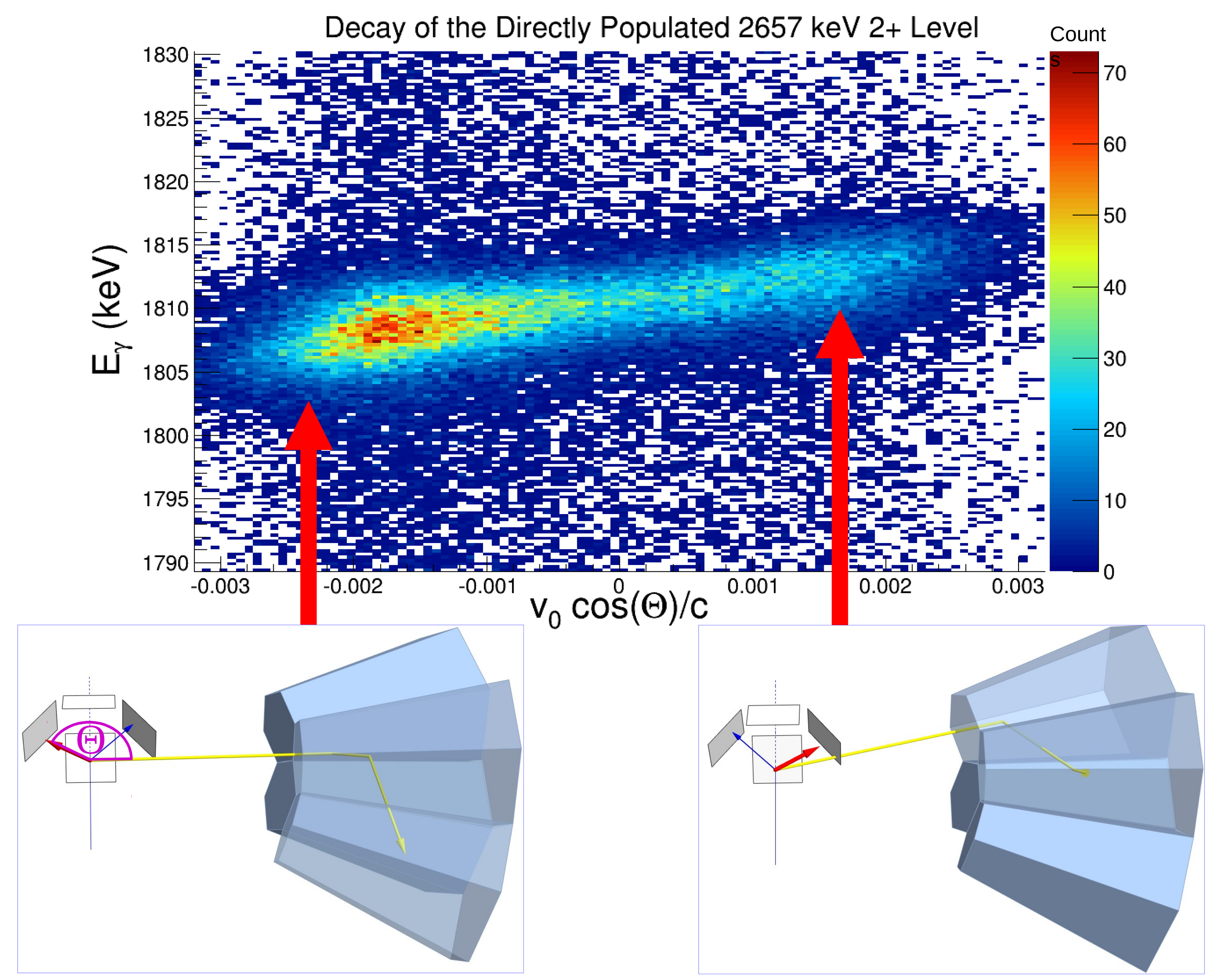


Fig. 2: Top: Doppler shifted ɤ data for the $2^+_2 \rightarrow 2^+_1$ in ^{56}Fe for known recoil and emission angles. Bottom: An illustration of the reaction: Phoswich Wall detects proton (blue) after scattering off ^{56}Fe (red) which emits a ɤ (yellow) that is detected by GRETINA. Θ is angle between ɤ and recoiling ^{56}Fe.

Slowing Down Simulation

SRIM[3] generates ^{56}Fe recoil trajectories and outputs (E, x, y, z) collision coordinates yielding v(t). ɤ-rays emit at a random time according to the exponential decay law toward detectors at every Θ. This monte carlo approach results in an average recoil emission velocity v_Θ for a given initial recoil energy E_0, Θ_0, and half-life $t_{1/2}$.

[3]J. Ziegler, srim.org

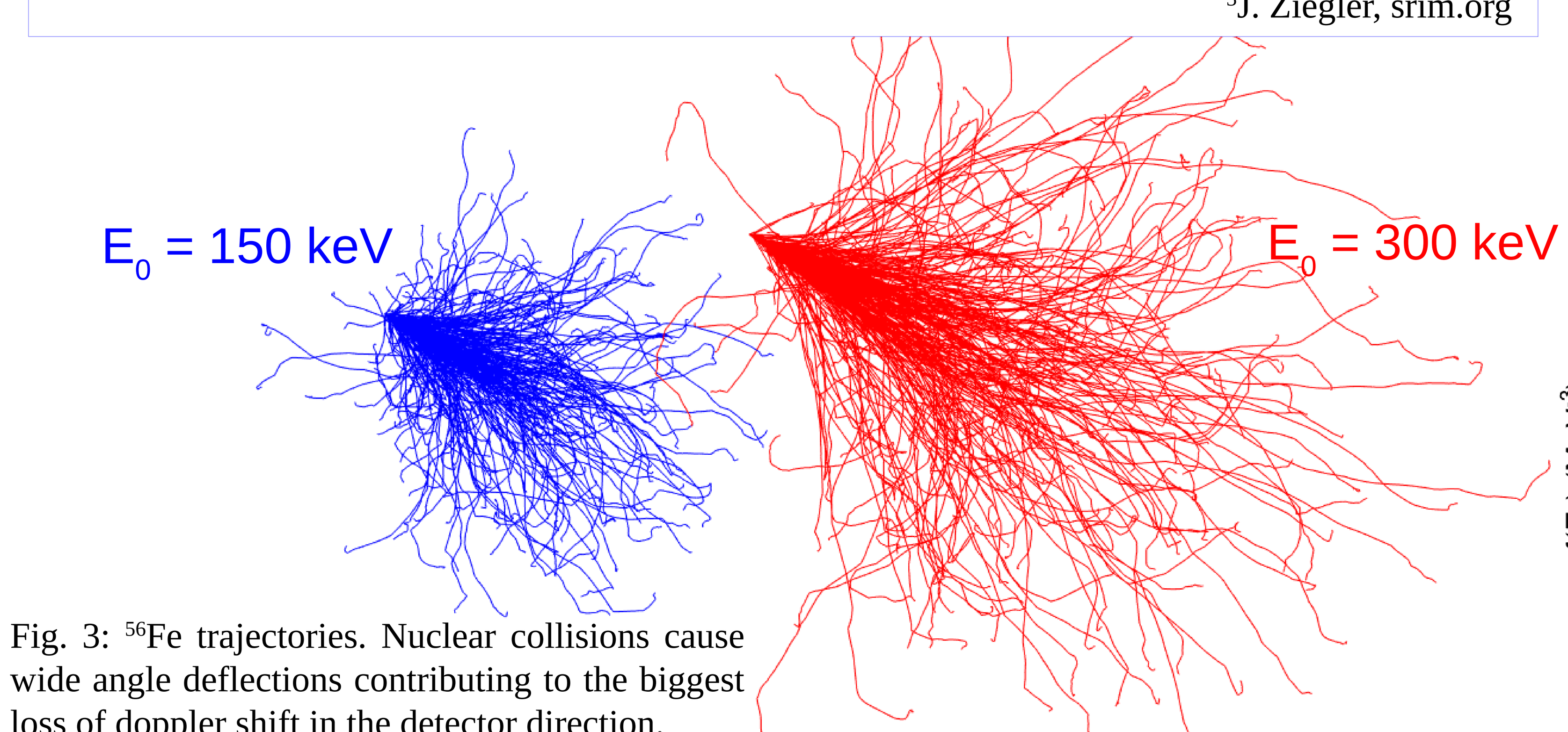
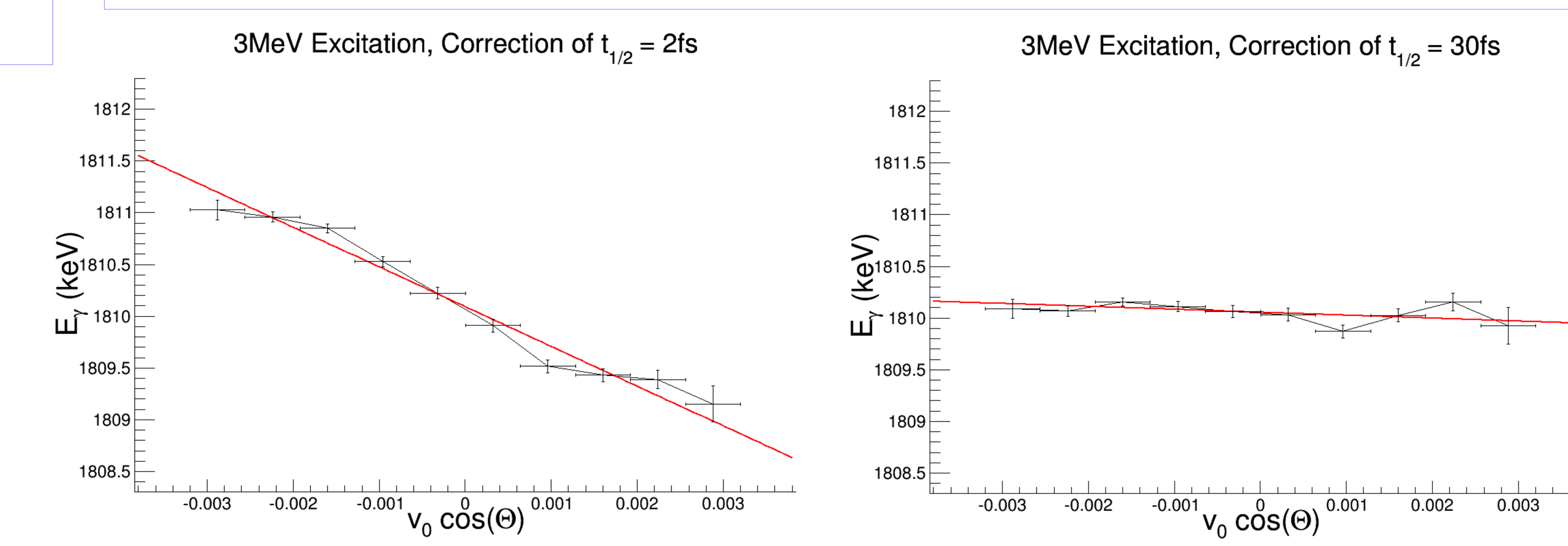


Fig. 3: ^{56}Fe trajectories. Nuclear collisions cause wide angle deflections contributing to the biggest loss of doppler shift in the detector direction.

Direct Lifetimes

Knowledge of the averge emission velocity removes the effect of the doppler shift according to $E_\gamma = E_{\gamma,\,obs} / (1 + v_\Theta)$ on an event by event basis. When $t_{1/2}$ is correct, no residual slope remains in the E_γ vs. v_Θ plot as seen below for the 1810 keV transistion.



Level(keV)	E_γ(keV)	$t_{1/2}$(fs)	ENDF	Comment
2657	1810	33(2)	21(1)	need to account for QC feeding
2960	2113	20(4)	28(3)	2nd peak in window
3120	2273	20(8)	19(1)	agreement
3123	1037	51(4)	47(12)	agreement
3370	2523	19(2)	17(3)	agreement
3345	2598	52(9)	29(5)	low statistics

Reproduces ENSDF Low Lying Lifetimes

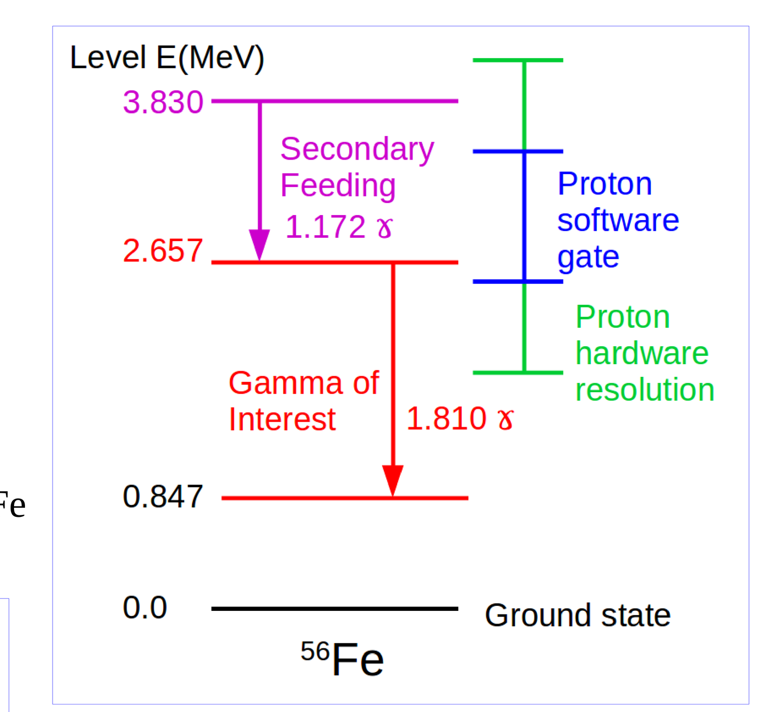
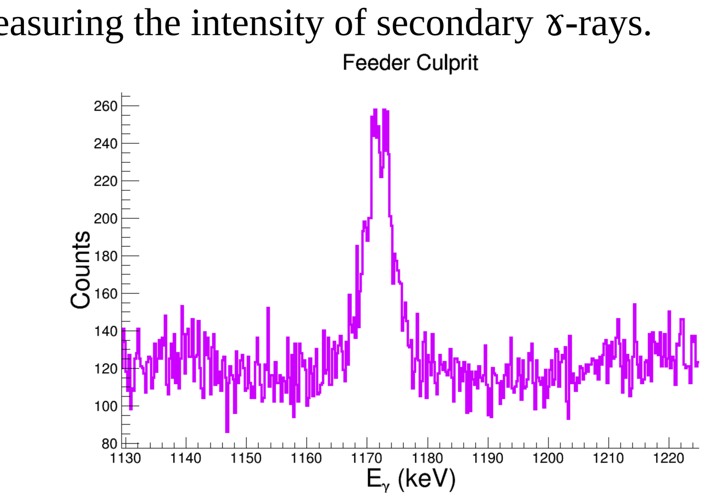


Fig. 4: Left: Level scheme of ^{56}Fe with proton resolution. The 1810 keV ɤ-ray will not have as much doppler shift if the proton populates the 3830 keV state which slows before decaying and emitting the primary ɤ-ray. Below: Quantifying indirect feeding requires measuring the intensity of secondary ɤ-rays.



Radiative Strength

Sliding the proton gate up in energy grants access to the average halflife of the quasicontinuum states in ^{56}Fe. A second exponential decay law accounts for the feeding halflife in the simulation. The radiative strength function $f(E_\gamma)$ relates to halflives as follows:

$$f(E_\gamma) = \frac{\hbar \ln(2)\,\rho(E_i)}{\bar{t}_{1/2}(E_i, E_\gamma)\,E_\gamma^{2L+1}}$$

with excitation energy E_i, level density $\rho(E_i)$ and transition multipolarity L assumed dipole

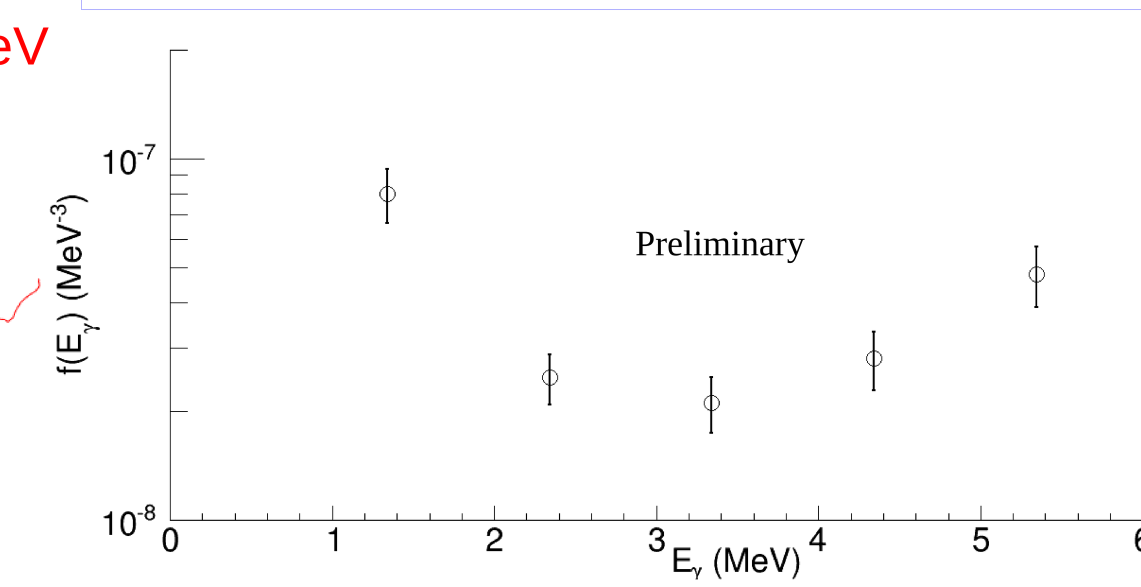


Fig. 5: Radiative Strength Function measured with the 1810 keV ɤ-ray. Indirect feeding from states 4 to 9 MeV modify the doppler shift of this primary ɤ-ray.