Constraining the $^{57}Ni(p,\gamma)^{58}Cu$ Reaction Rate with the Enge Split-pole Spectrograph

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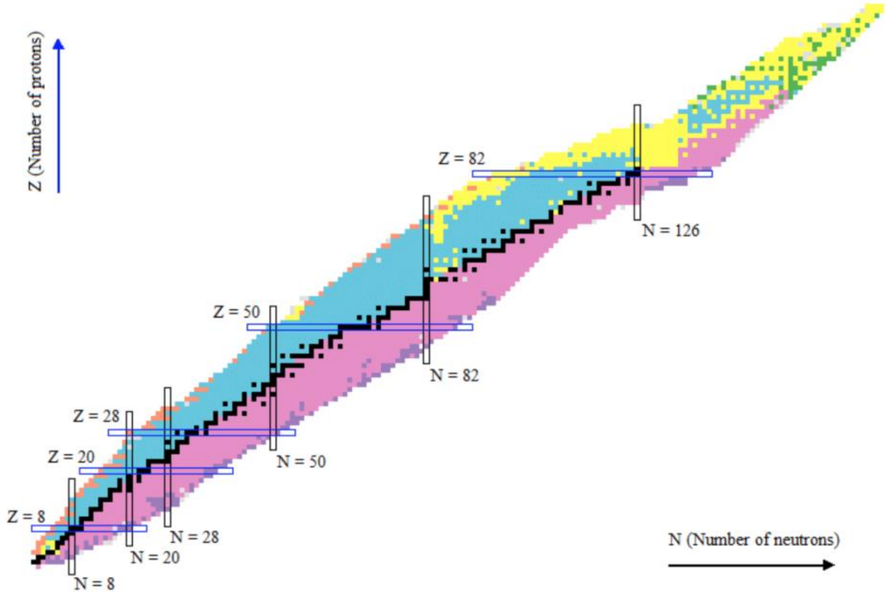
Motivation

- The goal of nuclear astrophysics is to understand the origin of the elements
- One important site for element formation, or nucleosynthesis, is core-collapse supernovae



https://chartde.blogspot.com/2017/06/chart-of-nuclides.html

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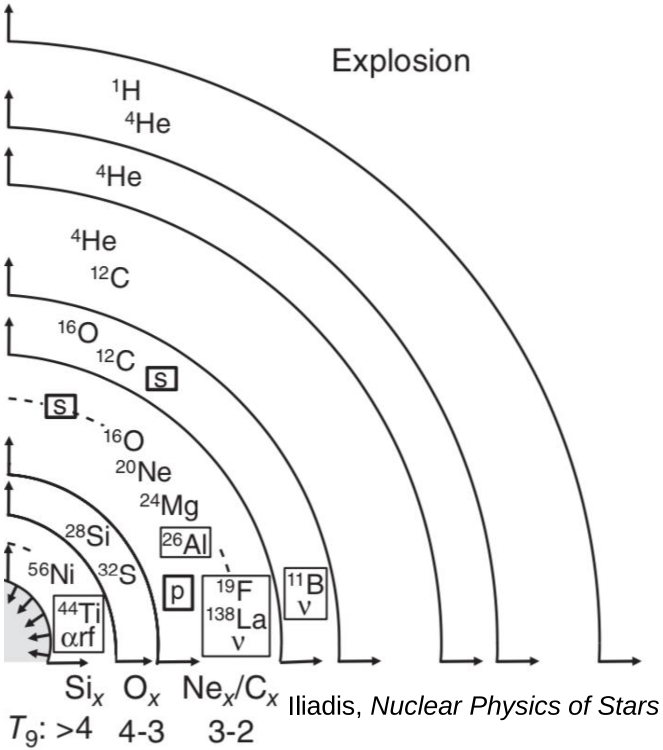
Core-collapse Supernovae

- Core reaches a point where it can no longer support itself against gravity
- At this point, the core collapse, leaving outer layers suspended
- When collapsing core reaches nuclear densities, it rebounds and creates a shock that propagates outward
- Rebounding shock initially compresses and heats material before it is ejected



Iliadis, *Nuclear Physics of Stars*

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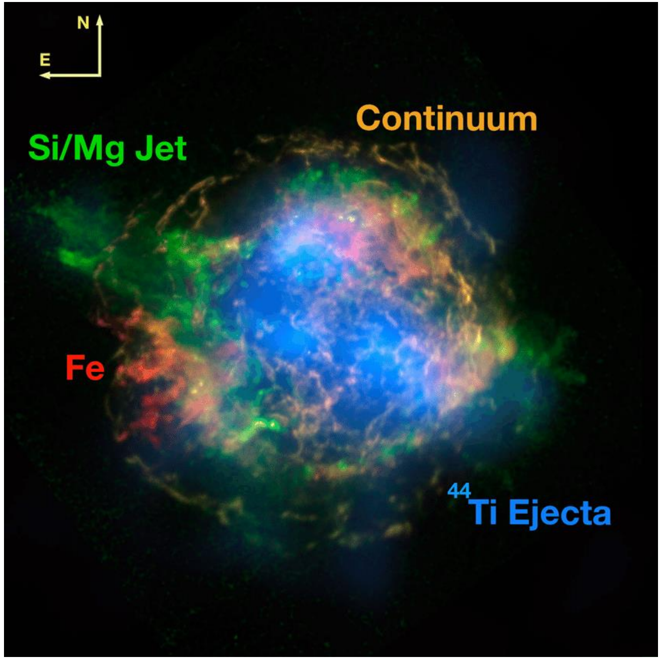
Core-collapse Supernovae

- During ejection, nucleosynthesis processes take place
- Certain nuclei emit characteristic gamma rays that can be detected on Earth and used to validate nucleosynthesis models; notably ^{44}Ti
- To better understand CCSN, necessary to understand the reactions that produce ^{44}Ti



Grefenstette ApJ **834**, 19 (2016)

^{57}Ni(p,γ)^{58}Cu Reaction Rate

- Magkotsios *et al.* demonstrated that ^{57}Ni(p,γ)^{58}Cu has a “significant” effect on ^{44}Ti production
- Hermansen *et al.* also observed this rate to affect ^{44}Ti production, as well as ^{59}Ni production, which has a characteristic gamma ray that will be detected by the coming generation of telescopes
- Currently, no experimental rates exist for this reaction

- Magkotsios *et. al,* ApJ Supp. Series **191**, 66-95 (2010)
- K. Hermansen, S. M. Couch, L. F. Roberts, H. Schatz and M. L. Warren ApJ **901**, 77 (2020)

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^{57}Ni(p,γ)^{58}Cu Reaction Rate

- In these high temperature environments, rate will be dominated by compound resonances through excited states in ^{58}Cu in the ~3-6 MeV excitation region
- Theoretical rates are based on the Hauser-Feshbach formalism, which approximates levels as a continuum
- This approximation may not be valid for reaction rate in this environment

E (keV)	J^π	E (keV)	J^π	E (keV)	J^π
3230 *10*		3717 *10*	(1)+	5065 *20*	(1)+
3280.2 *8*	(0+:4+)	3820 *20*		5160 *20*	
3310 *20*		3890 *20*		5451 *20*	(1)+
3421.0 *5*	(7+)	4010		5190.6 *23*	(7+)
3460.1 *1*	(1)+	4065.6 *6*	(7+)	5348.0 *8*	(9+)
3512.6 *7*		4210 *20*		5574.9 *8*	(9+)
3677.9 *8*	(1)+	4441.4 *6*	(8+)	5645 *20*	(1)+

Current known states in 3-6 MeV excitation range. From Caroline D. Nesaraja, Scott D. Geraedts and Balraj Singh, Nuclear Data Sheets **111**, 897 (2010)

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^{57}Ni(p,γ)^{58}Cu Reaction Rate

- Assuming level density falls short of 10 levels/MeV, rate can be constrained with nuclear structure information via narrow resonance formalism

$$N_A\langle\sigma\nu\rangle = 1.54 \times 10^{11}(\mu T_9)^{3/2}\sum_i(\omega\gamma)_i e^{-11.605E_i/T_9}$$

$$\omega\gamma = \frac{2J_r + 1}{(2J_1+1)(2J_2+1)}\frac{\Gamma_a\Gamma_b}{\Gamma_r}$$

- Requires precise determination of ^{58}Cu level energies, as well as proton/gamma branching ratios and spin
- Further, structure information of ^{58}Cu should be better known before proceeding with a RIB experiment

Review

To better understand the nucleosynthesis taking place in CCSN, we need to better understand how ^{44}Ti is produced

↓

To better understand how ^{44}Ti is produced, we need to constrain the ^{57}Ni(p,γ)^{58}Cu reaction rate

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To constrain the ^{57}Ni(p,γ)^{58}Cu reaction rate, we need to better understand the structure of ^{58}Cu, especially the level energies in the 3-6 MeV excitation range

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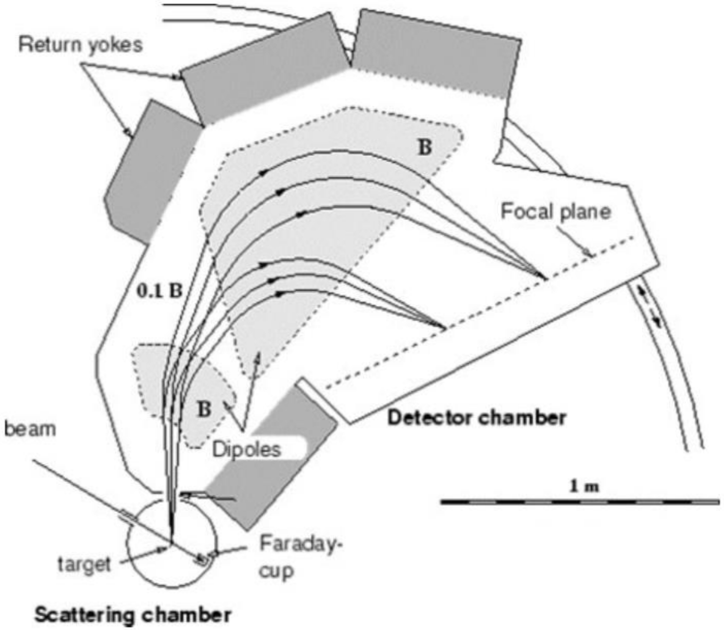
Enge Split-pole Spectrograph: Operation

- Creates a magnetic field that focuses particles with the same rigidity, ρ = p/Bq, at the same position on the focal plane
- Split-pole design provides second-order focusing and vertical focusing, which increases angular acceptance
- Can be rotated between 0° and 60° to measure angular distributions



Spencer and Enge, NIM 49, 181 (1967)

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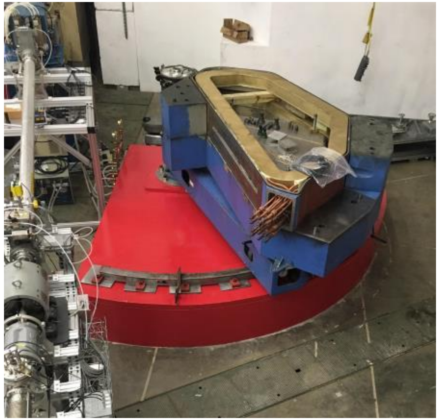
Enge Split-pole Spectrograph: Transfer

- Transferred from Oak Ridge National Laboratory in 2015, and installation began in early 2020
- As of the beginning of this year, spectrograph is fully operational



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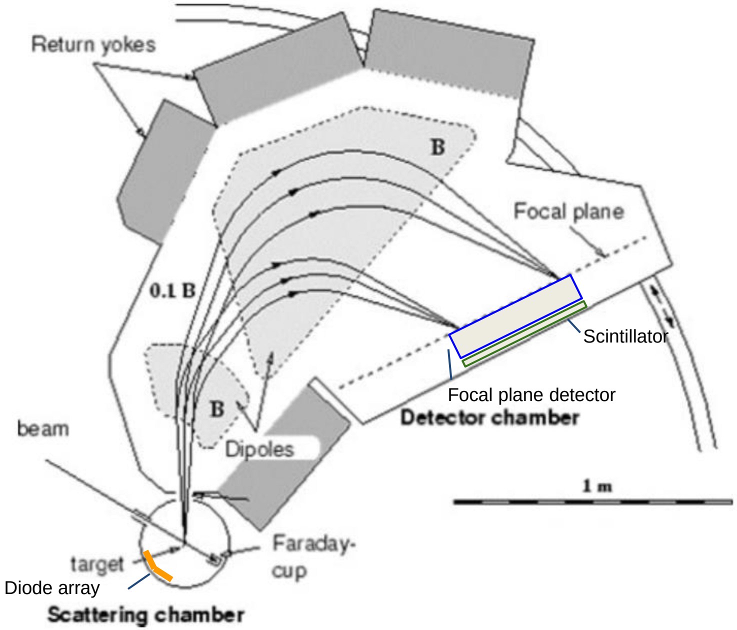
Enge Split-pole Spectrograph: Current Set-Up

- Position sensitive ionization chamber placed at the focal plane
- Scintillator placed behind the focal plane detector
- Silicon diode detectors placed in the target chamber to detect particle decays from residual nucleus



Spencer and Enge, NIM 49, 181 (1967)

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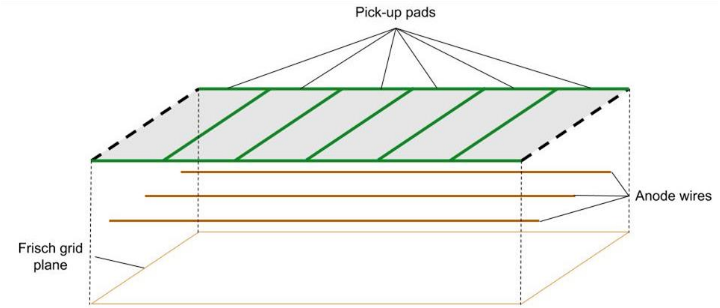
Focal Plane Detector

- Based on Yale design; comprised of a cathode and two anode sections. Charge collected at anode wires is induced on pick-up pads, connected to a delay line
- Signal is sent to both ends of the delay line; timing difference between signals can be converted to a position measurement
- Offers a position resolution of ~2.5 mm



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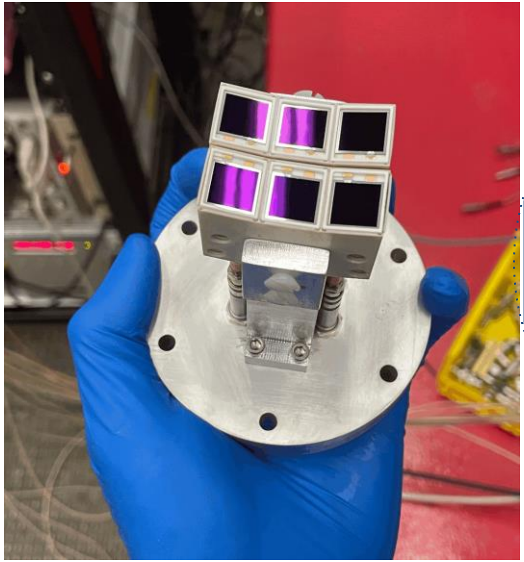
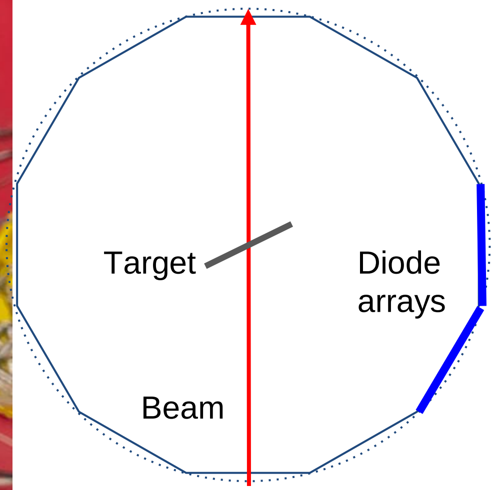
Diode Detectors

- Arrays of 6 detectors have been designed to connect to flanges on the target chamber
- This allows us to potentially cover angles from 20° to 160°
- For our purposes, will allow us to measure proton branching ratios





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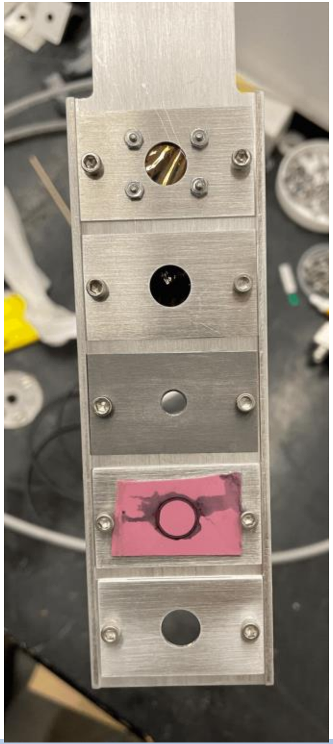
First Experiment (2/27-3/7)

- Measured $^{58}Ni(^{3}He,t)^{58}Cu$
- 21 MeV ^{3}He beam of ~40 nA
- ^{58}Ni target of 220 μg/cm^2 thickness
- Goal was to probe the structure of ^{58}Cu in the 3-6 MeV excitation range



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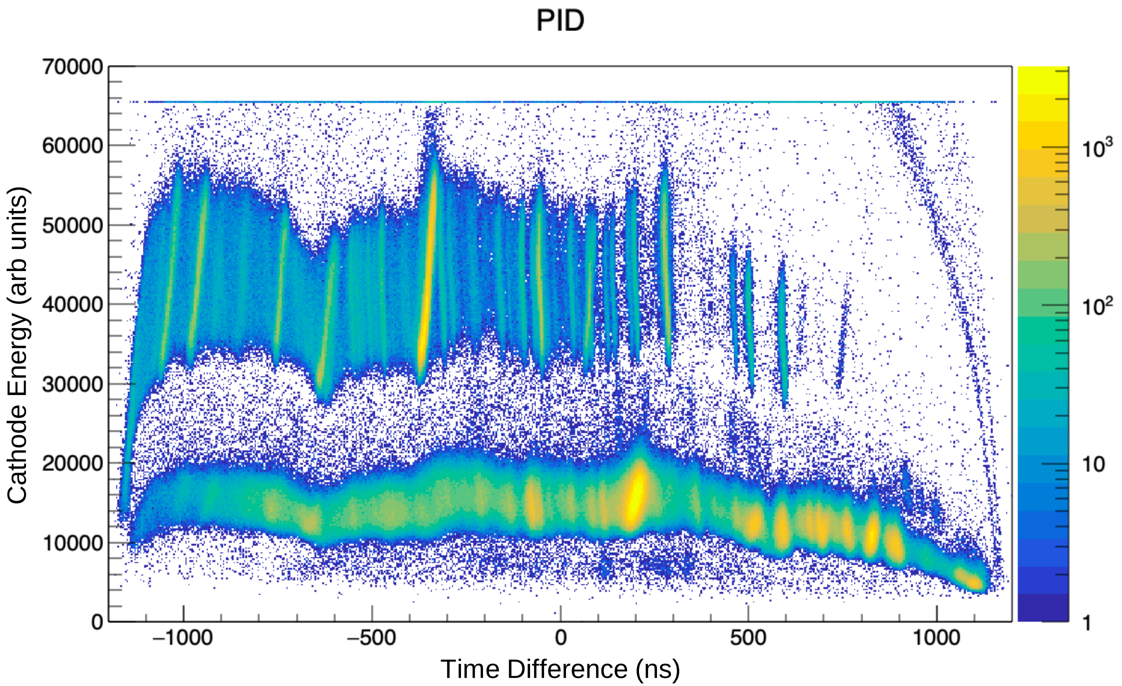
Particle Identification

- Due to low cross sections, PID is necessary to isolate triton peaks
- Can plot the energy deposited in the cathode vs. the position of the particles on the focal plane



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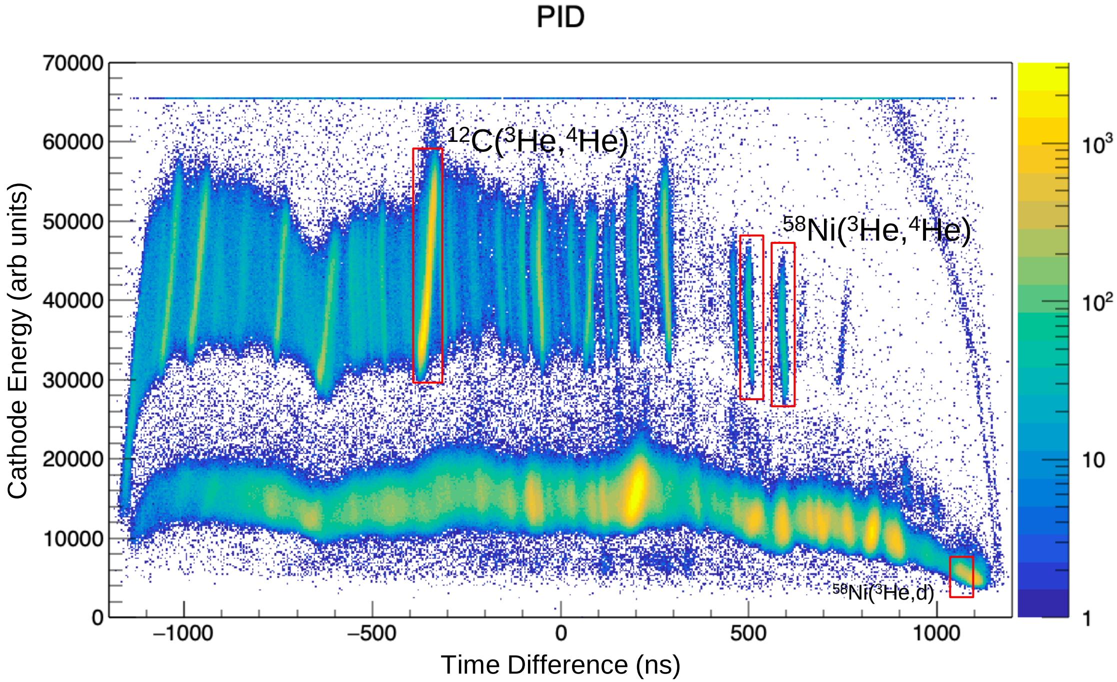
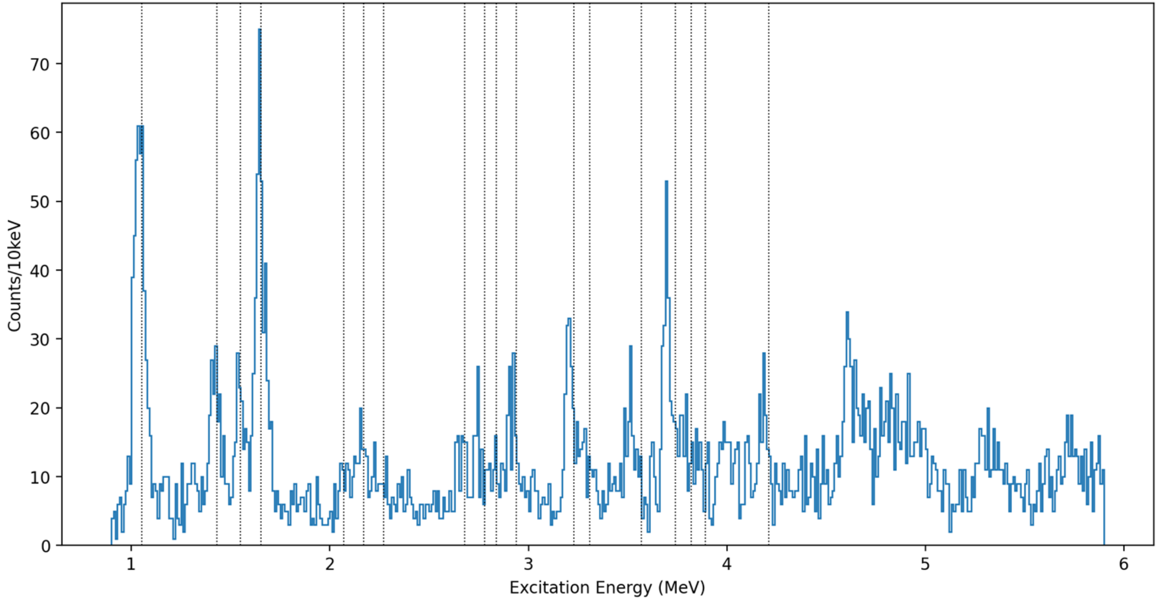
Calibration

- Used known peaks to convert focal plane position to energy



Excitation Spectrum

- Excitation energy of ^{58}Cu from detected triton energy
- Dashed lines show states identified in a previous ^{58}Ni(^{3}He,t)^{58}Cu measurement
- Measured at several angles



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MEANWHILE….because one thesis project isn’t enough for Scott…

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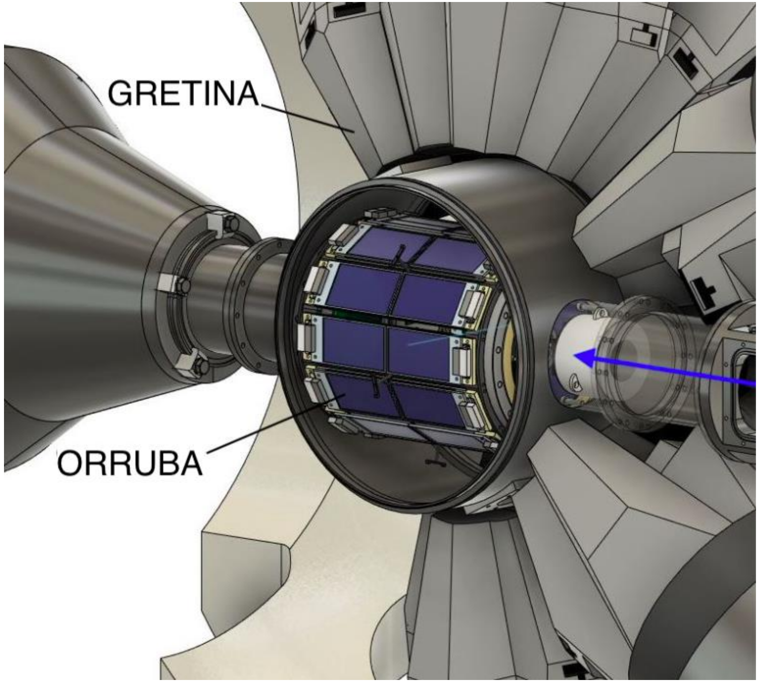
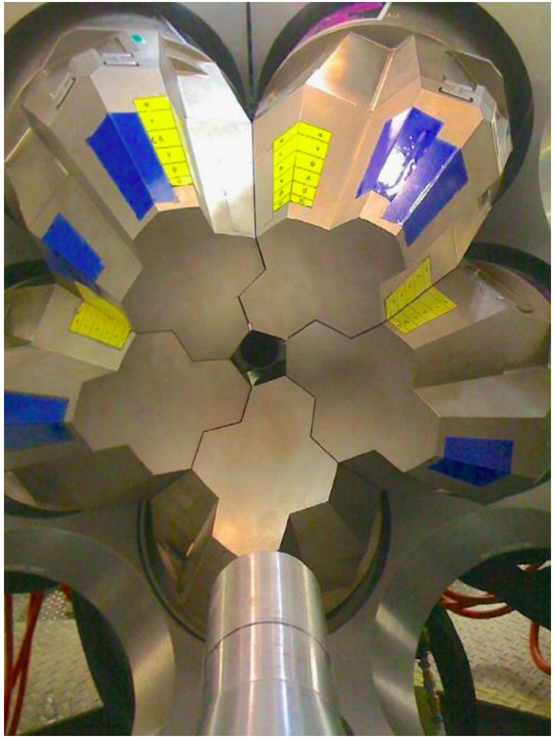
GODDESS

- Measured $^{58}Ni(^{3}He,t)^{58}Cu$ at ANL's ATLAS facility with GODDESS
- GRETINA– Germanium array for gamma ray detection
- ORRUBA– Silicon array for charged particle detection



GRETINA

- HPGe array with energy resolution of ~5 keV for a 1 MeV gamma
- Crystal are segmented which allows for position measurement with a resolution of ~2 mm
- This allows for gamma tracking and Doppler correction



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

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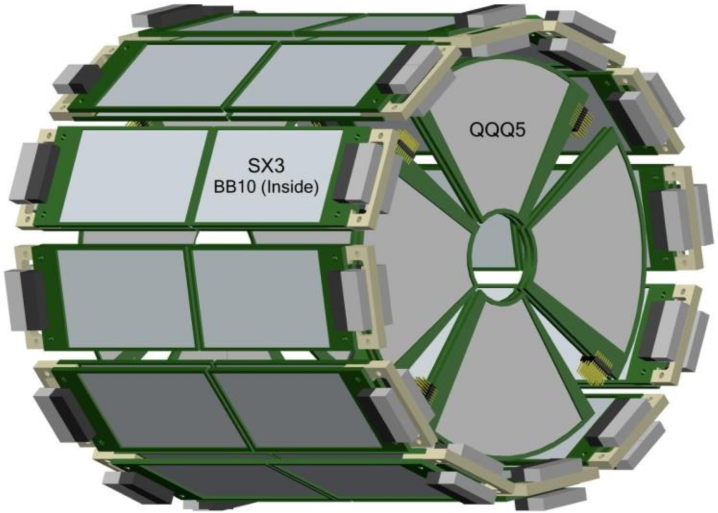
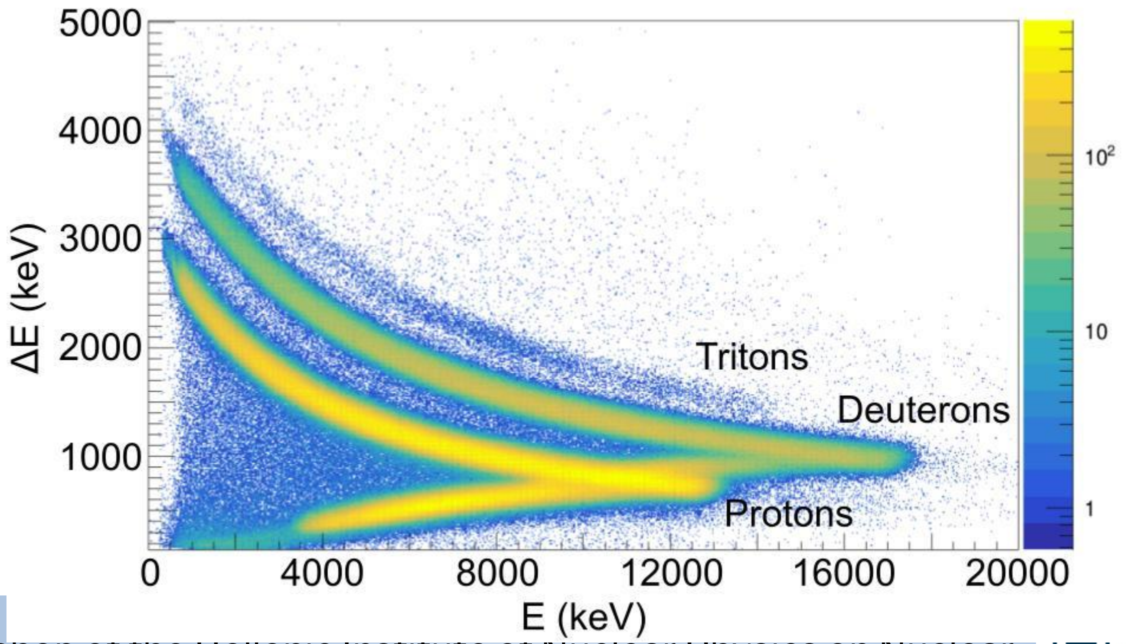
ORRUBA

- Nominally 4π silicon array
- Position resolution of ~2 mm
- Partially augmented with ΔE layer for particle identification



Preliminary Analysis

- Tritons clearly separated in PID plot



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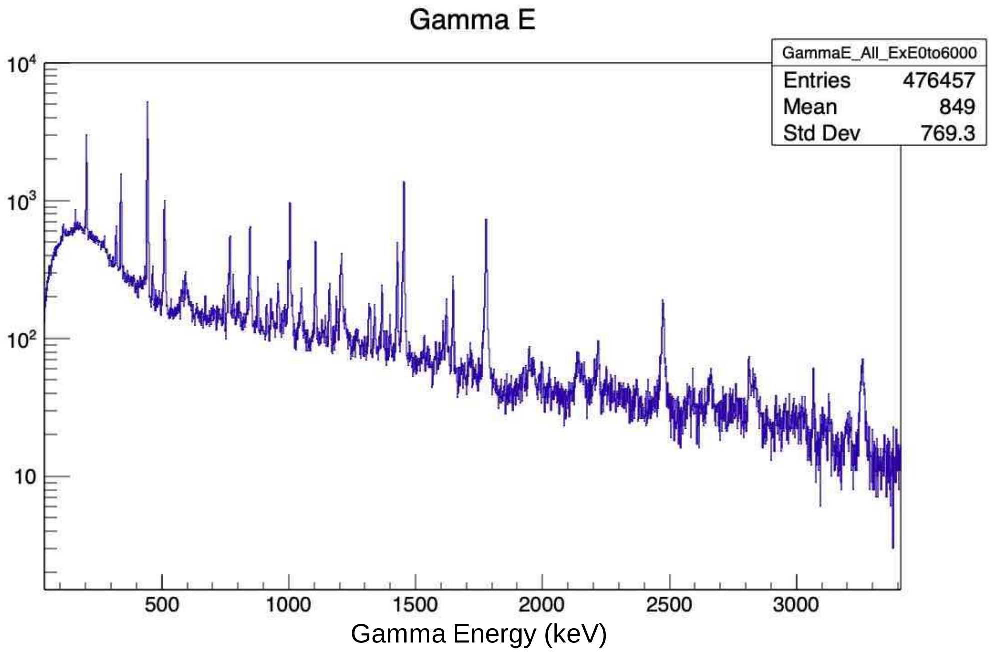
Preliminary Analysis

- Gammas in coincidence with tritons



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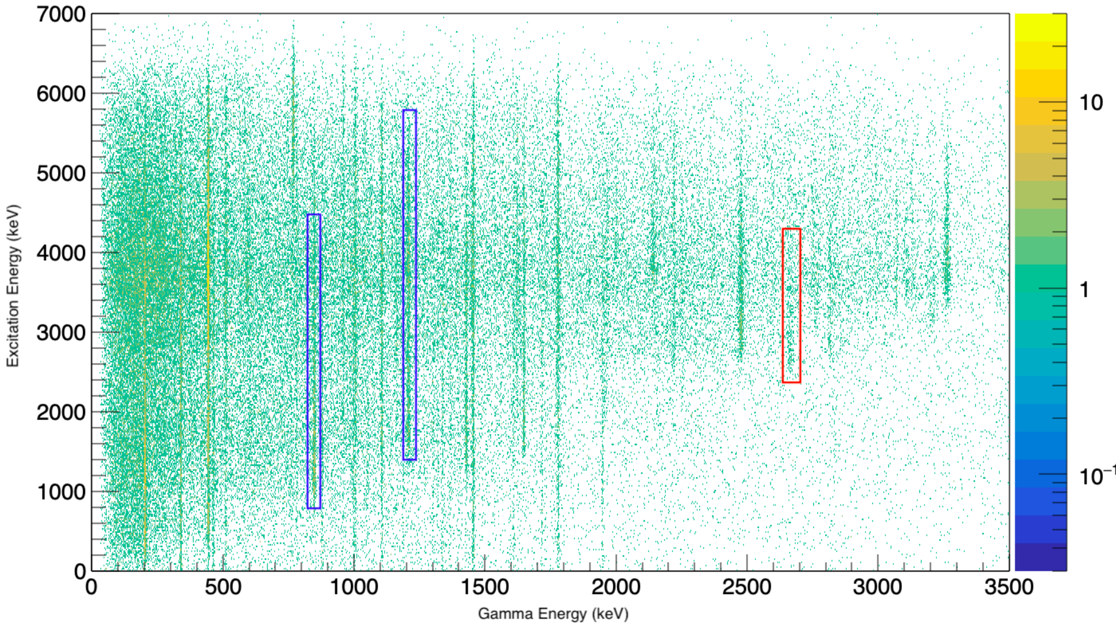
Preliminary Analysis

- γ ray energy correlated with excitation energy
- Previously identified γ rays, for example at 848 and 1208 keV
- Previously unidentified γ rays, for example at ~2665 keV



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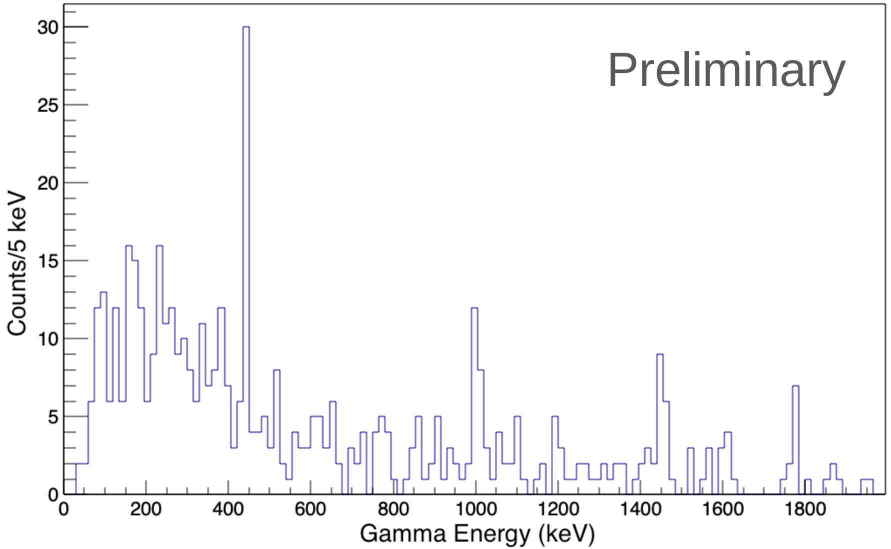
Preliminary Analysis

- Spectrum of γ ray energy in coincidence w/ 2665 keV γ ray, shows possible evidence of level at ~3109 keV, which has not been previously identified



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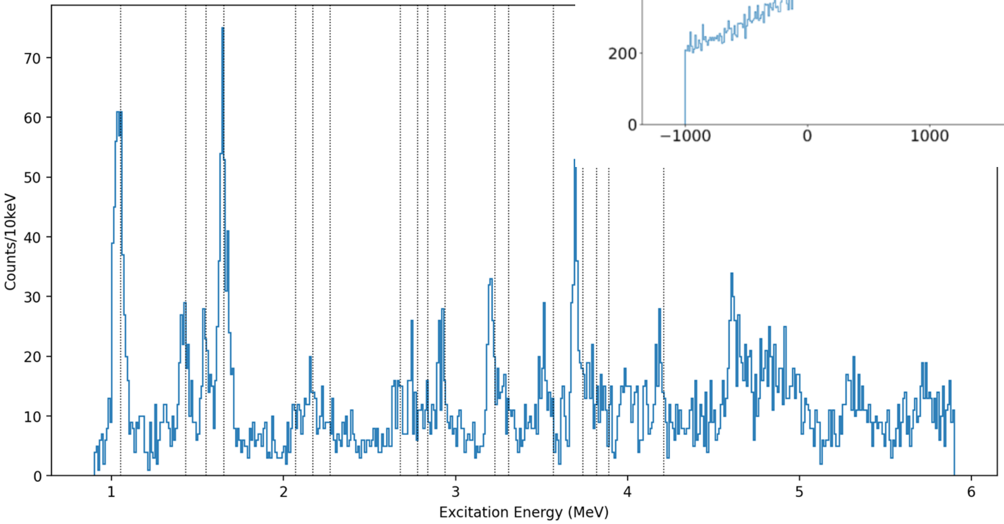
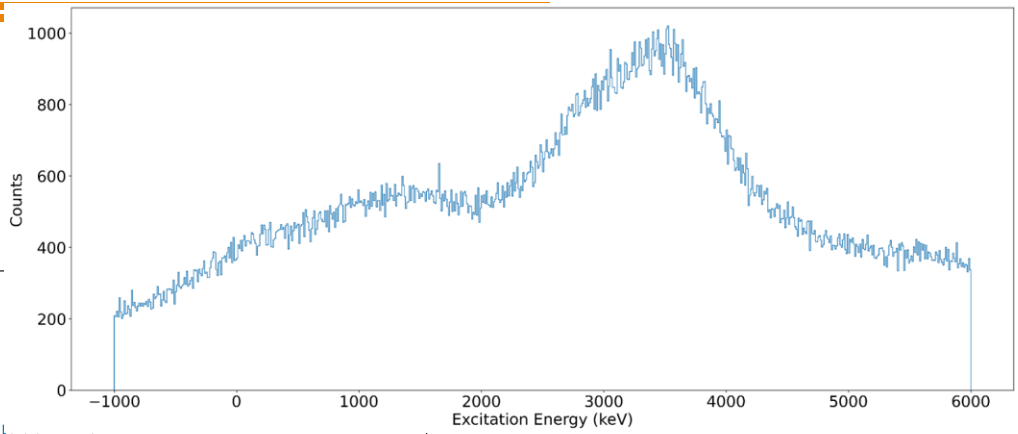
Excitation Spectrum





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Summary and Conclusion

- ^{57}Ni(p,γ)^{58}Cu affects the final production of ^{44}Ti and ^{59}Ni in CCSNe
- The reaction rate is uncertain, experimental constraint is needed, which requires precise determination of ^{58}Cu level energies
- ^{58}Ni(^{3}He,t)^{58}Cu has been measured with the ND Enge and GODDESS to determine level energies, proton branching ratios, gamma branching ratios, and constrain spin states
- PRISM nucleosynthesis calculations are also being performed to investigate the impact of the experiment rate on the production of ^{44}Ti and ^{59}Ni in CCSN

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- Scott Carmichael - graduate student extraordinaire
- GODDESS Team: S.D. Pain, M. Siciliano, J. Allen, D.W. Bardayan, C. Boomershine, C.M. Campbell, M.P. Carpenter, K.A. Chipps, J.A. Cizewski, P.A. Copp, H. Garland, R. Ghimire, J. Kovoor, T. Lauritsen, C. Müller-Gatermann, A. Ratkiewicz, W. Reviol, D. Seweryniak, H. Sims, C. Ummel, G. Wilson
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Back-up Slides

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Enge Angular Acceptance

- The opening of the Enge has a number of apertures that allows one to change the angular acceptance of the Enge
- The typical angular acceptance is ~ 10 msr

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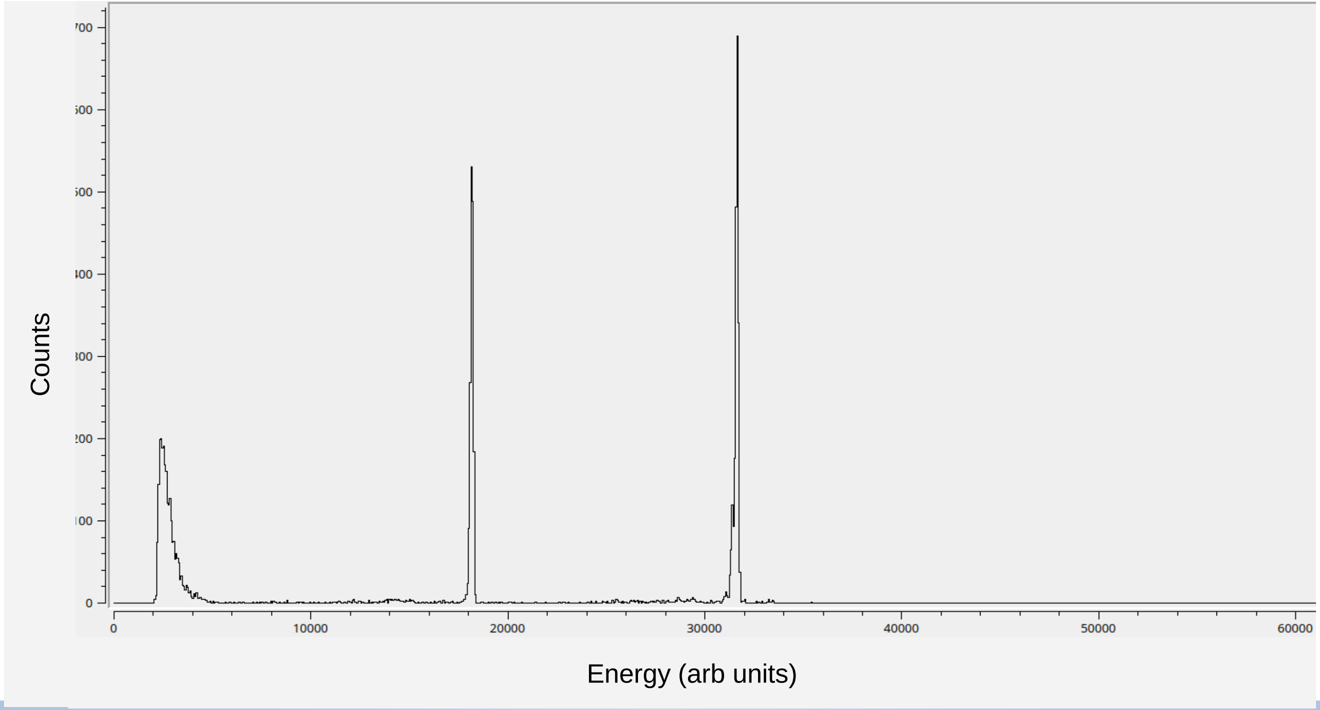
Diode Detector Spectrum



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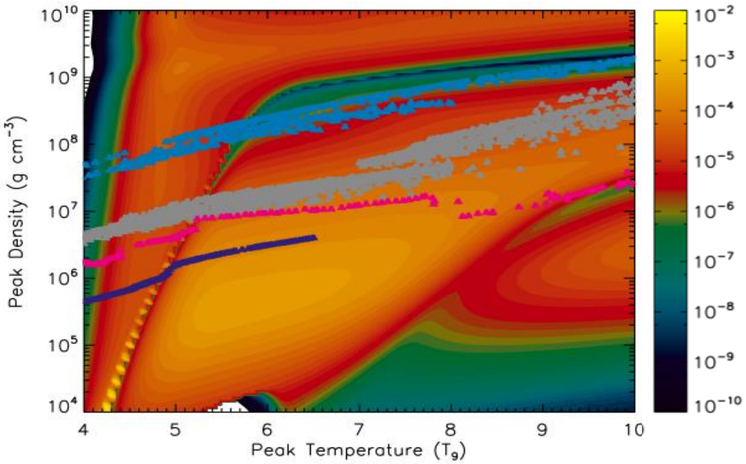
Core-Collapse Supernovae: Observation

- ^{44}Ti emits characteristic gamma ray, can be used to validate models



Magkotsios *et. al,* The Astrophysical Journal Supplement Series, 191, 66-95 (2010)

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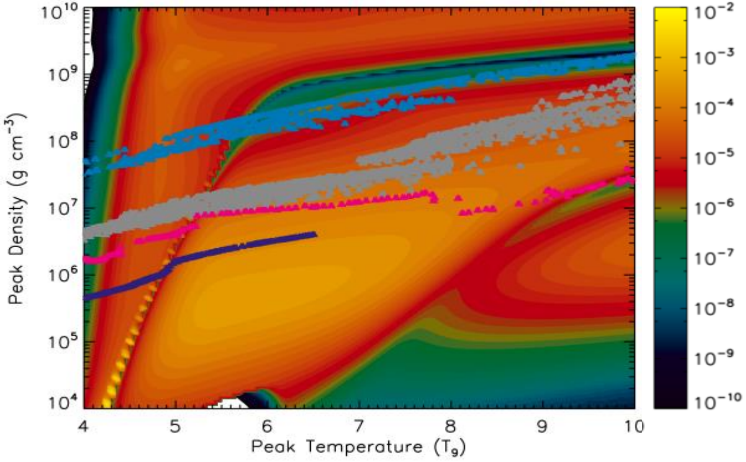

Magkotsios *et. al,* The Astrophysical Journal Supplement Series, 191, 66-95 (2010)

- Magkotsios *et. al.* determined the ^{57}Ni(p,γ)^{58}Cu reaction rate has a "primary" effect on the production of ^{44}Ti in core-collapse supernovae

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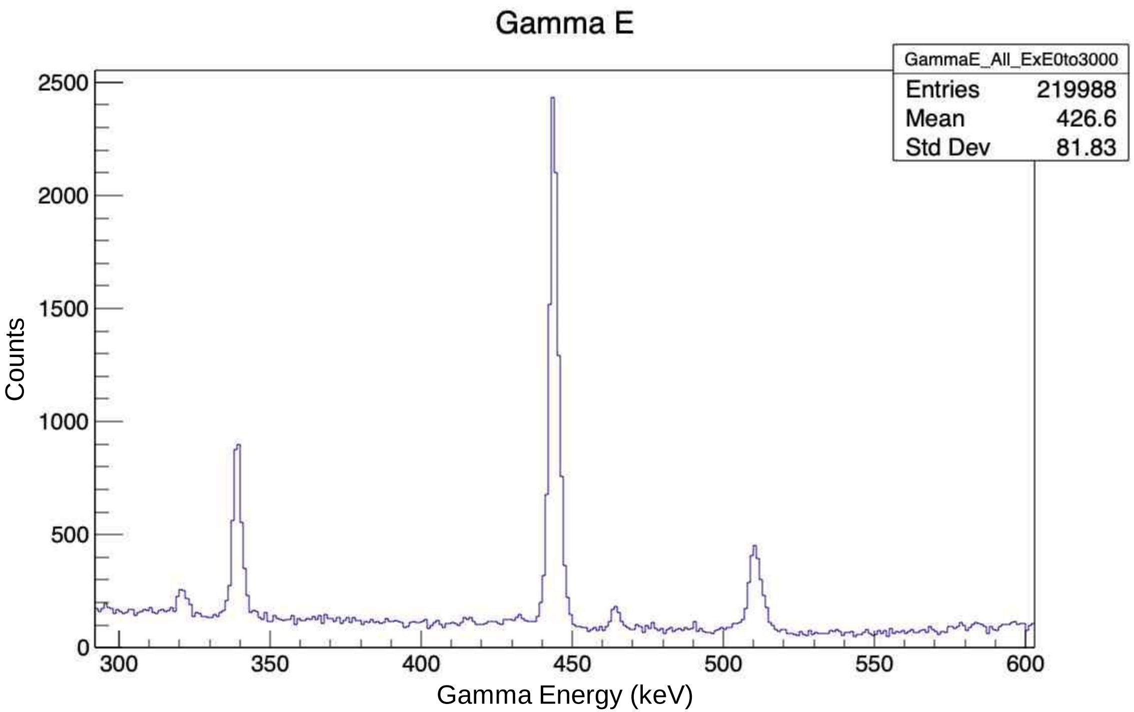
Preliminary Analysis



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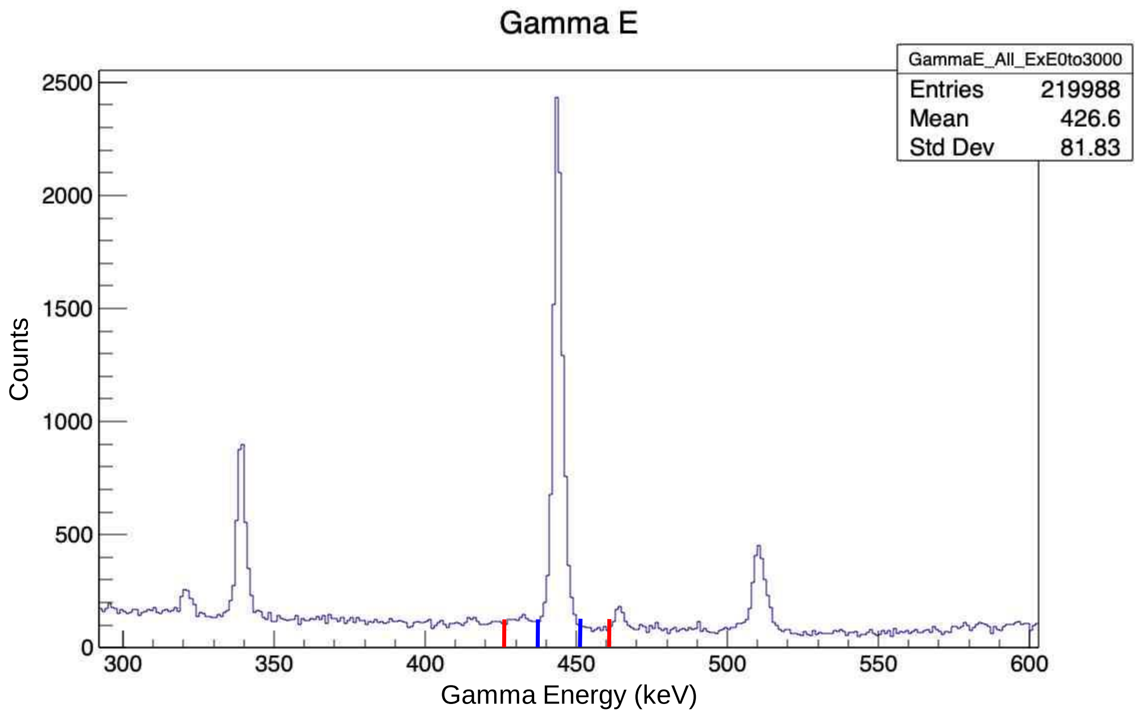

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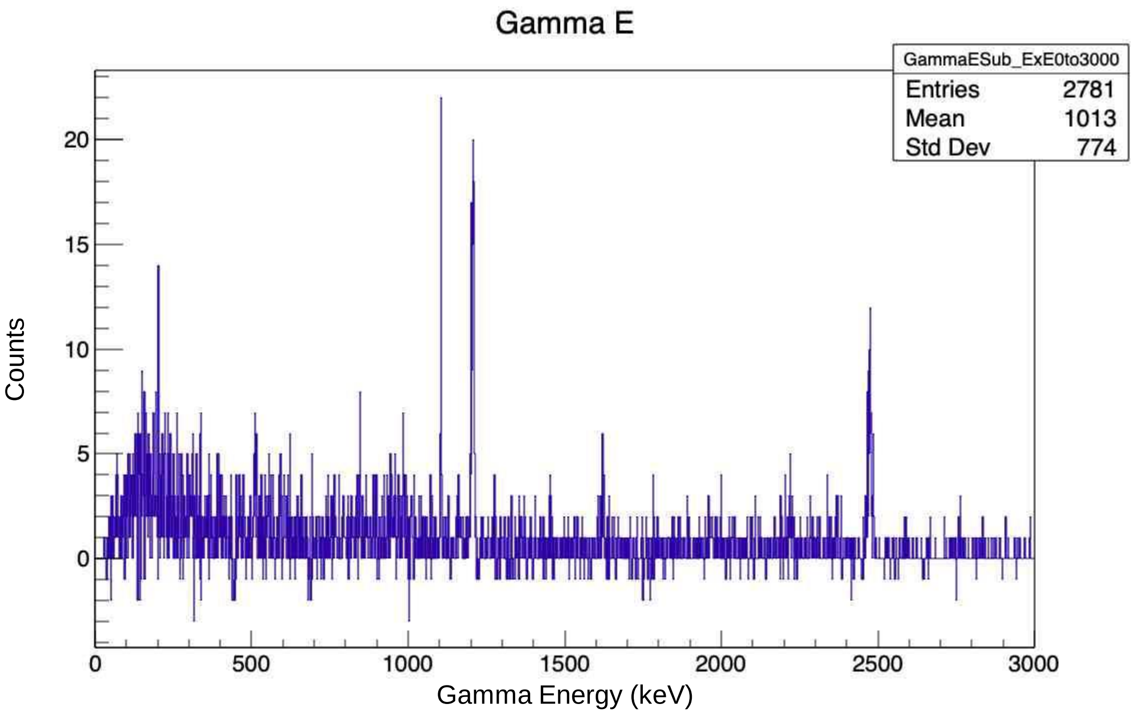

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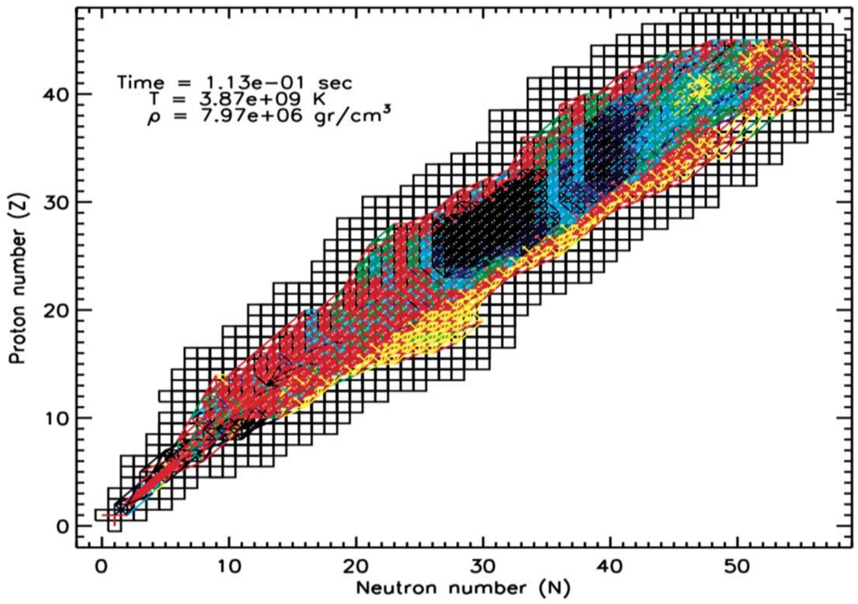
Alpha-rich Freeze-out

- Inner layers are initially in nuclear statistical equilibrium
- Material expands and quasi-static equilibrium (QSE) is established
- As expansion continues, nuclei fall out of equilibrium
- When ^{44}Ti falls out of equilibrium, ^{57}Ni(p,γ)^{58}Cu controls the relative abundances within the cluster



Georgios Magkotsios, *Nucleosynthesis During Freeze-out Expansions in Core-Collapse Supernovae*, Dissertation, University of Notre Dame (2011)

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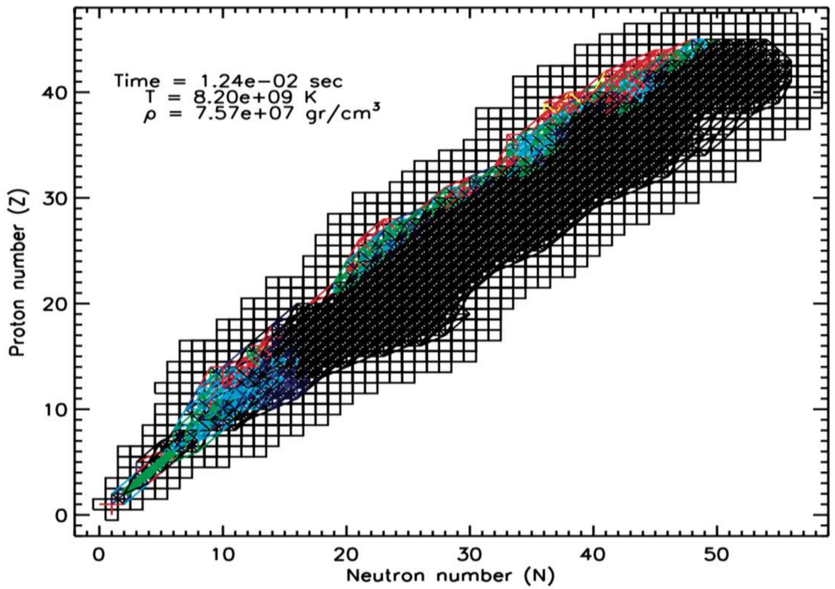

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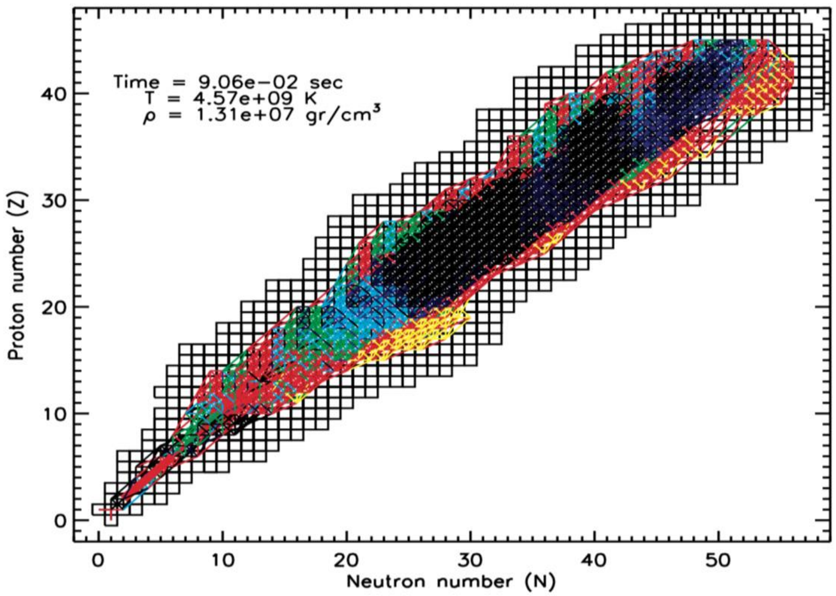

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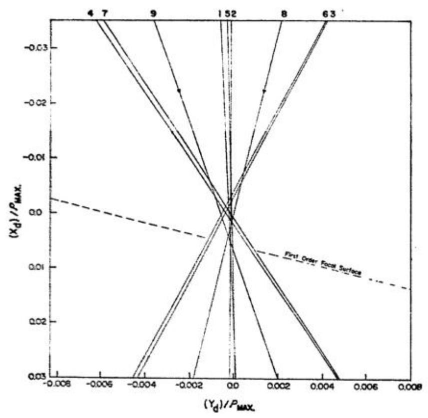
Commissioning Experiment

- Measured $^{12}C(p,p')^{12}C$
- 14 MeV proton beam
- ^{12}C target of 75 μg/cm^2 thickness
- Goal was to ensure we're on the focal plane, and to characterize the focal plane detector



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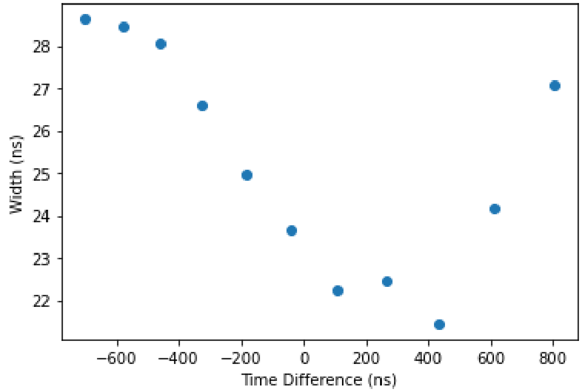
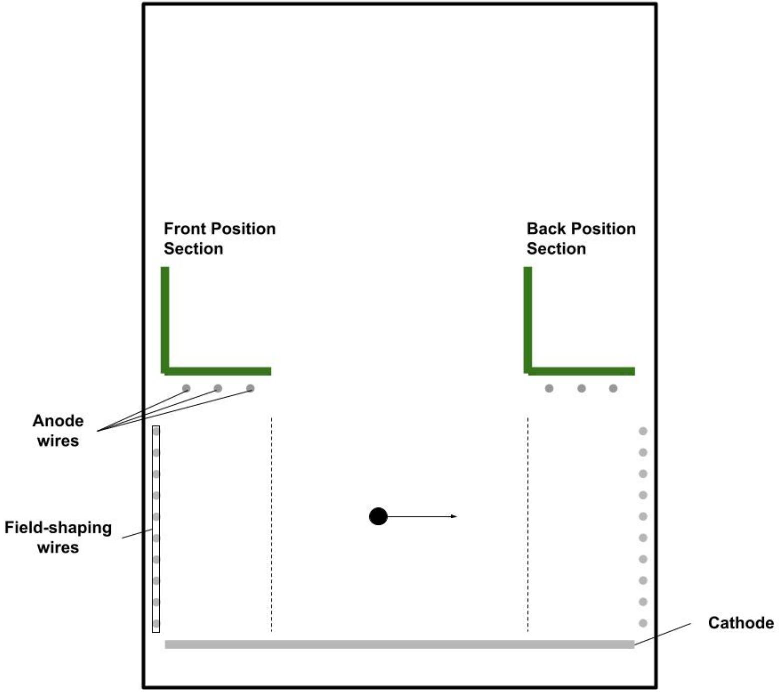


Peak width of elastic scattering peak, as function as position on delay line

Focal Plane Detector

- Based on Yale design; comprised of a cathode and two anode sections
- Anode wires are typically biased to ~1700 V to create an electron avalanche
- Electrons collected at the anodes induce a charge on pads that are connected to a delay line



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