^{58}Ni(^{3}He,t)^{58}Cu*(γ) measurements with GODDESS to constrain the astrophysical rate of ^{57}Ni(p,γ)^{58}Cu

S R Carmichael[1], S D Pain[2], M Siciliano[3], J Allen[1], D W Bardayan[1], C Boomershine[1], C M Campbell[4], M P Carpenter[3] K A Chipps[2], J A Cizewski[5], P A Copp[3], J Forson[2], H Garland[5], R Ghirmire[6], J Kovoor[6], T Lauritsen[3], C Müller-Gatermann[3], P D O'Malley[1], A Ratkiewicz[7], W Reviol[3], D Seweryniak[3], H Sims[5], C C Ummel[5], G Wilson[3]

[1] Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA
[2] Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[3] Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
[4] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[5] Department of Physics and Astronomy, Rutgers University, New Brunswick, New Jersey 08903, USA
[6] Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA
[7] Physics Division, Lawrence Livermore National Laboratory, Livermore, California 94551, USA

E-mail: scarmic1@nd.edu

Abstract.
The observation of γ rays from the decay of ^{44}Ti in the remnants of core-collapse supernovae (CCSNe) provides crucial information regarding the nucleosynthesis occurring in these events, as ^{44}Ti production is sensitive to CCSNe conditions. The final abundance of ^{44}Ti is also sensitive to specific nuclear input parameters, one of which is the ^{57}Ni(p,γ)^{58}Cu reaction rate. A precise rate for ^{57}Ni(p,γ)^{58}Cu is thus critical if ^{44}Ti production is to be an effective probe into CCSNe. To experimentally constrain the ^{57}Ni(p,γ)^{58}Cu rate, the structure properties of ^{58}Cu were measured via the ^{58}Ni(^{3}He,t)^{58}Cu*(γ) reaction using GODDESS (GRETINA ORRUBA Dual Detectors for Experimental Structure Studies) at Argonne National Laboratory's ATLAS facility. Details of the experiment, ongoing analysis, and plans are presented.

1. Introduction

Validating models of core-collapse supernovae (CCSNe), and the nucleosynthesis that takes place within their explosive environments, is necessary to further understand the origin of the elements. Through the observation of characteristic γ rays emitted in CCSNe remnants, the abundance of specific radioisotopes can be inferred. These inferred abundances can then be compared to model predictions as a method of validation.

One such radioisotope, ^{44}Ti, is produced during explosive silicon burning in CCSNe. This burning phase is usually governed by α-rich freeze-out from quasi-static equilibrium (QSE) [1], where equilibrium clusters form amongst nuclei with similar masses due to the fast reactions occurring among them. During α-rich freeze-out, one main cluster is initially present, but as the temperature decreases, lower mass nuclei subsequently drop out of equilibrium with the main cluster, and smaller clusters form among these lower mass nuclei. The predicted abundance of ^{44}Ti is sensitive to hydrodynamic conditions of the CCSN, as well as nuclear reaction rates. This makes it an ideal probe for CCSNe models. However, for this probe to be meaningful, it is crucial to precisely determine the reaction rates that significantly impact ^{44}Ti production.

2. The ^{57}Ni(p,γ)^{58}Cu Reaction Rate

According to Magkotsios *et al.* [2], the reaction rate of ^{57}Ni(p,γ)^{58}Cu strongly influences the yield of ^{44}Ti in CCSNe. Magkotsios *et al.* suggest this influence is due to the reaction determining the relative abundances of ^{44}Ti and neighboring nuclei when they drop out of the main equilibrium cluster during α-rich freeze-out.

More recent ^{44}Ti sensitivity studies were performed by Hermansen *et al.* [1] and Subedi *et al.* [3]. In Hermansen *et al.*, ^{57}Ni(p,γ)^{58}Cu was verified to affect the abundance of ^{44}Ti, but to a lesser extent than Magkotsios *et al.* In Subedi *et al.* the rate was not identified as having an influence on ^{44}Ti production. This was likely because the authors assumed the theoretical rate was well constrained by the Hauser-Feshbach model upon which it was based. However, this assumption is questionable since there are fewer states known than are usually assumed to ensure the validity of the model, specifically 10 levels/MeV (see Table 1).

At the high temperatures present in CCSNe, the rate of ^{57}Ni(p,γ)^{58}Cu will be dominated by resonances through excited states in ^{58}Cu. The relevant excited states will be determined by the temperatures at which ^{44}Ti is sensitive to this rate. Magkotsios *et al.* notes this temperatures range to be ~2-5 GK [2]. This implies the level energies of relevant states are expected to be in the 3-6 MeV range. Table 1 lists the current known levels in ^{58}Cu between 3 and 6 MeV [4].

Table 1: Energy and spin-parity of known states in ^{58}Cu between 3 and 6 MeV [4].

E (keV)	J$^\pi$	E (keV)	J$^\pi$	E (keV)	J$^\pi$
3230 *10*		3717 *10*	(1)+	5065 *20*	(1)+
3280.2 *8*	(0+:4+)	3820 *20*		5160 *20*	
3310 *20*		3890 *20*		5190.6 *23*	(7+)
3421.0 *5*	(7+)	4010		5348.0 *8*	(9+)
3460.1 *1*	(1)+	4065.6 *6*	(7+)	5451 *20*	(1)+
3512.6 *7*		4210 *20*		5574.9 *8*	(9+)
3570 *20*		4441.4 *6*	(8+)	5645 *20*	(1)+
3677.9 *8*	(1)+	4720 *10*	(1)+		

The states with high spin (J> 6) are not expected to significantly contribute to the reaction rate due to the high angular momentum transfer required for the reaction. Without these states, the level density falls short of 10 levels/MeV. With the current knowledge of the level structure of ^{58}Cu, it may be more appropriate to constrain the rate through the narrow resonance formalism. In this formalism, the reaction rate per particle pair (in cm^3 mole^{-1} s^{-1}) simplifies to [5]:

$$N_A\langle\sigma\nu\rangle = 1.54\times10^{11}(\mu T_9)^{3/2}\sum_i(\omega\gamma)_i e^{-11.605E_i/T_9} \text{ where } \omega\gamma = \frac{2J_r+1}{(2J_1+1)(2J_2+1)}\frac{\Gamma_a\Gamma_b}{\Gamma_r}$$

The sum is over all significant resonances i, μ is the reduced mass in amu, and T_9 is the temperature in GK. E_i and $(\omega\gamma)_i$ are the energy and strength of the i-th resonance in MeV, respectively. J_r, J_1, J_2 are the spin of the compound nucleus and reaction products, respectively.

Γ_r, Γ_a, Γ_b are the resonance width, and the decay widths of the entrance and exit channel, respectively.

For this indirect determination to be effective, the precise determination of the structural properties of ^{58}Cu is needed. Referring back to table 1, it is clear that this structure information is lacking. Due to the exponential dependence between the reaction rate and resonance energy, this is especially important for level energies. Current uncertainties on many relevant level energies are ∼10-20 keV, which could significantly affect estimations of the reaction rate.

3. Experimental Details

To further elucidate the structure of ^{58}Cu and more precisely measure level energies, the ^{58}Ni(^{3}He,t)^{58}Cu*(γ) reaction was measured at the ATLAS facility at Argonne National Laboratory using GODDESS (GRETINA ORRUBA Dual Detectors for Experimental Structure Studies) [6]. A ~ 1 enA beam of ^{3}He at 31.5 MeV was incident upon a ~ 1 mg/cm^2 ^{58}Ni target. Emitted tritons were detected by the $\sim 4\pi$ silicon array, ORRUBA (Oak Ridge Rutgers Barrel Array) [7]. The coincident γ-rays emitted in the deexcitation of the residual ^{58}Cu nucleus were detected by the germanium array, GRETINA (Gamma-Ray Energy Tracking In-beam Nuclear Array) [8]. A drawing of ORRUBA inside the GRETINA target chamber is shown in figure 1. Coupling these two arrays enables level energies to be reconstructed through measurements of γ ray energy, providing the high resolution needed to constrain the reaction rate.

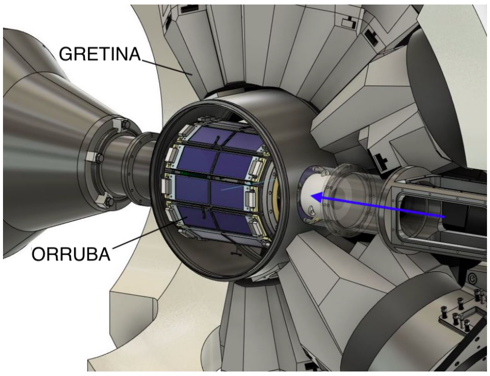

Figure 1: The ORRUBA array inside the GRETINA target chamber [9].

ORRUBA consists of silicon detectors in a barrel configuration with further silicon detectors on the ends, allowing for both energy and position measurements of charged particles. The array is partially comprised of ΔE-E telescopes for charged particle identification [7]. Particle identification is crucial to separate (^{3}He,t) events from other, more prominent, reaction channels.

GRETINA consists of 48 highly segmented coaxial germanium crystals. With this segmentation, the position of γ ray interactions is measured with ∼mm resolution. This allows for increased detection efficiency of high energy γ rays through tracking, and, when combined with the triton position measurements, provides precise Doppler corrections for γ rays [8].

4. Analysis

An example particle identification (PID) spectrum from the silicon telescopes is shown in figure 2. As can be seen, the particle species can be identified. By gating on the tritons, a spectrum of γ ray energy vs. ^{58}Cu excitation energy from triton-γ coincidences can be generated, as shown in figure 3. The excitation energy is determined from the triton energy and reaction kinematics. γ rays emitted in the deexcitation of ^{58}Cu will be correlated with excitation energy. γ rays due to random coincidences will instead result in a vertical line spanning the entire excitation range. In this spectrum, we do not only see known γ rays correlated with excitation energy (for example at 849 keV and 1208 keV) [4], but also γ rays not previously identified with decays in ^{58}Cu (for example at 2665 keV).

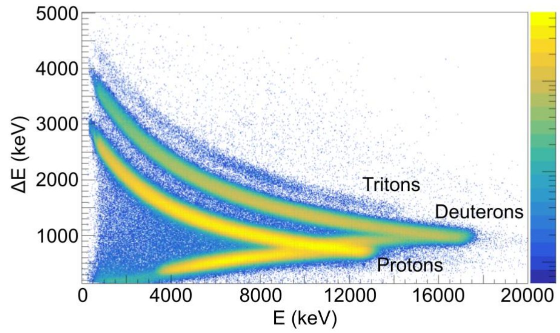

Figure 2: Example ORRUBA PID spectrum.

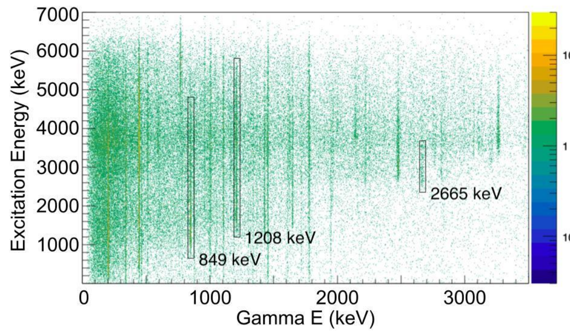

Figure 3: γ energy vs. ^{58}Cu excitation energy.

5. Conclusion and Future Plans

An experimental constraint on the ^{57}Ni(p,γ)^{58}Cu reaction rate would reduce the uncertainty in the final abundance of ^{44}Ti in CCSNe nucleosynthesis calculations. To this end, further studies of the structure of ^{58}Cu were performed. Preliminary analysis suggests previously unknown γ rays from ^{58}Cu decays have been identified. Analysis of triton-γ-γ coincidences is underway to reconstruct the level structure and decay scheme of ^{58}Cu. Once the structure properties of ^{58}Cu are more completely determined, they will be used to constrain the ^{57}Ni(p,γ)^{58}Cu reaction rate.

Acknowledgments

Research supported by the following institutions: University of Notre Dame (NSF grant no. PHY-2011890), Rutgers University (NSF grant number PHY-1812316 and DOE NNSA contract no. DE-NA0003897), Argonne National Laboratory (DOE Office of Science (NP) contract no. DE-AC02-06CH11357), Oak Ridge National Laboratory (DOE Office of Science (NP) contract no. DE-AC05-00OR22725), Lawrence Livermore National Laboratory (DOE Office of Science (NP) contract no. DE-AC52-07NA27344), University of Tennessee (DOE Office of Science (NP) contract no. DE-FG02-96ER40963).

This research used resources of Argonne National Laboratory's ATLAS facility, which is a Department of Energy Office of Science User Facility. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists, Office of Science Graduate Student Research (SCGSR) program. The SCGSR program is administered by the Oak Ridge Institute for Science and Education (ORISE) for the DOE. ORISE is managed by ORAU under contract number DE-SC0014664.

References

[1] Hermansen K, Couch S M, Roberts L F, Schatz H and Warren M L 2020 *The Astrophysical Journal* **901** 77
[2] Magkotsios G, Timmes F X, Hungerford A L, Fryer C L, Young P A and Wiescher M 2010 *The Astrophysical Journal Supplemental Series* **191** 66
[3] Subedi S K, Meisel Z and Merz G 2020 *The Astrophysical Journal* **898** 5
[4] Nesaraja C D, Geraedts S D and Singh B 2010 *Nuclear Data Sheets* **111** 897
[5] Rolfs C E and Rodney W S 1988 *Cauldrons in the Cosmos* (Chicago: University of Chicago Press)
[6] Pain S D *et al.* 2017 *Physics Procedia* **90** 455
[7] Pain S D *et al.* 2009 *AIP Conference Proceedings* **1090** 570
[8] Paschalis S *et al.* 2013 *Nuclear Instruments and Methods in Physics Research A* **709** 44
[9] Sims H 2021 private communication