Proposal:

Investigation of the Anomaly of Neutron Capture Cross Section for Production of s-process Nuclei $^{64,66}Cu$

Renu Kumari, Priyanka Khandelwal, S. Kumar, S. Mandal

Department of Physics & Astrophysics, University of Delhi

P. Verma

Department of Physics, Kalindi College, University of Delhi

S.C. Sharma

Nuclear Physics Division, BARC, Mumbai

R. Palit, V. Nanal

Tata Institute of Fundamental Research, Mumbai

Abstract:

Neutron capture plays a crucial role in nucleosynthesis in massive stars ($M/M_{\odot} \geqslant 8$), where most isotopes from Fe to Sr are created through neutron capture reactions. However, significant disparities exist in the literature regarding the neutron capture cross sections of $^{63}Cu(n,\gamma)^{64}Cu$ and $^{65}Cu(n,\gamma)^{66}Cu$. This proposal aims to investigate these cross-sections using neutron activation and offline gamma-ray spectroscopy techniques at the thermal neutron energy range, conducted at the PLF (Pelletron Linac Facility) at TIFR, Mumbai.

Introduction:

Neutron capture nucleosynthesis within massive stars stands as a cornerstone in galactic chemical evolution, wielding significant influence over the abundance patterns observed in ancient, metal-poor halo stars. The process, known as the S-process, operates along the beta stability curve, contributing to the distribution of elements within our solar system through two distinct mechanisms: a weaker component spanning from iron (Fe) to strontium (Sr), and a more dominant force shaping the mass range from yttrium (Y) to bismuth (Bi). This main component thrives within low-mass stars (with masses ranging from 1 to 3 times that of the Sun), particularly manifesting during the helium shell burning phase in thermally pulsating low-mass asymptotic giant branch (AGB) stars [1-4].

The production of isotopes during this process hinges upon the action of two neutron sources. Initially, the $^{13}C(\alpha, n)^{16}O$ reaction yields a neutron density of $n < 10^7$ cm^{-3} at relatively lower temperatures (around 1×10^8 K). Subsequently, at higher temperatures (approximately 2.7×10^8 K), the neutron density escalates to $n > 10^{10}$ cm^{-3} through the secondary neutron source reaction, $^{22}Ne(\alpha, n)^{25}Mg$ [1].

Conversely, the weak component emerges predominantly within high-mass stars (with masses equal to or greater than 8 times that of the Sun). In these stellar behemoths, the weak S-process unfolds across two pivotal evolutionary stages: convective carbon burning within the shell, characterized by temperatures around 1.5 × 10^9 K and neutron densities (n_n) of approximately 10^{12} cm^{-3}, and convective core helium burning, typified by temperatures near 3 × 10^8 K and neutron densities of roughly 10^6 cm^{-3}. Additionally, a partially convective helium-burning shell encircling the outer edge of the carbon shell may also contribute significantly to the final s-process yields [1-3].

Notably, $^{22}Ne(\alpha,n)^{25}Mg$ serves as the neutron source for both scenarios, operating at distinct temperatures and neutron densities [5]. Understanding the intricate relationship between s-process abundance and stellar cross sections is paramount, as uncertainties in specific cross sections can reverberate throughout the abundance patterns of related isotopes. This becomes particularly pronounced due to the insufficient neutron exposure within massive stars to achieve flow equilibrium. Therefore, accurately determining neutron capture cross-sections remains indispensable for elucidating the abundance of specific isotopes.

In light of these considerations, our primary objective is to undertake a thorough investigation into neutron capture nucleosynthesis within massive stars, with a particular focus on the weak s-process component. By meticulously measuring neutron capture cross sections for isotopes near the seed distribution around the iron, our aim is to refine our comprehension of abundance patterns and the processes governing galactic chemical evolution, especially in the context of metal-poor halo stars.

Motivation:

The precise determination of neutron capture cross-sections plays a critical role in refining nucleosynthesis models and uncovering the origins of isotopic abundances within stellar environments. Discrepancies and uncertainties in cross-section values not only impact individual isotope abundances but also propagate to subsequent isotopes along the s-process chain. Moreover, uncertainties in neutron exposure in massive stars can disrupt flow equilibrium, magnifying the influence of cross-section uncertainties on abundance determinations.

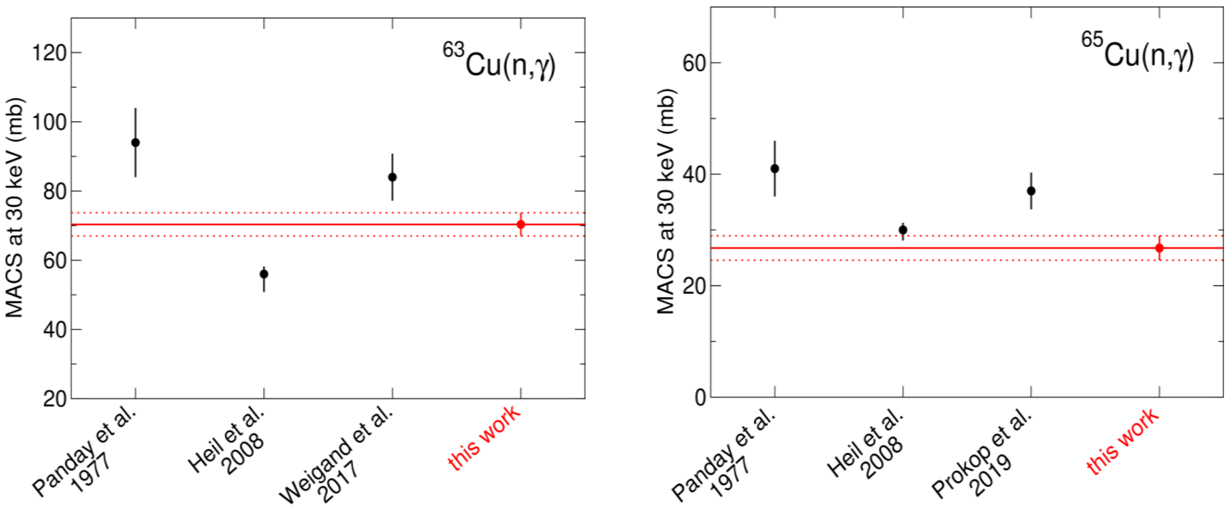

Figure. 1: A comparison of the obtained 30 keV σ_{MACS} (^{63}Cu and ^{65}Cu) with the previous experiments [6, 1, 7, 8, 10]. These plots are taken from [10]. The MACS for Panday et al. [6] was calculated using the prescription mentioned in Ref. [4].

In the literature, significant variations exist in the reported cross-section values of ^{63}Cu (n, γ) ^{64}Cu and ^{65}Cu (n, γ) ^{66}Cu. Pandey et al. (1977) reported Maxwellian-averaged cross sections (MACS) of 41±5 mbarn for ^{63}Cu and ^{65}Cu, respectively [6]. In contrast, Heil et al. in 2008 reported values of $56^{+2.2}_{-5.2}$ mbarn and $30^{+1.3}_{-1.9}3$ mbarn for the same reactions at kT=30 keV, approximately 40% and 30% lower than the values reported by Pandey et al. for ^{63}Cu and ^{65}Cu nuclei, respectively [1].

Recent experiments have yielded further disparities as shown in Figure 1. In 2017, utilizing activation and time-of-flight techniques, a value of 84.0±1.1 exp ± 6.7syst for ^{63}Cu was reported (Weigand et al., 2017 [7]), while another experiment in May 2019 reported a value of 37.0 ± 0.3stat ± 3.3syst for ^{65}Cu at kT=30 keV (Prokop et al., 2019 [8]). Similarly, a December 2019 experiment at kT=30 keV produced cross-section results of 70.4 ± 1.8exp ± 2.4syst and 26.8 ± 1.5exp ± 1.0syst for ^{63}Cu and ^{65}Cu, respectively, by counting the activity of irradiated targets (Weissman et al., 2019 [10]).

These discrepancies underscore the importance of testing these reactions at consistent energy levels. Resolving these disparities through precise measurements is imperative for advancing our understanding of nucleosynthesis and the synthesis of heavy elements in stars.

Methodology:

The proposed investigation will employ neutron activation analysis (NAA) techniques to determine the neutron capture cross sections of ^{63}Cu and ^{65}Cu. NAA involves irradiating stable isotopic samples with neutrons to induce neutron capture reactions, thereby transforming the samples into radioactive isotopes. The resulting radioactive isotopes emit characteristic gamma rays, which can be detected and analyzed using high-purity germanium (HPGe) detectors. By analyzing the gamma-ray spectra, the radioactive isotopes and parent elements can be identified, providing insights into the neutron capture reactions and cross-sections. The experiment will take place at the Pelletron Linac Facility (PLF) at TIFR, Mumbai, utilizing a neutron beam generated from the Pelletron accelerator.

The proton beam with an energy range of 7 to 10 MeV will be directed onto ^{9}Be targets to produce neutrons with a Maxwellian energy distribution at kT ~ 20 to 40 keV. Thick Beryllium targets may also be utilized for neutron production, subsequently moderated by a room-temperature paraffin moderator. The resulting epithermal neutron beam will range in energy from a few meV to a few MeV and will be collimated with an appropriate aperture (diameter 10-12 mm) to reduce the beam spot at the sample location. Target samples of ^{63}Cu and ^{65}Cu will be irradiated with the neutron beam placed at the 6m irradiation facility. Additionally, a ^{115}In foil will be irradiated with a neutron beam for calibration purposes.

Given the short half-lives of ^{64}Cu, ^{66}Cu, and ^{116}In ($t_{1/2}$= 54 min.), the detection system should be positioned close to minimize transportation time and maximize counting time, thus improving the measurement uncertainty. The Irradiation chamber should offer the option of fast sample removal. Two preferably clover detectors for gamma-ray measurements, along with an appropriate data acquisition system, will be required a few meters away from the irradiation facility. An X-ray detector will be employed for proper identification of the elements. Data will be collected both in singles and in coincidence between X-ray and gamma detectors.

This proposal aims to address existing discrepancies in neutron capture cross-section values for ^{63}Cu and ^{65}Cu, contribute to the refinement of nucleosynthesis models, and enhance our understanding of the synthesis of heavy elements in stellar environments. Therefore, efforts will be made to reduce the uncertainty of the measurements.

Beam Time Requirements:

Based on cross-section (Table 1(a) & 1(b)) estimations and gamma detector efficiency, the experiment will require 15 shifts for two targets and irradiation of ^{115}In foils for calibration purposes. The decay schemes for Cu and In nuclei are illustrated in Figures 2(a) and 2(b) respectively. A neutron yield of 10^7 has been employed in the count rate estimation.

Summary of the requirements:

Beam: Proton
Energy: 7 - 10 MeV
Current: 100 -300 pnA
Beamline: 6 m, irradiation facility
Neutron Production Target: ^{9}Be (Thickness: 5 mm, to stop 9MeV proton beam completely inside the target)**.
Irradiation target foils: ^{63,65}Cu and ^{115}In (0.1 – 1 mm thickness)
Detectors: Clove/HPGe, X-ray
Electronics & DAQ: Standard NIM, DAQ

(** Paraffin moderator may be used to moderate neutron energy if required.)

Beam Requires: 15 Shifts.

References:

[1] M. Heil, F. Käppeler, E. Ubersender, R. Gallino, and M. Pignatari, Phys. Rev. C 77, 015808 (2008).

[2] Burbidge, E. G. Burbidge, W. Fowler, and F. Hoyle, Rev. Mod. Phys. 29, 547(1957).

[3] Raiteri, C. M., Gallino, R., Busso, M., Neuberger, D. & Käppeler, Astrophysical Journal v. 419, 207 (1993).

[4] Z. Bao, H. Beer, F. Käppeler, F. Voss, K. Wisshak and T. Rauscher, At. Data Nucl. Data Tables 76, 70 (2000).

[5] Raiteri, C., M. Busso, R. Gallino, and G. Picchio, Astrophys. J. 371, 665 (1991).

[6] M. Pandey, J. Garg, and J. Harvey, Phys. Rev. C 15, 600 (1977)

[7] M. Weigand et al., Phys. Rev. C 95, 015808 (2017).

[8] C. J. Prokop, A. Couture, S. Jones, S. Mosby, G. Rusev, J. Ullmann, and M. Krtička, Phys. Rev. C 99, 055809 (2019).

[9] P. Punte et al., Phys. Rev. C 95, 024619 (2017).

[10] L. Weissman et al., Phys. Rev. C 100, 065804 (2019).

[11] Sabyasachi Paul et al., Rev. Sci. Instrum. 85, 063501 (2014)

Table 1 (a): MACS (mb) at kt= 30 keV for ^{63}Cu (n, γ) ^{64}Cu

Sr. No	Measured MACS (mb)	Reference
1	94±10	Pandey et al., 1977 [6]
2	$56^{+2.2}_{-5.2}$	M. Heil et al., 2008 [1]
3	84.0±1.1exp ± 6.7syst	Weigand et al. 2017 [7]
4	70.4 ± 1.8exp ± 2.4syst	Weissman et al., 2019 [10]

Table 1(b): MACS(mb) at kt= 30 keV for ^{65}Cu (n, γ) ^{66}Cu

Sr. No	Measured MACS(mb)	Reference
1	41±5	Pandey et al., 1977 [6]
2	$30^{+1.3}_{-1.9}$	M. Heil et al., 2008 [1]
3	37.0 ± 0.3 stat ± 3.3 syst	Prokop et al., May 2019 [8]
4	26.8 ± 1.5 exp ± 1.0 syst	Weissman et al., 2019 [10]

Figure 2 (a): Decay Scheme of ^{64}Cu ($T_{1/2}$ = 12.7 hrs.)

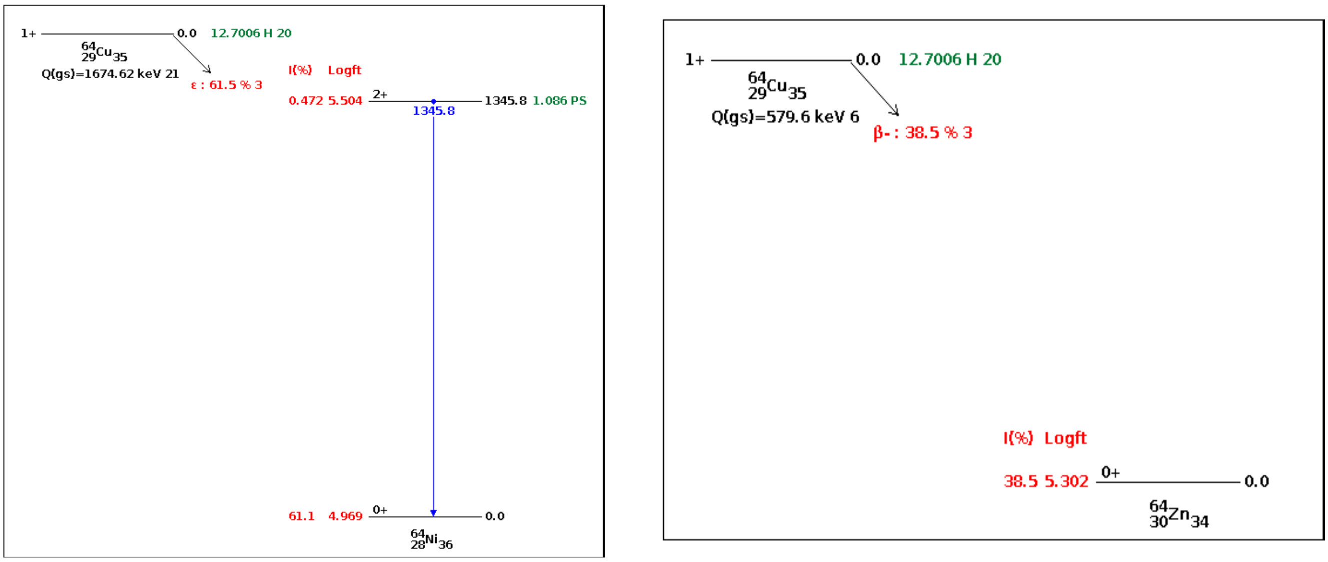

Figure 2 (b): Decay Scheme of ^{66}Cu ($T_{1/2}$ = 5.12 min.) and ^{116}In ($T_{1/2}$ = 54.2 min.)