EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

# The $^{59}$Cu(p,α) cross section and its implications for nucleosynthesis in core collapse supernovae

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## Abstract


The $^{59}$Cu(p,α) reaction is key for heavy element synthesis in the νp-process and for the production of cosmic X-ray sources, which have the potential to be detectable by satellite missions in the future. We propose to study this reaction at astrophysical energies for the first time using $^{59}$Cu beams from the HIE-ISOLDE facility. The reaction will be studied in inverse kinematics, detecting the emitted α-particles in coincidence with the recoiling $^{56}$Ni nuclei using two sets of Silicon detectors.


**Requested shifts**: 24 shifts, (split into 1 runs over 1 years)
**Beamline:** 2nd beam line (detection and chamber setup provided by Edinburgh)

## Introduction

The formation of elements beyond iron is one of the biggest unanswered question in nuclear astrophysics. The heavy elements are believed to be mainly produced by neutron capture reactions in the slow and the rapid neutron capture processes (called s-, and r- process, respectively). There are, however, several nuclei which reside on the proton rich side and cannot be formed by either of these processes. These nuclei are called 'p-nuclei' and may originate from the p-process, happening at high temperatures in supernova explosions, where proton rich nuclei are produced by a series of photodisintegration reactions on an existing s- and r-process seed distribution. However, stellar models currently fail to reproduce the high solar system abundances of the lighter p-nuclei $^{92,94}$Mo and $^{96,98}$Ru [1].

Recently, a new process was suggested which could account for their production, denoted as the νp-process [2]. The νp-process happens during core collapse supernova explosions, where intense neutrino fluxes originating from the cooling proto-neutron star deposit energy in the outer layers of stellar matter, leading to a supersonic outflow of stellar material, called neutrino-driven wind. This wind is proton rich, resulting in element formation via proton and alpha capture reactions. The reaction flow proceeds towards heavier masses due to the presence of free neutrons, which are produced by anti-neutrino absorption on free protons. These neutrons speed up the reaction flow since they can bridge slow charged particle rates and long beta decay lifetimes by (n,p) reactions, permitting element formation up to mass A~100. In a recent study, Arcones at al. [3] identified an end point nuclear cycle which is key to the ability of the νp-process to form elements with A>64. At high temperatures of ~3GK, the $^{59}$Cu(p,α)$^{56}$Ni reaction starts to dominate over $^{59}$Cu(p,γ), preventing the synthesis of heavier elements by cycling material back to $^{56}$Ni (see Fig. 1). This upper temperature limit for the νp-process depends strongly on the unknown $^{59}$Cu(p,α) reaction rate and excitation function, in fact only a slightly higher cross-over temperature would significantly increase the efficiency of the νp-process.

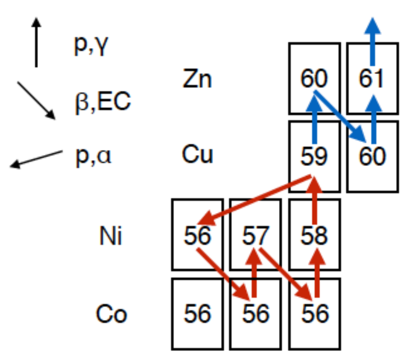


Fig. 1: Different reaction paths in the νp-process. At high temperatures, the reaction flow to heavier masses is blocked by the $^{59}$Cu(p,α) reaction, cycling most of the material back to $^{56}$Ni (red arrows). When temperatures drop below ~3 GK, the then stronger $^{59}$Cu(p,γ) reaction opens the path towards the formation of heavy elements (blue arrows).

Apart from its importance for heavy element formation, the $^{59}$Cu(p,α) reaction is also crucial for the abundances of the X-ray emitters $^{55}$Fe and $^{59}$Ni produced in supernova explosions. Both species hold promise to be detectable X-ray sources in the future, opening up new possibilities to study supernova explosion mechanisms. Jordan et al. [4] showed that the abundances of $^{55}$Fe and $^{59}$Ni are highly sensitive to variations in the $^{59}$Cu(p,α) reaction rate (a factor of 10 change in the reaction rate changes the expected $^{59}$Ni abundance by 44% and the $^{55}$Fe abundance by 30%).

Presently, there are no experimental cross section data for the $^{59}$Cu(p,α) reaction. We propose to measure this reaction in inverse kinematics at HIE-ISOLDE taking advantage of the intense $^{59}$Cu beam and beam energies of 5.0 MeV/u, which will be available for the first time. This will allow us to study the reaction in the Gamow window for temperatures between 2.5 and 4 GK.

## Experimental setup

The $^{59}$Cu(p,$\alpha$) reaction will be studied in inverse kinematics with a $^{59}$Cu beam impinging on a $CH_2$ target. The emitted $\alpha$ particles and the recoiling $^{56}$Ni nuclei will be detected in coincidence using two sets of silicon detectors. A similar setup has already been successfully used by members of the Edinburgh group for (p,$\alpha$) cross section measurements at TRIUMF [5], and has been proposed for studying the $^{37}$K(p,$\alpha$) reaction at HIE-ISOLDE [6] (accepted in 2012). Due to reaction kinematics, both reaction products will be emitted at forward angles in the laboratory system, with maximum emission angles of 40 degrees for the $\alpha$ particles, and 2.8 degrees for $^{56}$Ni recoils. A sketch of the setup is shown in Fig. 2. The $CH_2$ target and the detectors will be placed under vacuum in a reaction chamber. $\alpha$ particles will be detected using two Micron S2 type detectors located at a distance of 40 mm downstream of the $CH_2$ target. The detectors have an active area with an inner diameter of 22 mm and an outer diameter 70 mm, thus covering angles up to 40 degrees. The detectors will be arranged as $\Delta$E-E telescope with thicknesses of 70 $\mu$m and 1000 $\mu$m, respectively. The recoiling $^{56}$Ni nuclei will be detected using a Micron S2 type detector (thickness 70 $\mu$m) at a distance of 400 mm downstream of the target, covering angles of <5 degrees. The thicknesses are chosen such that the $\alpha$ and $^{56}$Ni particles are completely stopped in the detectors. A possible source of background in this measurement are reactions of the beam with the carbon present in the target. The $\Delta$E-E technique, coincident detection and position sensitivity of the detectors will allow to set constraints on the type of particle, the angular correlation between the reaction products and the Q-value of the reaction. After these cuts were applied in a previous (p,$\alpha$) measurement [5] using a similar setup, there was essentially no background present. The efficiency of the setup for the $^{59}$Cu(p,$\alpha$) reaction channel will be around 30%, assuming isotropic particle emission in the CM system. The detectors, the reaction chamber, and the $CH_2$ target will be provided by the Edinburgh group.

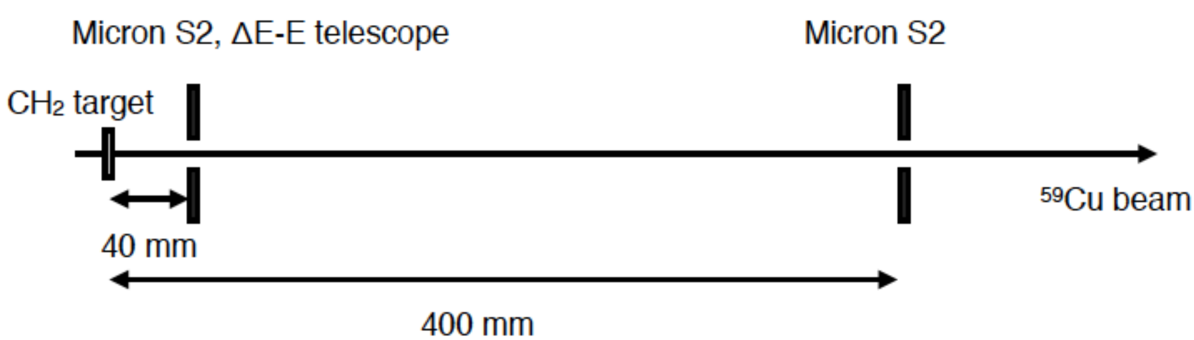


Fig. 2: The proposed experimental setup consisting of a $CH_2$ target, two Micron S2 detectors arranged as $\Delta$E-E telescope to detect $\alpha$ particles, and one Micron S2 detector to detect the $^{56}$Ni recoils. All these elements will be placed under vacuum in a reaction chamber.

## Beam Time Request

The following count rates were calculated assuming a beam intensity of 7E6 ions/μC, a proton current of 1.5 μA, and a transmission of 2%, resulting in 2.1E5 $^{59}Cu$ ions per second on target. The $CH_2$ target will have an areal density of 500 μg/cm$^2$. For reaction rate estimates, cross sections were calculated with the code NON-SMOKER [7] and the detection efficiency of 30% was taken into account. Table 1 summarizes the required beam energies with their expected count rates and allocated number of shifts. The first two columns show the beam energy to be delivered by HIE-ISOLDE in MeV/u and MeV. The third column, denoted with $E_{cm}$ lists the actually covered energy range in the center of mass system, as calculated from the energy loss of the $^{59}Cu$ beam in the target. To check the effect of possible background reactions, we plan to perform short runs of 2 hours using a $CD_2$ target of the same thickness at each beam energy. This was the approach used in a previous experiment [5] and no significant background was found.

In total, we request 19 shifts for the (p,α) measurement at 5 beam energies. Additionally, we request 1 shift for optimizing detector settings in-beam at the start of the experiment. As a conservative estimate, we request 4 shifts for changing the beam energy. If this measurement proves successful, we will prepare a follow-up proposal for a measurement at even lower beam energies to study the low energy end of the Gamow window.

| $E_B$ (MeV/u) | $E_B$ (MeV) | $E_{CM}$ (MeV) | XS (mb) | C/h | Shifts | C | Unc. (%) |
|---|---|---|---|---|---|---|---|
| 5.0 | 295 | 4.6-5.0 | 2.0 | 28 | 2 | 290 | 6 |
| 4.7 | 277 | 4.3-4.7 | 1.3 | 14 | 3 | 300 | 6 |
| 4.4 | 259 | 4.0-4.4 | 0.7 | 9 | 4 | 220 | 7 |
| 4.0 | 236 | 3.6-4.0 | 0.3 | 3 | 5 | 105 | 10 |
| 3.6 | 212 | 3.2-3.6 | 0.1 | 1.4 | 5 | 45 | 15 |

Table 1: $E_B$ denotes the $^{59}Cu$ beam energies in units of MeV/u and MeV to be delivered by HIE-ISOLDE, $E_{CM}$ is the covered energy range in the center of mass system. The reaction cross section calculated by the NON-SMOKER code is denoted as 'XS'. 'C/h' is the expected number of counts per hour and 'C' is the integrated number of counts for the allocated number of shifts minus 2 hours of background runs with a $CD_2$ target. 'Unc' is the expected statistical uncertainty.

## Summary of requested shifts:

- 1 (8h) for optimizing settings in-beam
- 19 (8h) shifts for (p,α) measurement
- 4 (8h) shifts for beam changes

Total: 24 shifts

## References:


[1] M. Arnould and S. Goriely Phys. Rep. 384,1 (2003).

[2] C. Fröhlich, et al. Phys. Rev. Lett. 96, 142502 (2006).

[3] A. Arcones, C. Fröhlich, and G. Martinez-Pinedo, Astroph. J. 750, 18 (2012).

[4] G. C. Jordan, S. S. Gupta, and B. S. Meyer, Phys. Rev. C68, 065801 (2003).

[5] P. Salter, et al. Phys. Rev. Lett. 108, 242701 (2012).

[6] M Aliotta et al., INTC-P-365, (2012).

[7] T. Rauscher, online at http://nucastro.org/nonsmoker.html.

## Appendix

### DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

| Part of the Choose an item. | Availability | Design and manufacturing |
|---|---|---|
| [if relevant, name fixed ISOLDE installation: MINIBALL + only CD, MINIBALL + T-REX] | Existing | To be used without any modification |
| | | |
| Reaction chamber, Silicon Detectors, DAQ, CH2 target | Existing | To be used without any modification<br>To be modified |
| | x New | x Provided by Edinburgh<br>CERN/collaboration responsible for the design and/ or manufacturing |
| [Part 2 experiment/ equipment] | Existing | To be used without any modification<br>To be modified |
| | New | Standard equipment supplied by a manufacturer<br>CERN/collaboration responsible for the design and/ or manufacturing |
| [insert lines if needed] | | |

### HAZARDS GENERATED BY THE EXPERIMENT

*(if using fixed installation)* Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

| ***Hazards*** | *[Part 1 of the experiment/ equipment]* | *[Part 2 of the experiment/ equipment]* | *[Part 3 of the experiment/ equipment]* |
|---|---|---|---|
| Thermodynamic and fluidic | | | |
| Pressure | [pressure][Bar], [volume][l] | | |
| Vacuum | | | |
| Temperature | [temperature] [K] | | |
| Heat transfer | | | |
| Thermal properties of materials | | | |

| | | | |
|---|---|---|---|
| Cryogenic fluid | [fluid], [pressure][Bar], [volume][l] | | |
| Electrical and electromagnetic | | | |
| Electricity | [voltage] [V], [current][A] | | |
| Static electricity | | | |
| Magnetic field | [magnetic field] [T] | | |
| Batteries | | | |
| Capacitors | | | |
| Ionizing radiation | | | |
| Target material | $CH_2$ | | |
| Beam particle type (e, p, ions, etc) | $^{59}$Cu ions | | |
| Beam intensity | 7E6 p/μC | | |
| Beam energy | 3.6-5.0 MeV/u | | |
| Cooling liquids | distilled water or alcohol | | |
| Gases | [gas] | | |
| Calibration sources: | standard mixed alpha | | |
| • Open source | x | | |
| • Sealed source | [ISO standard] | | |
| • Isotope | | | |
| • Activity | ~3kBq | | |
| Use of activated material: | | | |
| • Description | | | |
| • Dose rate on contact and in 10 cm distance | [dose][mSV] | | |
| • Isotope | | | |
| • Activity | | | |
| Non-ionizing radiation | | | |
| Laser | | | |
| UV light | | | |
| Microwaves (300MHz-30 GHz) | | | |
| Radiofrequency (1-300MHz) | | | |
| Chemical | | | |

| | | | |
|---|---|---|---|
| Toxic | [chemical agent], [quantity] | | |
| Harmful | [chemical agent], [quantity] | | |
| CMR (carcinogens, mutagens and substances toxic to reproduction) | [chemical agent], [quantity] | | |
| Corrosive | [chemical agent], [quantity] | | |
| Irritant | [chemical agent], [quantity] | | |
| Flammable | [chemical agent], [quantity] | | |
| Oxidizing | [chemical agent], [quantity] | | |
| Explosiveness | [chemical agent], [quantity] | | |
| Asphyxiant | [chemical agent], [quantity] | | |
| Dangerous for the environment | [chemical agent], [quantity] | | |
| **Mechanical** | | | |
| Physical impact or mechanical energy (moving parts) | [location] | | |
| Mechanical properties (Sharp, rough, slippery) | [location] | | |
| Vibration | [location] | | |
| Vehicles and Means of Transport | [location] | | |
| **Noise** | | | |
| Frequency | [frequency],[Hz] | | |
| Intensity | | | |
| **Physical** | | | |
| Confined spaces | [location] | | |
| High workplaces | [location] | | |
| Access to high workplaces | [location] | | |
| Obstructions in passageways | [location] | | |
| Manual handling | [location] | | |
| Poor ergonomics | [location] | | |

## 3.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*

*… kW*