Measurement of astrophysically important excitation energies of $^{58}\text{Zn}$ with GRETINA

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Abstract. The level structure of neutron-deficient $^{58}\text{Zn}$ has been extracted experimentally. This nucleus is important for the rapid proton-capture process. $^{58}\text{Zn}$ was produced by using a (d,n)-type transfer reaction on $^{57}\text{Cu}$ in inverse kinematics at beam energies of 75 MeV/u. Several $\gamma$-ray transitions have been identified. The experiment utilized the state-of-the-art GRETINA $\gamma$-ray energy tracking array in conjunction with the large-acceptance spectrometer S800 at NSCL. The excitation energies of the identified low-lying states in $^{58}\text{Zn}$ are important for constraining the $^{57}\text{Cu}(\text{p},\gamma)^{58}\text{Zn}$ reaction rate under X-ray burst conditions.

Introduction

Astrophysical Type I X-ray bursts take place in low-mass stellar binary systems consisting of a compact, dense neutron star, and a low-mass star. H/He-rich matter is accreted from the companion star onto the neutron star. The temperature and density of the accreted matter on the surface of the neutron star rises and eventually, at temperatures around $T_9 = 0.2$ ($T_9$ is measured in units of GigaKelvin), a thermonuclear runaway is ignited that powers the X-ray burst. Energy generation is mainly driven by $^{57}\text{Cu}(\text{p},\gamma)^{58}\text{Zn}$.
fast proton and $\alpha$-particle capture reactions in the so-called rapid proton-capture process (rp-process), whereas the much slower $\beta^+$-decays determine the overall timescale of the process (10-100 s) and the final composition of the nuclear ashes, see e.g. [1–3].

The rp-process may extend up to Te under some circumstances. Along the reaction path, $(p,\gamma)$ reaction rates on neutron-deficient nuclei need to be known to model the rp-process. At certain nuclei near the proton dripline, the so-called waiting points, the reaction flow that normally proceeds via rapid $(p,\gamma)$ reactions is hampered due to the nuclear structure by photo disintegration.

An important waiting point nucleus in the rp-process is the doubly-magic $^{56}$Ni ($N = Z = 28$). The Q-value for proton capture is relatively low ($Q = 0.695$ MeV) and the electron-capture lifetime is approximately 22000 s under stellar conditions, thus exceeding typical burst times. This leads to the formation of a $(p,\gamma)$-$(\gamma,p)$ equilibrium between $^{56}$Ni and $^{57}$Cu. Under these conditions, the reaction flow to heavier nuclei beyond $^{56}$Ni depends on the $^{57}$Cu$(p,\gamma)$ reaction rate (see Fig. 1).

So far, the reaction rate is almost entirely constrained by theory and it is dominated by the uncertainties in the excitation energies of low-lying states in $^{58}$Zn. In Ref. [4], shell model calculations are used to obtain the astrophysical important part of the level structure of $^{58}$Zn. The authors of Ref. [5] used updated shell-model calculations of the important states in $^{58}$Zn to reevaluate the previously derived reaction rate. However, typical uncertainties of a few 100 keV in the calculated excitation energies for excited states in $^{58}$Zn result in an uncertainty in the reaction rate of up to several orders of magnitude.

![Figure 1. Effective half-life of $^{56}$Ni under typical rp-process conditions ($\rho = 10^5$ g/cm$^3$) after variation of the $^{57}$Cu$(p,\gamma)$-$^{58}$Zn rate by a factor of 10 up and down in comparison with the rate by Forstner et al. [5].](image-url)

**Experimental procedure**

The experiment presented in this work aimed at measuring the excitation energies of low-lying states in $^{58}$Zn with high accuracy in order to calculate an updated reaction rate for proton capture on $^{57}$Cu. The measurement was performed at the National Superconducting Cyclotron Laboratory at Michigan State University.

Low-lying $\gamma$-decaying states in $^{58}$Zn above the proton separation threshold ($S_p = 2279(50)$ keV [6]) were populated via the $d(^{57}$Cu,$^{58}$Zn)n proton transfer reaction. The radioactive $^{57}$Cu beam was produced at the NSCL Coupled Cyclotron Facility by accelerating a stable $^{58}$Ni beam to 160 MeV/u and...
impinging on a 752 mg/cm² 9Be target at the entrance of the A1900 fragment separator. Nucleon exchange and pickup reactions were used to produce radioactive ⁵⁷Cu (see similar experimental technique in [7]). A 300 mg/cm² Al wedge was placed in the intermediate plane of the A1900 for further purification of the ⁵⁷Cu beam, which was subsequently transported to the experimental setup, where the purity was around 20%.

To induce the (d,n) proton transfer reaction the ⁵⁷Cu beam was directed onto a 225 mg/cm² CD₂ target. The target was placed in the center of the GRETINA array [8] which was used to detect in-flight γ-rays emitted from the deexcitation of the populated states in ⁵⁸Zn. The ⁵⁷Cu beam energy was \( E_{\text{beam}} \approx 75 \text{ MeV/u} \) at the secondary reaction target. The emerging neutron, produced in the d(⁵⁷Cu,⁵⁸Zn)n proton transfer reaction, was not observed. The ⁵⁸Zn recoil was identified in the focal plane of the S800 spectrometer by means of time-of-flight and energy loss. Angle and position of ⁵⁸Zn ions were also measured to reconstruct the kinematical properties of each event and to perform high-precision Doppler-correction of the γ-ray energies being emitted in the lab system.

**Preliminary results**

In this section, first preliminary results are presented. The left part of Fig. 2 shows the clear identification of ⁵⁸Zn events in the S800 focal plane, based on a time-of-flight measurement (between a fast plastic scintillator placed upstream of the target and the triggering detector of the same material in the focal plane) and an energy-loss measurement in an ion chamber (also situated in the focal plane). Calibration of the identification plot was achieved by assigning observed γ-ray transitions of isotopes in the vicinity of ⁵⁸Zn to the corresponding nuclei. As can be seen in Fig. 2 different other isotopes have also been identified.

Using the unique identification of the reaction products, a two-dimensional gate was applied to select the ⁵⁸Zn ions. Gamma-rays from ⁵⁸Zn can be identified through coincidence with identified ⁵⁸Zn ions in the S800 focal plane. The GRETINA γ-ray efficiency was around 5% for a γ-ray energy of 1 MeV. A γ-ray energy resolution of around 2% (FWHM) was obtained, mainly limited by the energy spread in the thick reaction target. Different peaks can be clearly identified (right part of Fig. 2). The strongest peak has an energy of \( E_γ = 1356(5) \text{ keV} \) and is assigned to belong to the decay of the first excited ²⁺ state to the ground state in ⁵⁸Zn. In the mirror nucleus ⁵⁸Ni, the first ²⁺ has an energy of 1454 keV, thus giving a shift of ∼100 keV. The shell-model calculation in [5] places this state at an energy of 1400 keV.

Other states in ⁵⁸Zn will be identified using γ–γ coincidences and guidance from the known level structure in the stable and experimentally well-known isospin mirror nucleus ⁵⁸Ni.

The astrophysical reaction rate for the ⁵⁷Cu(p,γ) reaction is mainly determined by the low-lying ²⁺ states in ⁵⁸Zn [5]. Since the theoretical predictions of the level energies exhibit large uncertainties, a tremendous reduction of uncertainty in the reaction rate is expected when using the experimentally extracted excitation energies with small errors.

**Summary**

The experimental technique and preliminary results of an experiment aiming at measuring the level structure of neutron-deficient ⁵⁸Zn have been presented. Several γ-ray transitions have been identified and a γ–γ coincidence analysis along with structure information from the isospin mirror partner ⁵⁸Ni is being performed to reconstruct the level structure. The experiment employed a new experimental approach by using a proton transfer reaction at relatively high beam energies combined with an angle-integrated measurement of the reaction products and the GRETINA array to extract astrophysically important excitation energies of low-lying states in ⁵⁸Zn.
Figure 2. Left: Identification of the reaction products via time-of-flight and energy-loss measurements in the focal plane of the S800. Clearly, $^{58}\text{Zn}$ was produced in the $^{57}\text{Cu}(d,n)$ reaction. Right: Preliminary Doppler-corrected $\gamma$-ray singles spectrum after gating on $^{58}\text{Zn}$ in the outgoing channel. Different $\gamma$-ray transitions can be identified.

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