EPJ Web of Conferences **66**, 07013 (2014)
DOI: 10.1051/epjconf/20146607013

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

C. Langer[1,2,a], F. Montes[1,2], A. Aprahamian[2,4], D. W. Bardayan[5], D. Bazin[1], B.A. Brown[1,3], J. Browne[1,2], H. Crawford[6], R. Cyburt[1,2], C. Domingo-Pardo[7], A. Gade[1,3], S. George[8], P. Hosmer[9], L. Keek[1,2], A. Kontos[1,2], I-Y. Lee[6], A. Lemasson[1], E. Lunderberg[1,3], Y. Maeda[10], M. Matos[11], Z. Meisel[1,2,3], S. Noji[1], A. Nystrom[2,4], G. Perdikakis[12,1], J. Pereira[1,2], S. Quinn[1,2,3], F. Recchia[1], H. Schatz[1,2,3], M. Scott[1,2,3], K. Siegl[2,4], A. Simon[1,2], M. Smith[2,4], A. Spyrou[1,2,3], J. Stevens[1,2,3], R. Stroberg[1,3], D. Weisshaar[1], J. Wheeler[1,2,3], K. Wimmer[12,1], and R.G.T. Zegers[1,2,3]

[1] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, USA*
[2] *Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824, USA*
[3] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[4] *Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[5] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[6] *Nuclear Science Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley CA, USA*
[7] *IFIC, CSIC-University of Valencia, E-46071 Valencia, Spain*
[8] *Max-Planck-Institute for Nuclear Physics, PO Box 103980, 69029 Heidelberg, Germany*
[9] *Department of Physics, Hillsdale College, Hillsdale, MI 49242, USA*
[10] *Department of Applied Physics, University of Miyazaki, Miyazaki, Miyazaki 889-2192, Japan*
[11] *Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[12] *Department of Physics, Central Michigan University, Mt. Pleasant, MI 48859, USA*

Abstract. The level structure of neutron-deficient ^{58}Zn has been extracted experimentally. This nucleus is important for the rapid proton-capture process. ^{58}Zn was produced by using a (d,n)-type transfer reaction on ^{57}Cu in inverse kinematics at beam energies of 75 MeV/u. Several γ-ray transitions have been identified. The experiment utilized the state-of-the-art GRETINA γ-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}Zn are important for constraining the ^{57}Cu(p,γ)^{58}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

[a] e-mail: langer@nscl.msu.edu

fast proton and α-particle capture reactions in the so-called rapid proton-capture process (rp-process), whereas the much slower β^+-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,γ) 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,γ) 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,γ)-(γ,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,γ) 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.

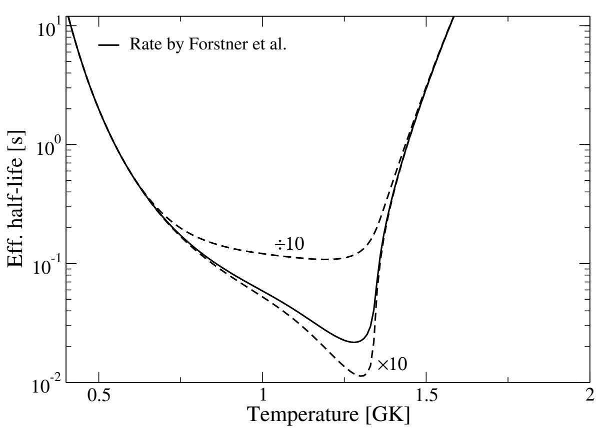

Figure 1. Effective half-life of ^{56}Ni under typical rp-process conditions ($\rho = 10^5$ g/cm^3) after variation of the ^{57}Cu(p,γ)^{58}Zn rate by a factor of 10 up and down in comparison with the rate by Forstner et al. [5].

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 γ-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/cm^2 ^{9}Be target at the entrance of the A1900 fragment separator. Nucleon exchange and pickup reactions were used to produce radioactive ^{57}Cu (see similar experimental technique in [7]). A 300 mg/cm^2 Al wedge was placed in the intermediate plane of the A1900 for further purification of the ^{57}Cu beam, which was subsequently transported to the experimental setup, where the purity was around 20 %.
To induce the (d,n) proton transfer reaction the ^{57}Cu beam was directed onto a 225 mg/cm^2 CD_2 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 ^{58}Zn. The ^{57}Cu beam energy was $E_{\rm beam} \approx 75$ MeV/u at the secondary reaction target. The emerging neutron, produced in the d(^{57}Cu,^{58}Zn)n proton transfer reaction, was not observed. The ^{58}Zn recoil was identified in the focal plane of the S800 spectrometer by means of time-of-flight and energy loss. Angle and position of ^{58}Zn 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 ^{58}Zn 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 ^{58}Zn 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 ^{58}Zn ions. Gamma-rays from ^{58}Zn can be identified through coincidence with identified ^{58}Zn 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 $E_\gamma = 1356(5)$ keV and is assigned to belong to the decay of the first excited 2_1^+ state to the ground state in ^{58}Zn. In the mirror nucleus ^{58}Ni, the first 2_1^+ 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 ^{58}Zn will be identified using $\gamma - \gamma$ coincidences and guidance from the known level structure in the stable and experimentally well-known isospin mirror nucleus ^{58}Ni.
The astrophysical reaction rate for the ^{57}Cu(p,γ) reaction is mainly determined by the low-lying 2^+ states in ^{58}Zn [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 ^{58}Zn have been presented. Several γ-ray transitions have been identified and a $\gamma - \gamma$ coincidence analysis along with structure information from the isospin mirror partner ^{58}Ni 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 ^{58}Zn.

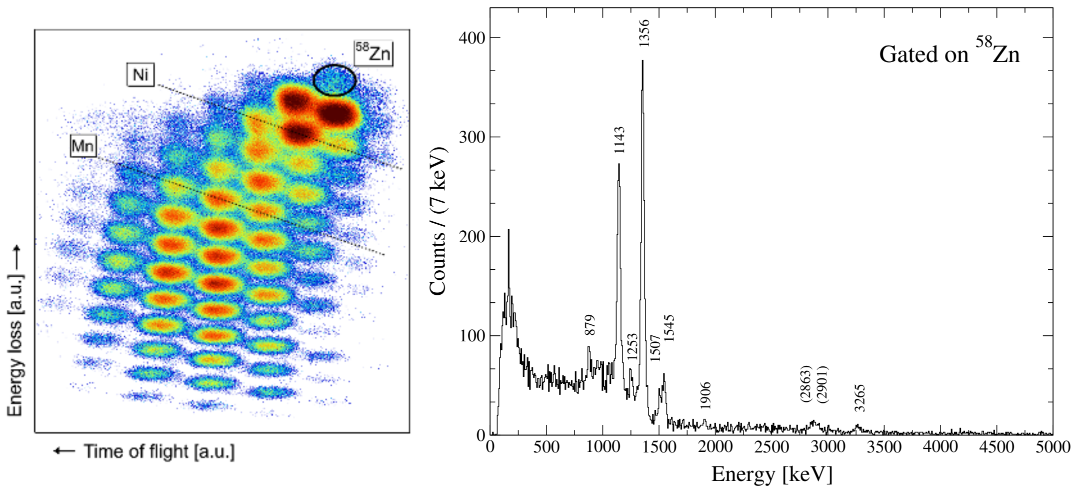

Figure 2. Left: Identification of the reaction products via time-of-flight and energy-loss measurements in the focal plane of the S800. Clearly, ^{58}Zn was produced in the ^{57}Cu(d,n) reaction. Right: Preliminary Doppler-corrected γ-ray singles spectrum after gating on ^{58}Zn in the outgoing channel. Different γ-ray transitions can be identified.

Acknowledgements

This work is supported by NSF grants PHY11-02511 and PHY08-22648 (Joint Institute for Nuclear Astrophysics). GRETINA was funded by the U.S. DOE Office of Science. Operation of the array at NSCL is supported by NSF under Cooperative Agreement PHY-1102511 (NSCL) and DOE under grant DE-AC02-05CH11231 (LBNL). C.D.P. acknowledges support from MINECO, Spain, under grant FPA2011-29854

References

[1] H. Schatz, A. Aprahamian, J. Görres, M. Wiescher, T. Rauscher, J. F. Rembges, F. K. Thielemann, B. Pfeiffer, P. Möller, K. L. Kratz et al., Physics Reports **294**, 167 (1998)

[2] H. Schatz, A. Aprahamian, V. Barnard, L. Bildsten, A. Cumming, M. Ouellette, T. Rauscher, F. K. Thielemann, M. Wiescher, Physical Review Letters **86**, 3471 (2001)

[3] J. José, C. Iliadis, Reports on Progress in Physics **74**, 096901 (2011)

[4] H. Herndl, J. Görres, M. Wiescher, B. A. Brown, L. Van Wormer, Physical Review C **52**, 1078 (1995)

[5] O. Forstner, H. Herndl, H. Oberhummer, H. Schatz, B. A. Brown, Physical Review C **64**, 45801 (2001)

[6] M. Wang, G. Audi, A. H. Wapstra, F. G. Kondev, M. MacCormick, X. Xu, B. Pfeiffer, Chinese Physics C **36**, 1603 (2012)

[7] A. Gade, P. Adrich, D. Bazin, B. A. Brown, J. M. Cook, C. Aa. Diget, T. Glasmacher, S. McDaniel, A. Ratkiewicz, K. Siwek et al., Physical Review Letters **102**, 182502 (2009)

[8] S. Paschalis, I. Y. Lee, A. O. Macchiavelli, C. M. Campbell, M. Cromaz, S. Gros, J. Pavan, J. Qian, R. M. Clark, H. L. Crawford et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **709**, 44 (2013)