

Experimental study on the γ -emission probability of unbound states in ^{131}Sn for understanding r -process

S. Bae^{1,2,*}, N. Imai¹, T. Chillery³, S. Michimasa¹, D. Suzuki⁴, D. S. Ahn⁵, K. Y. Chae⁶, S. Cherubini^{7,8}, M. La Cognata⁸, M. Dozono^{9,4}, M. Egeta^{10,4}, F. Endo¹⁰, N. Fukuda⁴, T. Haginouchi^{10,4}, S. Hanai¹, S. Hayakawa¹, J. W. Hwang⁵, Y. Hijikata^{4,9}, S. Ishio^{10,4}, N. Iwasa^{10,4}, K. Kawata¹, S. Kubono⁴, R. Kojima¹, L. Lamia^{7,8}, J. Li¹, N. Nishimura¹, K. Okawa¹, H. J. Ong^{11,12,4}, S. Ota¹², S. Palmerini¹³, R. G. Pizzone^{7,8}, T. Saito¹, Y. Shimizu⁴, S. Shimoura^{1,4}, T. Sumikama⁴, H. Suzuki⁴, H. Takeda⁴, A. Tumino^{14,8}, X. Tang¹¹, H. Tanaka^{15,4}, M. Tanaka⁴, T. Teranishi^{15,4}, Y. Togano⁴, R. Yokoyama¹, R. Yoshida^{8,4}, K. Yoshida⁴, M. Yoshimoto⁴, Y. Wang¹⁶, and Z. Xiao¹⁶ for the SAKURA Collaboration

¹Center for Nuclear Study, the University of Tokyo, Hirosawa 2-1, Wako, 351-0198, Saitama, Japan

²Institute for Rare Isotope Science, Institute for Basic Science, Daejeon 34000, Korea

³Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare, Via G. Acitelli 22, L'Aquila—Localita Assergi, 67100, AQ, Italy

⁴RIKEN Nishina Center, Hirosawa 2-1, Wako, 351-0198, Saitama, Japan

⁵Center for Exotic Nuclear Studies, Institute of Basic Science, Expo-ro 55, Yuseong-gu, 34126, Daejeon, Republic of Korea

⁶Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea

⁷Dipartimento di Fisica e Astronomia "E. Majorana", University of Catania, Via S. Sofia 62, 95125 Catania, Italy

⁸Laboratori Nazionali del Sud - Istituto Nazionale di Fisica Nucleare, Via S. Sofia 62, 95123 Catania, Italy

⁹Graduate School of Science, Kyoto University, Yoshida-honmachi, Sakyo, Kyoto 606-8501, Japan

¹⁰Department of Physics, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan

¹¹Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

¹²Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki, 567-0047, Osaka, Japan

¹³INFN Sezione di Perugia, Via A. Pascoli, 06123 Perugia, Italy

¹⁴Facoltà di Ingegneria e Architettura, Università degli Studi di Enna, Italy

¹⁵Department of Physics, Kyushu University, Motoooka 744, Nishi, Fukuoka, 819-0395, Fukuoka, Japan

¹⁶Tsinghua University, Beijing 100084, China

Abstract. The r -process is responsible for the production of more than half of the elements heavier than iron, but the physical conditions and astronomical sites for r -process nucleosynthesis have not been determined. Nuclear properties of radioactive isotopes near ^{132}Sn has large impacts on the r -process elemental abundance. A drastic decrease of the neutron capture rate is expected beyond $N = 82$, but due to a lack of experimental data, there are large uncertainties in neutron capture rates, which result in a large variation in the final elemental abundance of r -process. In particular, evaluating the compound nucleus reaction is theoretically challenging. At the OEDO-SHARAQ beamline in RIKEN RIBF, a surrogate reaction technique was developed to study the decay of neutron-capture-induced compound nucleus by experimentally determining the γ -emission probability, in which the reactions heavy residues are identified with the SHARAQ spectrometer, and the γ -emission probability is obtained based on the number of heavy residues with increased neutron number. A $^{130}\text{Sn}(d,p)$ experiment was conducted in inverse kinematics with this method to identify the γ -emission probabilities of the neutron unbound states in ^{131}Sn . The obtained γ -emission probabilities were used to deduce the neutron capture cross-section of ^{130}Sn using the surrogate ratio method.

1 Introduction

The rapid neutron capture process, r -process, is an important pillar of stellar nucleosynthesis, which is responsible for the production of more than half of the elements heavier than iron. The idea of r -process was first suggested more than 50 years ago [1], but the physical conditions and astronomical sites for r -process have not been determined yet because of the lack of experimental data for the properties of involving neutron-rich exotic nuclei, such as nu-

clear masses, β -decay half lives, and neutron capture rates. We targeted the neutron capture rates among them.

There are two main mechanisms for the neutron capture process in r -process nucleosynthesis: the compound nucleus (CN) reaction and the direct radiative capture (DRC). The CN reaction is usually dominant over the DRC except for the cases in which level densities around one neutron separation energy (S_{1n}) become fairly low ($< 10^{-1}$ MeV) [2]. The CN neutron capture is a multi-step process where free neutrons colliding with a target nucleus form unbound excited states. The CN neutron cap-

*e-mail: shbae@cns.s.u-tokyo.ac.jp

ture rates can usually be determined with the knowledge of γ -emission probabilities of the neutron unbound states. Experimental efforts to identify the γ -emission probabilities usually suffered from the low γ -emission probabilities and the low γ -ray detection efficiencies.

One of the critical isotopic regions in r -process is the region near ^{132}Sn , which has the neutron magicity with 82 neutrons. A drastic decrease of the neutron capture rate when crossing the neutron magic number is expected due to the large energy gap after the shell closure. Due to a lack of experimental data, r -process models rely on extrapolations towards $N = 82$ region based on theoretical calculations. This results in large uncertainties of estimated neutron capture rates and large variances on the modeled r -process elemental abundances [3].

At the Optimized Energy-Degrading Optics (OEDO) beamline [4, 5] in RIKEN Radioactive Ion Beam Factory (RIBF) [6, 7], an alternative method was employed to identify experimental γ -emission probability whereby the reacted heavy residues are identified with the SHARAQ spectrometer downstream of the OEDO beamline [8], and the γ -emission probability is obtained from the ratio of heavy residues with one-neutron increment to the total heavy residue yield [9]. The practical difficulties of γ -emission probability determination from γ -ray detection can be detoured in this way. The $^{130}\text{Sn}(d,p)$ experiment was conducted with this method to identify the γ -emission probabilities of the neutron unbound states in ^{131}Sn and reduce the uncertainties in r -process model predictions. The experimental details and the analysis results are summarized in the following sections.

2 Experiment

The experiment was performed at the OEDO-SHARAQ beamline which is located downstream of BigRIPS separator in RIKEN RIBF. The secondary ^{130}Sn beam was produced from the in-flight fission of 345 MeV/u ^{238}U beam impinging on 3-mm-thick rotating ^9Be target at the BigRIPS F0 focal plane. The intensity of ^{130}Sn was around 10^5 pps, and the beam was delivered to the FE9 of OEDO beamline [4] where the kinetic energy of ^{130}Sn beam was degraded from approximately 170 MeV/u to 23 MeV/u using angle-tuneable wedge-shaped Al degrader [10]. The dispersion of degraded beam energy was 5.5%. The ^{130}Sn ions bombarded a CD_2 target of $287 \mu\text{g}/\text{cm}^2$ thickness. The upstream side of the target was surrounded with TiNA; an array of Si and CsI(Tl) detectors to measure the recoil protons [11] covering about $100 - 170$ degrees of lab angle. The half of the SHARAQ spectrometer was utilized to separate heavy reaction residues with different mass-to-charge ratio (A/Q). The strip-readout PPACs (SR-PPACs) [12] were installed at FE9, FE12 and S1 focal planes [4, 5] to measure the timing and position of traveling heavy ions. Separately, $^{130}\text{Te}(d,p)$ and $^{124}\text{Sn}(d,p)$ reactions were measured as reference isotopes for application of the surrogate ratio method [13] and validation of the surrogate ratio method, respectively. The schematic drawing of the experimental configuration is displayed in Fig. 1

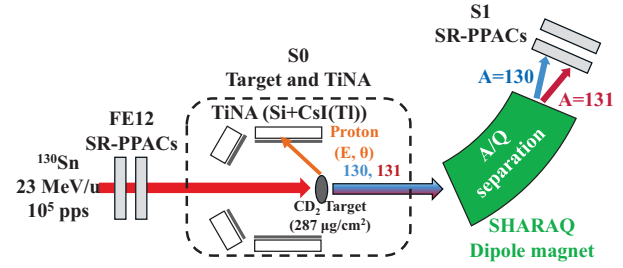


Figure 1. A schematic overview of the experimental setup after the FE12 focal plane. The TiNA array and target were installed in the vacuum chamber at the S0 focal plane, and the SHARAQ dipole magnet is located downstream of S0

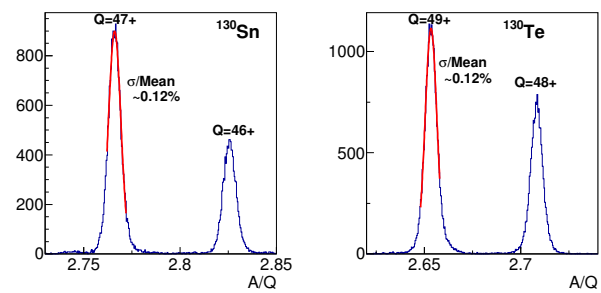


Figure 2. The optimized A/Q distributions from optics run for ^{130}Sn (left) and ^{130}Te (right) without CD_2 target. The Li-like and Be-like peaks are shown.

3 Analysis and Results

The designated ions among other secondary beam ions were identified based on the time-of-flight (TOF) from the F3 focal plane of BigRIPS beamline to FE9 and the x-position at FE9 SR-PPACs. Further A/Q separation of heavy ions after the (d,p) reaction was established based on the TOF from FE9 to FE12 and from FE12 to S1, and the positions and angles measured at FE9, FE12 and S1 focal plane by the SR-PPACs. Polynomial terms up to third order, formed by the products of measured angular and positional data were considered in optimization of A/Q determination. The conjugate gradient method [14] was implemented to minimize the variance of peaks in A/Q distribution. The resulting A/Q resolution in σ was around 0.12% of the mean value for Li-like ^{130}Sn and ^{130}Te ions as shown in Fig. 2. The A/Q values of Li-like ^{130}Sn and ^{130}Te differ from the $A = 130$ values by more than 6σ .

The excitation energy of the compound nucleus was obtained considering the energy-momentum conservation based on the energies and momenta of the incident beams and detected recoil protons. When the excitation energy was combined with the optimized A/Q values, clear transitions in A/Q values can be seen where the excitation energy is S_{1n} or S_{2n} for both Sn and Te isotopes as shown in Fig. 3. The $A = 131$ isotopes are dominant below the S_{1n} , and $A = 130$ isotopes appear and become dominant above S_{1n} . Above S_{2n} , $A = 129$ components start to appear. The number ratio of $A = 131$ isotopes to the sum

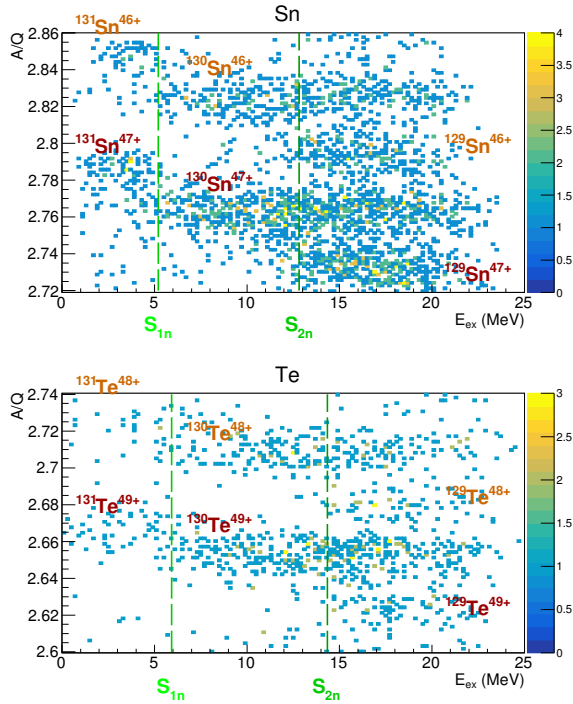


Figure 3. The preliminary A/Q versus excitation energy distribution for Sn and Te isotopes. The sudden change of A/Q values at the one and two neutron separation energies (S_{1n}, S_{2n}) are clearly seen.

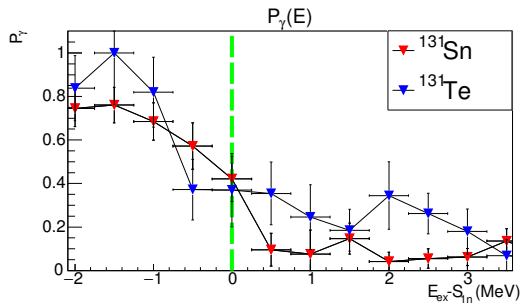


Figure 4. The preliminary results on the γ -emission probability, P_γ , of ^{131}Sn and ^{131}Te . The energy binning is only considered in the x-axis error bars. The y-axis error bars represent statistical uncertainties, which are large due to low statistics.

of $A = 130, 131$ isotopes was taken as the γ -emission probabilities. The obtained γ -emission probabilities of both isotopes along the excitation energy is displayed in Fig. 4. The γ -emission probability decreased crossing the S_{1n} . The uncertainties in x-axis are from the integrated energy range, but the resolution of excitation energy is not included. The statistical uncertainties are depicted as error bars along y-axis, which are relatively large due to the low statistics.

The surrogate ratio method [13] was implemented to obtain preliminary neutron capture cross-section of ^{130}Sn . In the surrogate ratio method, the neutron capture cross-section can be deduced by scaling the known neutron

cross-section of the reference isotope, ^{130}Te [15], with the ratio of compound nucleus formation cross-sections in the neutron capture reactions, and the ratio of measured γ -emission probabilities. The preliminary cross-sections were consistent to the theoretical values calculated with TALYS within the statistical uncertainties [16]. However, the surrogate ratio method basically assumes Weisskopf-Ewing approximation in which the γ -emission strength is independent of the spin-parities of unbound states [13]. Ratkiewicz *et al.* demonstrated that there can be discrepancies between experimental neutron capture cross-sections and the results from surrogate ratio method while the absolute surrogate method [13], in which the spin-parity distribution of the unbound intermediary in (d,p) and neutron capture reactions are considered, can give consistent neutron capture cross-sections [17]. To address this issue, we will apply the absolute surrogate method for ^{130}Sn as a next step. We will also test the validity of surrogate ratio method using ^{124}Sn which was another reference isotope in the previous experiment. ^{124}Sn is a stable isotope with a known experimental neutron capture cross-section [18] which will be compared with the outcome of our surrogate ratio method.

4 Summary

The $^{130}\text{Sn}(d,p)$ reaction measurement was conducted at OEDO-SHARAQ beamline to study the neutron capture rate in the second waiting point of r -process, which can be critical to the r -process nucleosynthesis. The clear transition of mass numbers of heavy reaction residues at neutron separation energies was identified both for Sn and Te isotopes. The γ -emission probabilities of the two isotopes were obtained from the ratio of heavy residues with different masses. The surrogate ratio method was applied to deduce preliminary neutron capture cross-section of ^{130}Sn . The known neutron capture cross-sections of the reference isotope, ^{130}Te and the obtained γ -emission probabilities were used for the surrogate ratio method. The result was consistent to the theoretical calculation using TALYS, but the limitation of surrogate ratio method necessitates the application of absolute surrogate method. The absolute surrogate method for ^{130}Sn is in progress, and the validation of surrogate ratio method through analysis on the ^{124}Sn data will follow.

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