PoS PROCEEDINGS OF SCIENCE

Neutron transfer reactions with tin beams and r-process nucleosynthesis

J. A. Cizewski[*1], B. Manning [1], K. L. Jones [2], R. L. Kozub [3], S. Ahn [2], G. Arbanas[4], D. W. Bardayan [5], J. C. Blackmon [6], K. Y. Chae [5,7], K. A. Chipps [8], S. Hardy [1,9], R. Hatarik [1], M. E. Howard [1], R. Kapler [2], J. F. Liang [5], M. Matos [6], B. H. Moazen [2], C. D. Nesaraja [5], F. M. Nunes [10], P. D. O'Malley[1], S. D. Pain [5], W. A. Peters [11], S. T. Pittman [2], A. Ratkiewicz [1], K. T. Schmitt[2,5], D. Shapira [5], M. S. Smith [5]

[1]*Department of Physics and Astronomy, Rutgers University, New Brunswick, NJ 08903, USA*
[2]*Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA*
[3]*Department of Physics, Tennessee Technological University, Cookeville, TN 38505, USA*
[4]*Reactor and Nuclear Systems Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[5]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[6]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA*
[7]*Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea*
[8]*Department of Physics, Colorado School of Mines, Golden, CO 80401, USA*
[9]*Department of Physics, University of Surrey, Guilford, Surrey, GU2 7XH, United Kingdom*
[10]*Department of Physics and Astronomy, Michigan State University & National Superconducting Cyclotron Laboratory, East Lansing, MI 48824, USA*
[11]*Oak Ridge Associated Universities, Oak Ridge, TN 37830, USA*
E-mail: `cizewski@rutgers.edu`

Uncertainties in neutron capture rates can affect the predictions of abundances in r-process nucleosynthesis because neutron capture can be important at late times. To probe the direct component of neutron capture reactions, we have recently completed measurements of the neutron transfer (d,p) reaction with beams of ^{126,128}Sn and the stable ^{124}Sn. These studies complete the systematics of (d,p) reactions on neutron-rich even-mass Sn isotopes, following the previous work with ^{130,132}Sn beams. These Sn(d,p) studies are used to map the evolution of shell structure away from stability and to deduce direct neutron capture rates.

XII International Symposium on Nuclei in the Cosmos
August 5-12, 2012
Cairns, Australia

1.Introduction

About one half of the elements heavier than iron are synthesized in the r or rapid neutron capture process that occurs in explosive environments such as supernova explosions or mergers of neutron stars. While the final r-process abundances depend primarily on the neutron densities and temperatures during (n,γ)-(γ,n) equilibrium, uncertainties in neutron capture rates can affect the predictions of abundances during freeze out from the r-process at late times. Recent studies by Beun, Surman and colleagues [1,2] have noted that a factor of ten increase in certain cross sections, such as ^{130}Sn(n,γ), can change by almost 20% calculated global r-process abundances in some r-process models across a wide mass range. In the region near ^{130}Sn both direct and statistical, compound nuclear (n,γ) processes are expected to be important [3]. Measurements of the neutron spectroscopic strengths constrain direct neutron capture rates, for which predictions [4] have varied by as much as 3 orders of magnitude for ^{130}Sn. This manuscript reports on recent measurements of Sn(d,p) reactions with unstable beams of ^{126,128,130,132}Sn.

2. Experimental techniques

Neutron transfer reactions have been measured in inverse kinematics with radioactive ion beams of ^{132,130,128,126}Sn and stable ^{124}Sn at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory. The beams interacted with CD_2 targets and reaction protons were measured in arrays of position-sensitive silicon-strip detectors. The ^{132,130}Sn studies used an early implementation of the Oak Ridge Rutgers University Barrel Array (ORRUBA) [5] that consists of silicon strip detectors, each 7.5 cm in length with four 1-cm wide resistive strips to provide position information. These first studies have been published [6,7]. More recently, highly segmented SuperORRUBA detectors have been developed with 64 1.2-mm x 4-cm strips on the front side, and four orthogonal 7.5 cm x 1-cm strips on the backside, as described in these proceedings [8].

The ^{126,128}Sn(d,p) reaction studies [9] used six SuperORRUBA detectors at back angles of 90°-125° complemented by six detectors from the SIlicon Detector ArRay (SIDAR) [10] at very backward angles from 125° to 160°. In addition, two SuperORRUBA silicon detectors covered angles from 67° to 90° to measure elastically scattered deuterons for beam normalization. In the ^{126,128}Sn(d,p) studies, heavy reaction products were measured in an ionization chamber at 0° and in coincidence with reaction protons. Examples of proton energy vs. angle histograms and Q-value spectra obtained with the SuperORRUBA detectors are displayed in Figs. 1 and 2, respectively.

3. Experimental results and direct neutron capture cross sections

A summary of the energy levels populated in the ^{132,130}Sn(d,p) studies and combined with preliminary results from the ^{126,128}Sn(d,p) measurements is presented in Table 1. In the ^{132}Sn(d,p) study [6] the single-neutron excitations of $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$ and $2f_{5/2}$ above the N=82 closed shell are populated in ^{133}Sn. The $7/2^-$ and $3/2^-$ spin and parity assignments to ground and first excited states in ^{133}Sn are robust, while candidates for the $1/2^-$ and $5/2^-$ states are more tentative.

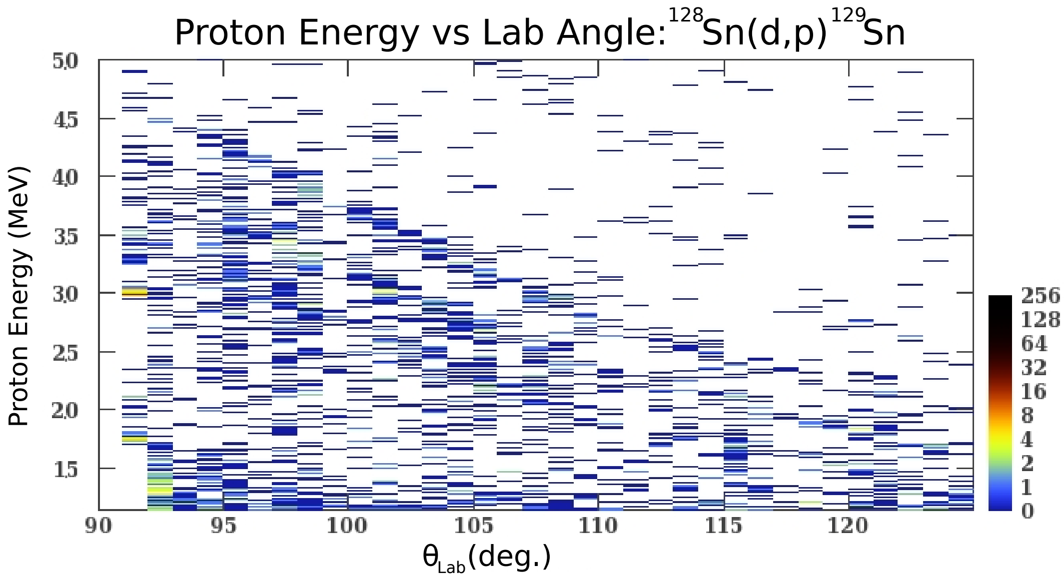

Figure 1. (color online) Proton energy in MeV as a function of laboratory angle for the ^{128}Sn(d,p) reaction study at HRIBF. The three groups correspond to excitations in ^{129}Sn above the N=82 gap, the candidates for the $2f_{7/2}$, $3p_{3/2}$ and $3p_{1/2}$ configurations. Adopted from Ref. [9].

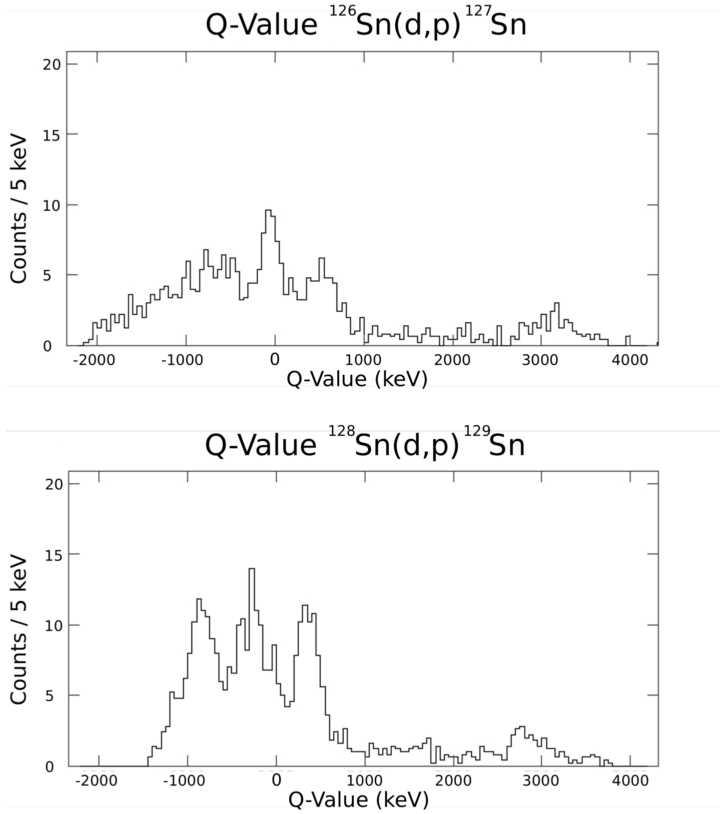

Figure 2. Preliminary Q-value spectra from six SuperORRUBA detectors for the (top) ^{126}Sn and (bottom) ^{128}Sn (d,p) reaction studies at HRIBF. Adopted from Ref. [9].

For all four of the states populated in ^{133}Sn the spectroscopic strengths are consistent with unity, assuming all of the spin-parity assignments. The ^{130}Sn(d,p) spectrum is remarkably similar to that for ^{132}Sn(d,p), with all of the observed strength populating configurations above the N=82 neutron shell gap. Similarly, the ^{126,128}Sn(d,p) reactions predominantly populate excitations above the N=82 shell gap, with candidates for the $2f_{7/2}$ and $3p_{3/2}$ states in ^{127,129}Sn at similar excitation energies to their counterparts in ^{131}Sn. The analysis of the ^{126,128}Sn(d,p) data is ongoing and will be combined with ^{126,128}Sn(^{9}Be,^{8}Be γ) studies to reduce uncertainties in the excitation energies, as well as help to confirm spin-parity assignments.

Table 1. Summary of ^{133,131,129,127,125}Sn excitations above the N=82 shell gap populated in (d,p) reaction studies in inverse kinematics

	$E_x(7/2^-)$ (keV) ($2f_{7/2}$)	$E_x(3/2^-)$ (keV) ($3p_{3/2}$)	$E_x(1/2^-)$ (keV) ($3p_{1/2}$)	$E_x(5/2^-)$ (keV) ($2f_{5/2}$)
^{133}Sn	0	854	1363	2005
^{131}Sn	2628	3404	3986	4655
^{129}Sn*	≈2800	≈3400	≈4000	
^{127}Sn*	≈2800	≈3400		
^{125}Sn*	≈2800	≈3500	≈4000	

Energy uncertainties for A<132 isotopes are ≈50 keV. The preliminary results for the lighter isotopes (*) benefitted from particle-gamma coincidences to support identification of the states. Results taken from Refs. [6,7,9]. The $2f_{7/2}$ $7/2^-$ state in ^{125}Sn has been previously observed at E_x=2798 keV [11].

The work in Ref. [4] summarized the predictions for the ^{130}Sn direct (n,γ) cross sections, that ranged over three orders of magnitude. The spread in direct capture cross section values came from several mass model calculations, as well as reflecting uncertainties in the energies of the $3p_{3/2}$ and $3p_{1/2}$ states in ^{131}Sn, which some models had predicted to be unbound. The ^{130}Sn(d,p) measurements not only demonstrate that the $3p_{3/2}$ and $3p_{1/2}$ configurations in ^{131}Sn are bound, but the measured spectroscopic strengths, that are consistent with unity, also constrain direct neutron capture calculations.

Direct capture calculations include the semi-direct process that proceeds via the giant dipole resonance. The direct-semi-direct neutron capture cross-section calculations are summarized in Fig. 3; details of the calculations are discussed in Ref. [7]. The results show that direct $3p_{3/2}$ and $3p_{1/2}$ neutron captures dominate the calculated Maxwellian-averaged cross section, in particular at the Gamow-window energy of 30 keV. These calculations, constrained by experiment, considerably reduce the uncertainties in direct (n,γ) cross sections at neutron energies important for r-process nucleosynthesis.

However, direct (n,γ) is only a part of the total (n,γ) cross section on ^{130}Sn. For this nucleus, compound nuclear processes may be stronger, as predicted by Ref. [3]. Alternatively, it is possible that the level density near the N=82 shell closure and at the energy of the Gamow window may be too small for such processes to dominate [7]. Therefore, to further understand the (n,γ) cross sections, additional information regarding the compound nuclear component is needed. While the formation of the compound nucleus can be calculated with optical models, there are significant uncertainties in the decay of the compound nucleus, which depends upon level densities and gamma-ray strength functions. To inform (n,γ) cross sections, and in particular, the decay of the compound nucleus, on short-lived nuclei requires a validated surrogate of the desired reaction [12]. A promising reaction is (d,pγ) which has been shown [13] to reproduce ratios of measured [14] (n,γ) cross sections on ^{171,173}Yb when the side-feeding intensities of the low-lying gamma-ray transitions are used. The (d,p) reaction is a good candidate for a surrogate (n,γ) reaction because it brings in relatively low angular momentum and the reaction protons at forward center-of-mass angles are concentrated at back angles in the laboratory when measured in inverse kinematics with radioactive ion beams. The techniques to measure (d,pγ) reactions in inverse kinematics include efforts [15] to couple the ORRUBA array of position-sensitive detectors to the Gammasphere array of Compton-suppressed HPGe detectors at Argonne National Laboratory.

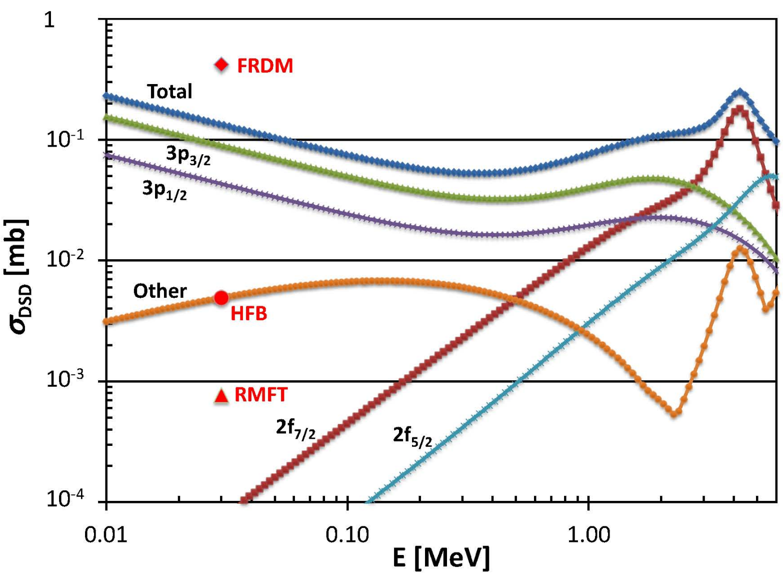

Figure 3. (color online) Direct-semi-direct neutron capture cross sections as a function of neutron energy on ^{130}Sn for single-neutron excitations. The calculations from Ref. [7] are compared to the earlier study of Ref. [4] with FRDM, HFB, and RMFT mass models at E_n=30 keV.

4. Summary

Uncertainties in neutron capture near the r-process path nucleus ^{132}Sn during freeze out from the r process have been predicted to affect r-process abundances [1,2]. To inform the spectroscopic properties of these nuclei, the (d,p) reaction has been measured with radioactive ion beams of ^{126,128,130,132}Sn and stable ^{124}Sn. The reactions predominantly populate neutron configurations above the N=82 shell closure, including the $3p_{3/2}$ and $3p_{1/2}$ states important in direct neutron capture. The spectroscopic properties of ^{131}Sn have been used to constrain direct neutron capture cross sections with ^{130}Sn. Future studies with the (d,pγ) reaction show promise of informing the statistical component of (n,γ) cross sections.

References

[1] J. Beun et al., *J. Phys. G* **36** (2009) 025201.

[2] R. Surman, J. Beun, G.C. Mclaughlin, W.R. Hix, *Phys. Rev. C* **79** (2009) 045809.

[3] S. Chiba et al., *Phys. Rev. C* **77** (2008) 015809.

[4] T. Rauscher et al., *Phys. Rev. C* **57** (1998) 2031.

[5] S.D. Pain et al., *Nucl. Instr. Meth. B* **261** (2007) 1122.

[6] K.L. Jones et al., *Nature* **465** 09048 (2010) and *Phys. Rev. C* **84** (2011) 034601.

[7] R. L. Kozub et al., *Phys. Rev. Lett.* **109**, 172501(2012).

[8] D.W. Bardayan et al., these proceedings *Proc. of Science*, **NIC XII** and to be published.

[9] B. Manning et al., CAARI 2012 *AIP Conference Proceedings* (in press).

[10] D. W. Bardayan et al., *Phys. Rev. C* **63** (2001) 065802.

[11] I. Tomandl et al., *Phys. Rev. C* **83** (2011) 044326.

[12] J.E. Escher et al., *Rev. Mod. Phys.* **84** (2012) 353.

[13] R. Hatarik, et al., *Phys. Rev. C* **81** (2010) 011602(R).

[14] K. Wisshak et al., *Phys. Rev. C* **61** (2000) 065801.

[15] A. Ratkiewicz et al., CAARI *AIP Conference Proceedings* (in press).