THE UNIVERSITY of TENNESSEE
KNOXVILLE

Experimental Low-Energy Nuclear Physics Group,
University of Tennessee
Continuation of the Outstanding Junior Investigator Award,
Dr. Kate L. Jones
DE-SC0001174
December 18, 2014

GROUP MEMBERS PAID BY AWARD AT VARIOUS TIMES

Faculty (tenured/tenure track): K.L. Jones, R. Surman (Union College, currently Notre Dame University)
Post-docs: A. Bey
Graduate Students: A. Ayres, M. Park, C. Thornsberry
Undergraduate Students: K. Hasse, A. Sachs, R. Sinclair

PHYSICS ADDRESSED/GOALS:

- Study of the structure of exotic nuclei via the one-neutron knockout reaction on medium-mass fragmentation beams.
- Low- and high-spin structure of exotic nuclei via transfer reactions in coincidence with gamma rays.
- Sensitivity studies for r-process nucleosynthesis.

ACCOMPLISHMENTS/HIGHLIGHTS (January 2010 – August, 2014):

- Precise measurement of 1p-2h states in ^{131}Sn with gamma rays confirms similarity with single-particle states in ^{133}Sn.
- Population of high-spin states in ^{131}Sn via a transfer reaction on ^{130}Sn^{m}.

- Determination of the J^{π} of ^{105}Sn and ^{107}Sn and study of the ground states of ^{106}Sn and ^{108}Sn via the one-neutron knockout reaction.
- Fabrication of the GODDESS chamber to be installed at GAMMASPHERE.
- Identification of the most influential neutron-capture rates in a weak r-process

ABSTRACT Direct reactions are powerful probes for studying the atomic nucleus. Modern direct reaction studies are illuminating both the fundamental nature of the nucleus and its role in nucleosynthetic processes occurring in the cosmos. This report covers experiments using knockout reactions on neutron-deficient fragmentation beams, transfer reactions on fission fragment beams, and theoretical sensitivity studies relating to the astrophysical r-process. Results from experiments on ^{108,106}Sn at the NSCL, and on ^{131}Sn at HRIBF are presented as well as the results from the nucleosynthesis study.

NEUTRON KNOCKOUT REACTIONS ON BEAMS OF ^{108,106}Sn Characterizing the nature of single-particle states outside of double shell closures is essential to a fundamental understanding of nuclear structure. This is especially true for those doubly magic nuclei lying far from stability that are much less studied and where the shell closures influence nucleosynthetic pathways. There is experimental and theoretical evidence for a reversal of the spins of the ground and excited states in ^{101}Sn compared to ^{103}Sn coming from the near degeneracy of the $d_{5/2}$ and $g_{7/2}$ orbitals and strong pairing for the $(g_{7/2})^2$ configuration. Owing to low production rates there is a lack of spectroscopic information and until recently, there were no firm J^{π} assignments for odd-mass tin isotopes lighter than ^{109}Sn.

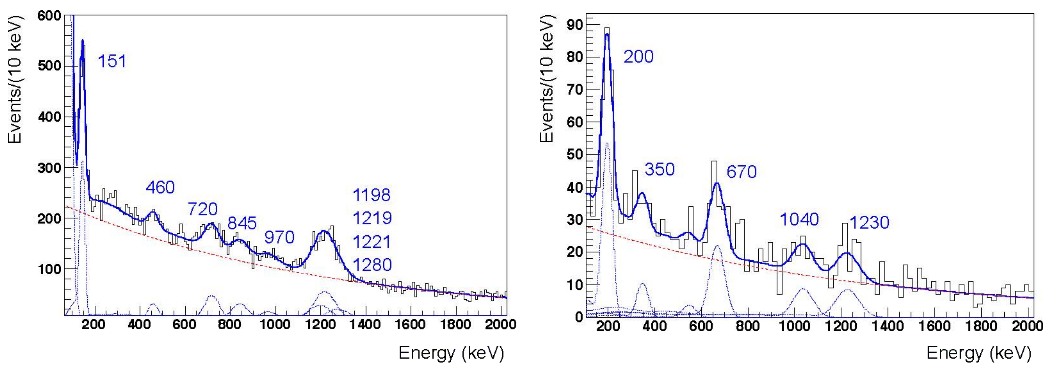

Fig 1. Doppler-corrected γ -ray spectra for ^{107}Sn (left) and ^{105}Sn (right) from the one-neutron knockout reaction on ^{108}Sn and ^{106}Sn. The 150-keV and the 200-keV γ rays coming from the deexcitation of the first excited states are clearly observed. The higher-lying γ rays originate from knocking out more deeply-bound neutrons from below the N=50 shell gap, which then cascade through intermediate states as revealed by γ- γ coincidences (not shown).

In 2011 we measured residues and γ rays emerging from reactions of ^{108,106}Sn beams on a ^{9}Be target. The experiment used the NSCL's high-efficiency γ ray-detector array CAESAR in conjunction with the S800 spectrograph for coincident particle γ ray spectroscopy. The reaction residues, identified from their Bρ and known γ rays, were detected in the S800 focal plane detector system allowing momentum measurements. The momentum distributions reflect the ℓ-value of the knocked-out neutron, thereby characterizing the final state, tagged by γ rays (Fig. 1) measured in coincidence. The momentum distributions (Fig. 2) clearly discriminate between ℓ=2 and ℓ= 4 knockout. Cross sections have been extracted for one-neutron knockout. Inclusive cross-sections of 144 ± 19 mb for ^{108}Sn to ^{107}Sn and 78 ± 21 mb for ^{106}Sn to ^{105}Sn were measured. Exclusive cross-sections, where information about the final state of the residual nucleus from measured γ rays, were extracted only from the

^{108}Sn beam data. A cross section for direct population of the first excited state of ^{107}Sn was measured as14 ± 4 mb. The high-energy γ rays from the knockout of deeply bound neutrons (below N = 50) could not be observed directly. However, a cross section for final states that decay through the multiplet of states at 1200 keV was found to be 59 ± 11 mb. Because of an incomplete gamma level scheme for ^{107}Sn, only an upper limit of the cross section for direct population of the ground state can be provided (<71mb).

These data have been presented at a number of conferences and are the subject of conference proceedings. The results for ^{106}Sn, which are limited by the level of statistics collected in just one day, are included in the conference proceedings for the Zakopane Conference on Nuclear Physics that will be published in Acta Physica Polonica in March 2015.

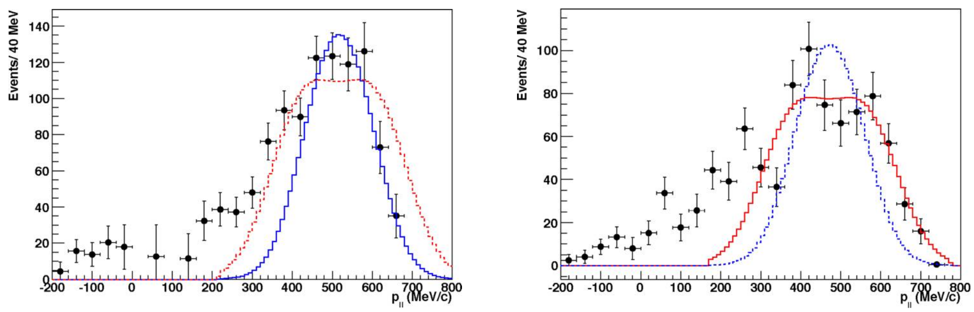

Fig 2. Momentum distributions for knockout from a ^{108}Sn beam to the ground state (first excited state) in ^{107}Sn are displayed in the left (right) panels. In blue the calculated momentum distribution of ^{107}Sn residues following the one-neutron knockout from ^{108}Sn assuming the knocked-out neutron is in the $d_{5/2}$ orbital; in red the calculated momentum distribution of ^{107}Sn residues assuming the knocked-out neutron is in the $g_{7/2}$ orbital.

GAMMA SPECTROSCOPY AROUND ^{132}Sn VIA TRANSFER REACTIONS. The ^{130}Sn(d,p) measurement, led by Ray Kozub of Tenn. Tech. revealed four neutron 1p-2h states from across the N=82 shell closure for the first time. These states are of interest for studying the evolution of single-particle structure around ^{132}Sn and neutron capture at late times in the astrophysical r-process. The (n,γ) cross-sections are extremely sensitive to the energies of the p-wave neutron states. Owing to the limited resolution of the measurement, and the non-observation of known states in ^{131}Sn that could have provided internal calibrations, the energy of the four states of interest had large uncertainties associated with them.

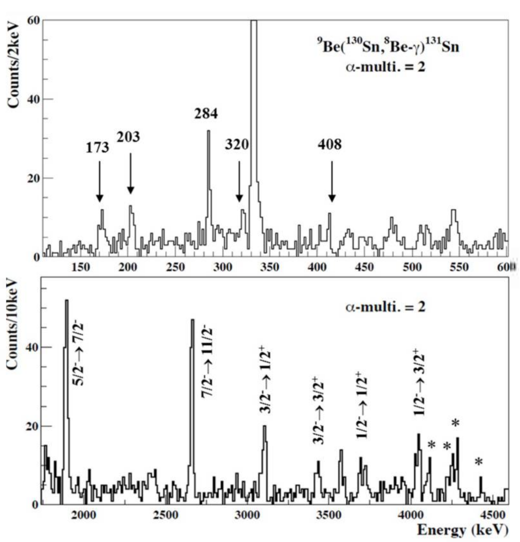

Fig. 3 Doppler-corrected γ ray spectra following the population of states via the ^{130}Sn(^{9}Be,^{8}Be) reaction in inverse kinematics. The upper panel shows low energy transitions between known high spin states. The lower panel shows the first γ ray measurements of 1p-2h states from above the N=82 shell closure in ^{131}Sn as well as high-energy transitions from the known high spin states, marked with a star.

In March 2012 the ^{130}Sn(^{9}Be,^{8}Be) reaction was used at the HRIBF to populate states in ^{131}Sn, and the subsequent γ rays were detected in the CLARION array. Clean reaction channel selection was possible by detecting two highly correlated α particles in HYBALL. The observed 1p-2h excitations in ^{131}Sn were found to be remarkably similar to their single-particle counterparts in ^{133}Sn, providing further evidence for the robustness of the doubly magic closure at ^{132}Sn.

In addition to γ rays from the four states from above N=82, a number of high-spin states, up to spin 19/2^{+}, were observed (see Figs. 3 and 4). The population of these states can be explained as transfer on the 7^{-} isomer ($T_{1/2}$=1.7 min.) component of the ^{130}Sn beam. There has been no experimental evidence of similar high-spin states being populated using the same reaction on beams of ^{132}Sn or ^{134}Te where the beams are known to only contain those isotopes in the ground state. The initial analysis of these data is complete, and the first publication is currently under revision before being submitted to PRC as a rapid comm.

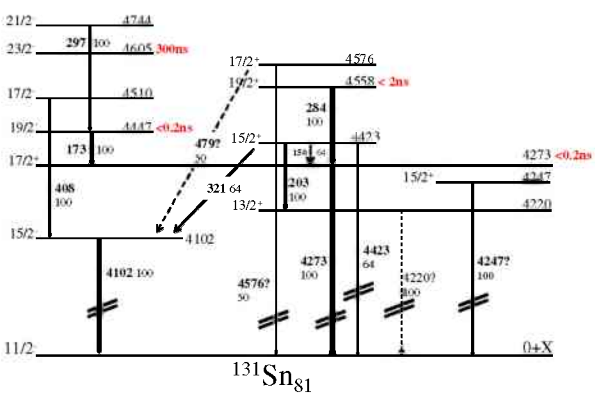

Fig. 4 Partial level scheme showing the decay of high-spin states in the E_x = 4 – 5 MeV range to the 11/2^{-} isomer in ^{131}Sn.

SENSITIVITY STUDIES FOR R-PROCESS NUCLEOSYNTHESIS We investigated the role neutron capture rates of nuclei in the *A*~80 region play on rapid neutron capture (r-process) nucleosynthesis. We found these capture rates to be influential primarily in the production of the *A*~80 r-process abundance peak nuclei, in a low entropy weak r-process. To identify the most important neutron capture rates for this process and study their mechanisms of influence, we ran a series of sensitivity studies. For each sensitivity study, we chose a baseline simulation, then varied a single neutron capture rate in the simulation by a factor of 100, repeated the simulation, and compared the resulting abundance patterns. We chose a wide range of potential weak r-process conditions as our baseline simulations and studied the impact of all of the capture rates in the *A*~80 region. We found that as the r-process falls out of equilibrium, changes in key capture rates can cause a shift in where the few remaining free neutrons are captured and thus modify the global weak r-process pattern. The nuclei with particularly influential capture rates that should be the target of future experiments are shown in Fig. 5.

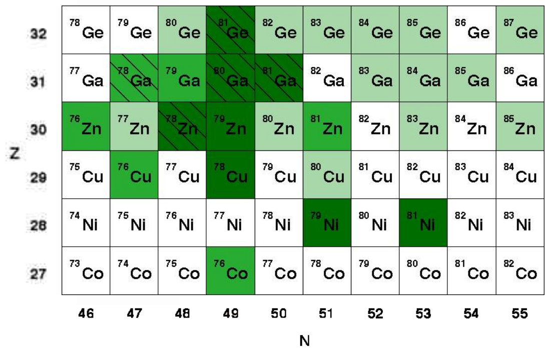

Figure 5: Shows the nuclei whose capture rates affect at least a 5-10% (lightest green), 10-15%, or >15% (darkest green) change to the overall *r*-process abundance pattern when increased by a factor of 100 over a baseline simulation. Hatchmarks indicate the nuclei whose capture rates affect at least a 5% change in ten or more simulations.

CURRENT STATUS The analyses for ^{107,105}Sn are essentially complete and the first publication is close to completion. It is expected that the manuscript will be submitted early in 2015. The one-, two-, and three-neutron knockout from ^{106}Cd has also been analyzed for comparison with the tin results, and a second publication is being drafted.

The UTK group submitted a proposal to the RIKEN PAC to measure neutron knockout reactions on beams of ^{104}Sn and ^{102}Sn, which will allow the assignment of the J^{π} of ^{101}Sn. This proposal was accepted with an A/B ranking, owing to the challenging nature of making these studies with such a weak beam.

The first results from the ^{131}Sn studies have been presented at a number of conferences and are the subject of a paper submitted to PRL. The manuscript is currently being revised for submission to PRC as a rapid communication. A new student, Sean Burcher, is starting to look at the data from reactions of ^{130}Sn on both the ^{9}Be target (the subject of the work by A. Bey) and on a ^{13}C target for intensity comparisons. Additionally, we will soon be working with the PAN Krakow group to compare our data on ^{131}Sn with theirs from fission taken with Gammasphere.

UTK is one of the lead institutions on GODDESS, the coupling of the silicon detector array ORRUBA to GAMMASPHERE. The chamber was largely fabricated in the UT physics department. GODDESS will be used in future measurements with transfer reactions where γ rays are measured in coincidence with charged particles for vastly improved energy resolution, as well as the possibility to observe γ cascades. In July 2013 GODDESS was installed for the first time in GAMMASPHERE. The GODDESS ion chamber has also been fabricated, partly at UT, and newly designed end cap detectors have arrived from MICRON and have been tested. The detector system is now complete and ready for the initial runs at ANL.

The group is collaborating on JENSA, a recycling gas jet target for transfer and astrophysically relevant measurements. A UTK student (funded externally) was located at MSU when JENSA was moved there in early 2014.

The UTK group will continue to work on transfer reaction experiments, including performing reaction calculations using TWOFNR and FRESCO in the analysis. The group, working closely with Filomena Nunes, has built up some expertise in DWBA and Adiabatic wave approximation (ADWA) calculations, and in testing the sensitivities to various inputs.

GRADUATE STUDENT AND POST-DOC TRACKING INFORMATION

TABLE 2: GRADUATE STUDENT TRACKING INFORMATION (Fall 2008 – Fall 2014)

Grad. Student Name	Advisor	Date joined the group	Graduation date	Degree (MS/PhD)	Present institution	Present Position
A. Ayres	K.L. Jones	Fall 2009	Spring 2014	PhD	IBM San Antonio	
M. Park	K.L. Jones	Fall 2012	Summer 2013	MS		
C. Thornsberry	K. L. Jones	Spring 2013	(2016)	(PhD)		
Externally supported						
R. Kapler	K. L. Jones	Fall 2007	Spring 2009	MS	TRU Waste Processing	Radiological Engineer
B. Moazen	K. L. Jones/ J. C. Blackmon	Fall 2006	Fall 2009	PhD	US Enrichment Company	Senior Scientist
K. Schmitt	K. L. Jones	Fall 2007	Fall 2011	PhD	ORTEC/ AMETEC	Process Engineer
S. Pittman	K. L. Jones/ D. Bardayan	Fall 2007	Fall 2011	PhD	LSU	Postdoc
S-H. Ahn	K. L. Jones/ D. Bardayan	Spring 2010	Summer 2013	PhD	NSCL	Postdoc
S. Munoz	K.L. Jones	Fall 2013	Fall 2014	MS		
P. Thompson	K. L. Jones/ D. Bardayan	Spring 2013	(2016)	(PhD)		
S. Burcher	K.L. Jones/ S.D. Pain	Fall 2014	(2018)	(PhD)		

Table 3: POSTDOCTORAL TRACKING INFORMATION (Fall 2008 – Spring 2013)

Post-doc Name	Advisor	Beginning Date	End Date	Present Institution	Present Position
A. Bey	K.L. Jones	Nov 2009	Sept 2012		

Bibliography

Letters (2012 – 2014)

1) *Neutron single particle structure in ^{131}Sn and direct neutron capture cross sections.*
R. L. Kozub et al, Phys. Rev. Lett. **109,** 172501 (2012).

2) *Halo Nucleus ^{11}Be: A Spectroscopic Study via Neutron Transfer.*
K. T. Schmitt et al. Phys. Rev. Lett. **108**, 192701 (2012).

3) *Doubly-Magic nature of ^{132}Sn and ^{208}Pb through lifetime and cross-section measurements*
J.M Allmond et al. Phys Rev. Lett. **112**, (2014).

Other refereed journals (2012 – 2014)

1) *^{26}Al + p elastic and inelastic scattering reactions and galactic abundances of ^{26}Al.*
S.T. Pittman et al. Phys. Rev. **C 85**, 065804 (2012).

2) *Searching for resonances in the unbound ^{6}Be nucleus by using a radioactive ^{7}Be beam.*
K.Y. Chae et al. Jour. Kor. Phys. Soc. **61**, 1786 (2012).

3) *^{19}Ne levels studied with the ^{18}Ne(d,n)^{19}Ne*(^{18}F+p) reaction*
A.S. Adekola et al. Phys. Rev. **C 85**, 037601 (2012).

4) *Low-energy structure of ^{66}Co and ^{68}Co populated through β decay*
S.N. Liddick et al. Phys. Rev. **C 85**, 014328 (2012).

5) *Low-energy level schemes of ^{66,68}Fe and inferred proton and neutron excitations across Z=28 and N=40*
S.N. Liddick et al. Phys. Rev. **C 87**, 014325 (2013).

6) *Transfer reaction experiments with radioactive beams: from halos to the r-process.*
K. L. Jones Phys. Scr. **152**, 014020 (2013).

7) *Reactions of a ^{10}Be beam on proton and deuteron targets*
K.T. Schmitt et al. Phys. Rev. **C 88**, 064612 (2013).

8) *Sensitivity studies for the weak r process: neutron capture rates*
R. Surman, M. Mumpower, R. Sinclair, K.L. Jones, W.R. Hix, and G.C. McLaughlin, AIP Advances **4**, 041008 (2014).

9) $2\pi 1\nu$ states populated in ^{135}Te from ^{9}Be-induced reactions with a ^{132}Sn beam
J.M Allmond et al. Phys Rev. **C 90**, 014322 (2014).

Conference Proceedings directly relevant to project (2012 – 2014)

1) *Neutron capture rates and r-process nucleosynthesis*
R. Surman, M. Mumpower, G.C. McLaughlin, R. Sinclair, W.R. Hix, K.L. Jones, Capture Gamma-Ray Spectroscopy and Related Topics - Proceedings of the 14th International Symposium, World Scientific (2013).

2) *Neutron Knockout on Beams of* $^{108,106}Sn$ *and* ^{106}Cd
G. Cerizza et al. "First International African Symposium on Exotic Nuclei" (2013) – Forthcoming publication World Scientific (January 2015)

3) *Neutron Knockout on Beams of* $^{108,106}Sn$ *and* ^{106}Cd
G. Cerizza et al. "Conference on Application of Accelerators in Research and Industry" (2014) – Forthcoming publication Physics Procedia

4) *Recent direct reaction experimental studies with radioactive tin beams*
K.L. Jones et al. "Zakopane Conference on Nuclear Physics 2014" Forthcoming publication in Acta Physica Polonica (March 2015).

Book Chapters

1) *Doubly-magic* ^{132}Sn
Kate L. Jones, McGraw-Hill Yearbook of Science and Technology, p64 -66 (2012).

Talks directly related to project (2012 – 2014)
1) *Nuclear Physics: A touch of magic*, Kate L. Jones, Southeast conference for Undergraduate Women in Physics, University of Tennessee, January 2012.

2) *Structure, Reactions, Astrophysics - Overlaps in Low-Energy Nuclear Physics*, K. L. Jones, Colloquium, Rutgers University, April 2012.

3) *Transfer reaction experiments: from halos to the r-process*, Kate L Jones, Nobel Symposium NS 152 – Physics with Radioactive Beam, 2012 June 2012, Gothenburg, Sweden.

4) *Structure, Reactions, Astrophysics - Overlaps in Low-Energy Nuclear Physics*, K. L. Jones, Colloquium, Vanderbilt University, August 2012.

5) *r-process: recent accomplishments, open questions and attainable goals,* Kate L. Jones and Rebecca Surman, Nuclear Astrophysics Town Meeting, Detroit, October 2012.

6) *Study of light tin isotopes via single-nucleon knockout reactions*, A. Ayres, Division of Nuclear Physics meeting, Newport Beach, California, October 2012.

7) *Transfer reaction experiments with fission fragments*, K. L. Jones, Fifth International Conference on Fission and Properties of Neutron-Rich Nuclei. Sanibel Island, FL, November 2012.

8) *Transfer reactions with fission fragments*, Kate L. Jones, 6th LACM-TORIJIN-JUSTIPEN workshop, Joint Institute for Heavy Ion Research, Oak Ridge, November 2012.

9) *Knockout Reactions with Light Tin Isotopes at the NSCL*, Giordano Cerizza, Stockpile Stewardship Academic Alliance Meeting, Lawrence Livermore National Lab, March 18 – 19, 2013.

10) *Study of light tin isotopes via single-neutron knockout reactions* Andrew Ayres, Division of Nuclear Physics Meeting, Denver, Colorado, April 2013.

11) *Star dust and atom smashers* Kate Jones, Pregame faculty showcase, University of Tennessee, September 2013.

12) *High resolution single-neutron transfer measurements in* ^{131}Sn Anissa Bey, XXIII Mazurian Lakes Conference on Physics, Piaski, Poland, September 2013.

12) *Nuclear structure around* ^{132}Sn *investigated with transfer reactions*, Kate Jones, Conference experience for undergraduate students invited talk Division of Nuclear Physics Meeting, Newport News, Virginia, October 2013.

13) *Neutron-knockout on beams of* $^{106,108}Sn$ Kate L. Jones Division of Nuclear Physics Meeting, Newport News, Virginia, October 2013.

14) *High resolution single-neutron transfer measurements in* ^{131}Sn Anissa Bey (Presented by Kate Jones) Division of Nuclear Physics Meeting, Newport News, Virginia, October 2013.

15) *Neutron-knockout reaction on a beam of* ^{106}Cd, Giordano Cerizza, Division of Nuclear Physics Meeting, Newport News, Virginia, October 2013.

16) *Neutron-knockout on beams of* $^{108,106}Sn$ *and* ^{106}Cd, Giordano Cerizza, International African Symposium on Exotic Nuclei, iThemba lab, Cape Town, South Africa, December 2013.

17) *Knockout reactions of* $^{108,106}Sn$ *and* ^{106}Cd *beams*, Giordano Cerizza, Rutgers University SSAA Center of Excellence Presentation, Los Alamos National Laboratory, March 2014.

18) *Cooking up the elements; nucleosynthesis in stars and stellar explosions* Dr. Kate Jones, SPS Zone 8 meeting, University of Tennessee, April 2014.

19) *The sensitivity of r-process nucleosynthesis to individual nuclear properties*, Rebecca Surman, American Physical Society April Meeting, Savannah, Georgia, April 2014.

20) *ORRUBA, VANDLE, HAGRiD the Cizewski triangle*, Kate Jones, Nuclear Symmetries and Stewardship Science: the research of Jolie Cizewski, Lawrence Berkeley National Laboratory, May 2014.

21) *Neutron-knockout on beams of ^{108,106}Sn and ^{106}Cd*, Giordano Cerizza, 23rd International Conference on the Application of Accelerators in Research and Industry (CAARI 2014), San Antonio, Texas, May 2014.

22) *Sensitivity studies for r-process nucleosynthesis*, Rebecca Surman, Advances in Radioactive Isotope Science (ARIS) 2014, Tokyo, Japan, June 2014.

23) *Neutron knockout on neutron-deficient beams*, Kate Jones, Direct Reactions with Exotic Beams, Darmstadt, Germany, June 2014.

24) *Recent direct reaction experimental studies with heavy-mass radioactive ion* beams, Kate Jones, Zakopane, Poland, September 2014.

25) *Spectroscopic studies close to ^{100}Sn*, Giordano Cerizza, Sunflower Workshop, University of Tokyo, Japan, September 2014.