PROCEEDINGS OF SCIENCE

PoS(NIC X)142

Neutron Transfer Measurements on Neutron-rich N=82 Nuclei

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Calculations of r-process nucleosynthesis rely significantly on nuclear structure models as input, which are not well tested in the neutron-rich regime, due to the paucity of experimental data on the majority of these nuclei. High quality radioactive beams have recently made possible the measurement of (d,p) reactions on unstable nuclei in inverse kinematics, which can yield information on the development of single-neutron structure away from stability in close proximity to suggested r-process paths. The Oak Ridge Rutgers University Barrel Array (ORRUBA) has been developed for the measurement of such reactions. An early partial implementation of ORRUBA has been utilized to measure the ^{132}Sn(d,p)^{133}Sn and ^{134}Te(d,p)^{135}Te reactions for the first time.

10th Symposium on Nuclei in the Cosmos
July 27 - August 1 2008
Mackinac Island, Michigan, USA

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1. Introduction

Neutron-induced nuclear reactions on unstable neutron-rich nuclei along r-process paths, especially near closed neutron shells, are thought to be important in determining the reaction flow as the environment cools, and therefore influence the final elemental abundances [1]. Due to the short lifetimes of the nuclei involved, direct measurements of neutron-capture cross sections are impractical. However, the development of radioactive beams is now enabling the first measurements of the single-particle structure of a limited set of these nuclei to be studied [2, 3]. In particular, the (d,p) reaction preferentially populates levels with low orbital angular momentum and with significant single-particle structure, which are of astrophysical interest [4], and can be performed in inverse kinematics on deuterated plastic targets [5].

Furthermore, the majority of nuclei involved in the r-process are beyond the reach of present facilities. Their masses (or, equivalently, neutron separation energies) are calculated globally and included in r-process codes. The measurement of single-particle structure on unstable nuclei provides an important benchmark of nuclear structure models away from stability, facilitating an improvement of effective interactions in such models and consequently improvement in the calculation of global masses.

2. ORRUBA

The performance of (d,p) reactions using heavy ion beams, incident on deuterated plastic targets, is complicated by the strongly inverse kinematics and the relatively weak intensities currently obtainable with radioactive beams. The inverse kinematics result in the forward peaks of the proton angular distributions (in the center of mass (CoM) system) being distributed over a significantly larger range of angles in the laboratory frame, backwards of around $\theta_{lab} = 90^{\circ}$. Consequently, a large solid-angular coverage is required for efficient measurement of the proton ejectiles. Furthermore, the large CoM to laboratory frame transformation also results in proton ejectiles with

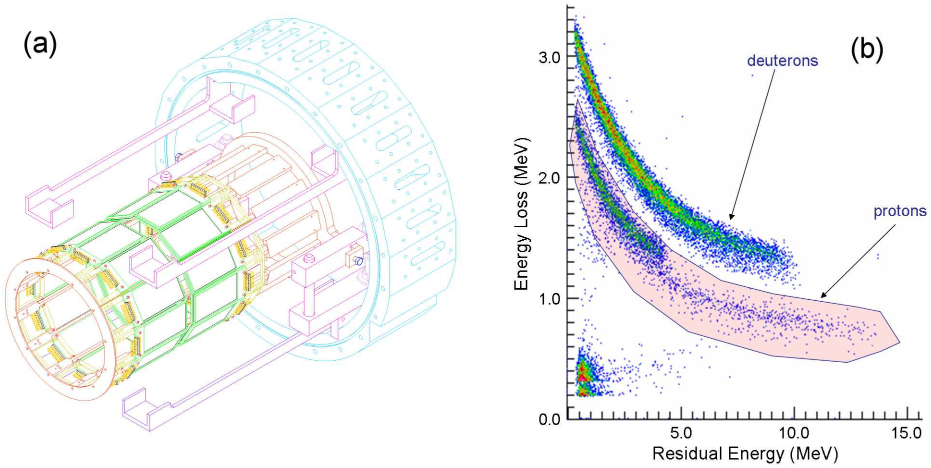

Figure 1: (color online). Panel (a): three dimensional representation of the Oak Ridge Rutgers University Barrel Array. Panel (b): particle-identification plot from a forward-angle ORRUBA telescope. The two loci correspond to protons and deuterons.

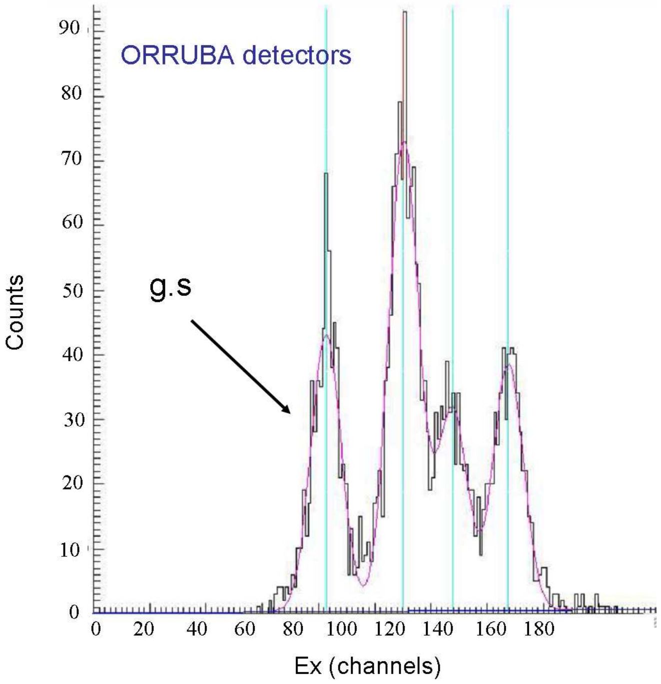

Figure 2: Preliminary excitation energy spectrum for ^{133}Sn, showing yield to the ground state and three excited states located at ~0.8 MeV, ~1.2 MeV and ~2.0 MeV (left-to-right).

energies that are strongly dependent on angle, requiring proton detection with a high resolution in energy and angle in order to achieve sufficient energy resolution in the CoM system.

The Oak Ridge Rutgers University Barrel Array (ORRUBA) [6] is a new array of silicon detectors, developed to meet the requirements of performing transfer reactions in inverse kinematics, with particular emphasis on the measurement of (d,p) reactions on nuclei in the $A \sim 130$ region. The array consists of two rings of silicon detectors, designed to operate typically with one ring forward and one backward of $\theta_{lab} = 90^\circ$, as illustrated in Figure 1 (a). The forward-angle ring consists of detector telescopes comprised of 65μm thick non-resistive silicon strip detectors for ΔE measurement. Position sensitive 1000μm thick resistive strip stopping detectors are employed as stopping detectors for the forward angle ring. The backward angle ring is comprised of a single layer of 500μm thick resistive strip detectors. In its standard configuration, the array gives approximately 80% coverage in azimuthal angle over the polar angular range 43° to 137°.

An example particle identification spectrum, taken from the ^{134}Te(d,p)^{135}Te measurement discussed below, is shown in Figure 1 (b). Clear separation is obtained between protons and deuterons. Elastically scattered carbon atoms from the CD$_2$ target had insufficient energy to reach the E detector, stopping in the ΔE layer. Consequently, these events do not appear in the plot and are excluded from all subsequent analysis, which requires a signal in the E detector.

3. Measurements of (d,p) around A~132

The recent measurements of (d,p) reactions at the Holifield Radioactive Ion Beam Facility (HRIBF) at ORNL have focused on the single-neutron structure around the doubly-magic ^{132}Sn

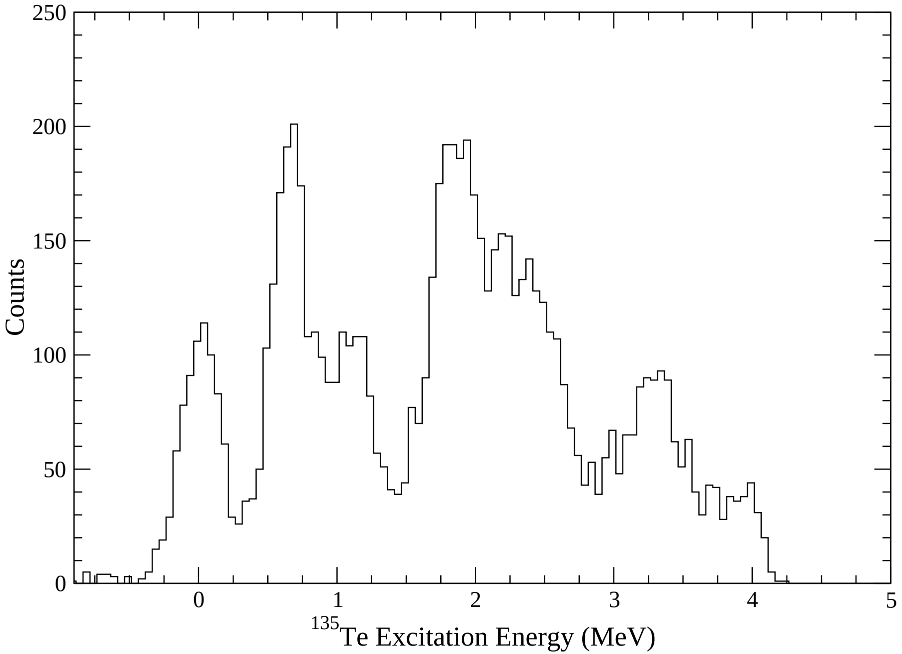

Figure 3: Preliminary excitation energy spectrum of ^{135}Te derived from data from forward-angle detectors.

nucleus. States in ^{133}Sn have been previously observed via the β-decay of ^{133}In [7] and the prompt γ decay of fission fragments of ^{248}Cf [8]. The population of states in ^{133}Sn through β-decay is predominantly those of higher spin, such as 7/2$^+$, 9/2$^+$ and 11/2$^+$. Consequently, there is a paucity of knowledge on the lower spin states, with a particular lack of convincing observation of the location of the 1/2$^-$ state corresponding to the $p_{1/2}$ strength, despite a highly tentative placement via a β decay measurement. Many more states in ^{135}Te, which lies two protons above the Z=50 shell closure of the Sn isotopes, have been observed in previous experiments [9], but the tentative J$^{\pi}$ assignments in the literature are from systematics and shell-model predictions, which are unconfirmed experimentally. The location of the single-particle strength, particularly the location of states with large p strength, is of particular interest as it can have a significant impact on direct and semi-direct neutron-capture cross sections at astrophysical energies, which are predicted to exceed compound capture cross sections in the region of the N=82 shell closure [4].

Three measurements of (d,p) reactions have been performed: ^{130}Sn(d,p)^{131}Sn, ^{132}Sn(d,p)^{133}Sn [10] and ^{134}Te(d,p)^{135}Te. The first experiment is reported elsewhere in these proceedings [11]; the latter two are reported here. All three measurements utilized a partial implementation of the ORRUBA and SIDAR detector arrays, covering angles forwards and backwards of $\theta_{lab} = 90^\circ$ with a total of 19 large area silicon detectors. For the Te measurement, a beam of ^{134}Te at 643 MeV ($\sim$4.7 MeV/nucleon) impinged on a 70 μg/cm^2 CD$_2$ target, rotated at 45° to provide an effective target thickness of $\sim$100 μg/cm^2. For the the Sn measurement, the beam energy was 630 MeV and a 100 μg/cm^2 CD$_2$ target was implemented, rotated at 60° to provide an effective target thickness of $\sim$200 μg/cm^2. For both measurements, at angles forwards of $\theta_{lab} = 90^\circ$ protons were detected in four ORRUBA telescopes, comprised of 65 μm thick ΔE detectors and 1000 μm thick resistive-strip detectors for measurement of residual energy and position. These telescopes subtended the angular range $\theta_{lab} = 57^\circ - 92^\circ$. Backwards of $\theta_{lab} = 90^\circ$, where particle identification is not required, a single layer of silicon was used in the form of six 1000 μm thick resistive-strip ORRUBA detectors and three annular SIDAR detectors in a half-lampshade configuration. These detectors covered the ranges $\theta_{lab} = 57^\circ - 92^\circ$ and $\theta_{lab} = 136^\circ - 162^\circ$ respectively.

A preliminary ^{133}Sn excitation energy spectrum containing data from the backward-angle ORRUBA detectors (Figure 2) shows the population of four resolved states below the neutron separation energy ~4 MeV. These peaks probably correspond to states with predominantly $^{132}\mathrm{Sn}\otimes\nu(f_{7/2})$, $^{132}\mathrm{Sn}\otimes\nu(p_{3/2})$, $^{132}\mathrm{Sn}\otimes\nu(p_{1/2})$ and $^{132}\mathrm{Sn}\otimes\nu(f_{5/2})$ configurations respectively. Angular distributions, provided by further analysis, are expected to provide conclusive confirmation of the transferred angular momentum, validating these assignments. The excitation energy spectrum obtained preliminarily for ^{135}Te from the forward-angle ORRUBA detectors (Figure 3) shows the population of a number of states up to ~4 MeV. The ground- and first-excited states are well resolved, and yield preliminary angular distributions which are compatible with $5/2^-$ and $3/2^-$ assignments. That more than four states are strongly populated, in contrast to the cases of the ^{132}Sn(d,p) and ^{130}Sn(d,p) experiments [11], is indicative that the single-particle strength is fragmented over more levels. This may potentially provide some *p*-strength at higher excitation energies, closer to the neutron separation energy, which would crucially affect the magnitude of the direct capture cross section at astrophysical energies. Further analysis is currently underway in order to extract yields and angular distributions for the states populated, providing spectroscopic information imperative to direct capture calculations.

4. Acknowledgements

This work was supported in part by the U.S. Department of Energy under contract numbers DE-FG52-03NA00143 (Rutgers, ORAU), DE-AC05-00OR22725 (ORNL), DE-FG02-96ER40955 (TTU), DE-FG02-96ER40990 (TTU), DE-FG03-93-ER40983 (UTK), DE-FG03-93ER40789 (Mines); the National Science Foundation; and the LDRD program of ORNL.

References

[1] R. Surman and J. Engel, Phys. Rev. C **64** (2001) 035801.

[2] J. S. Thomas *et al.*, Phys. Rev. C **71** (2005) 021302R.

[3] J. S. Thomas *et al.*, Phys. Rev. C **76** (2007) 044302.

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

[5] K.L. Jones *et al.*, Phys. Rev. C **70** (2004) 067602.

[6] S.D. Pain *et al.*, Nucl. Inst. Methods Phys. Res. B **261** (2007) 1122.

[7] P. Hoff *et al.*, Phys. Rev. Lett. **77** (1996) 1020.

[8] W. Urban *et al.*, Eur. Phys. J. **A5** (1999) 239.

[9] P. Hoff, B. Ekstrom, and B. Fogelberg, Z. Phys. A **332** (1989) 407.

[10] K.L. Jones *et al.*, Acta. Phys. Pol. **B38** (2007) 1205.

[11] R.L. Kozub *et al.*, these proceedings.