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Single-particle structure of neutron-rich nuclei

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Abstract. Neutron transfer (d,p) reactions have been measured with rare isotope beams of ^{132}Sn, ^{130}Sn and ^{134}Te accelerated to ≈4.5 MeV/u interacting with CD_2 targets. Reaction protons were detected in an early implementation of the ORRUBA array of position-sensitive silicon strip detectors. Neutron excitations in the $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$ and $2f_{5/2}$ orbitals were populated.

1. Introduction

The properties of nuclei near neutron and proton shell closures provide critical benchmarks in predicting properties of nuclei away from closed shells. Establishing these benchmarks is especially important for neutron-rich nuclei far from stability. The origin of about half of the elements heavier than iron comes from the rapid-neutron capture process of nucleosynthesis, proposed to occur in massive explosions in the cosmos, such as supernova explosions or collisions of neutron stars. Observed r-process abundances cannot be reproduced [1, 2] with traditional nuclear shell and astrophysics models, suggesting a quenching of the shell structure far from stability.

Abundances of heavy elements synthesized in the r process can also be sensitive to neutron capture (n,γ) cross sections [3, 4]. For nuclei with low neutron separation energies, near shell closures or with a large excess of neutrons, neutron capture is dominated by direct capture which depends upon the single-neutron spectroscopic factors of low-spin excitations.

To help to solidify the role of ^{132}Sn with N=82 and Z=50 as a benchmark for extrapolations to even heavier nuclei, single-neutron excitations in ^{133}Sn were measured. Neutron transfer reactions with beams of ^{130,132}Sn and ^{134}Te also provide information needed to calculate direct capture cross sections.

Table 1. Preliminary results from the ^{130,132}Sn and ^{134}Te (d,p) measurements

	Adopted E_x(MeV)	J^π	Preliminary Results E_x(MeV)	ℓ transfer	J^π
^{131}Sn	0.000	$(3/2^+)$	(not observed)		
S_n=5.25 MeV			≈2.7	(3)	$(7/2^-)$
			≈3.4	(1)	$(3/2^-)$
			≈4.0	(1)	$(1/2^-)$
			≈4.7	(3)	$(5/2^-)$
^{133}Sn	0.000	$(7/2^-)$	0.0	(3)	$(7/2^-)$
S_n=2.42 MeV	0.854	$(3/2^-)$	≈0.85	(1)	$(3/2^-)$
	1.561	$(9/2^-)$			
	(1.656)	$(1/2^-)$	≈1.4	(1)	$(1/2^-)$
	2.005	$(5/2^-)$	≈2.0	(3)	$(5/2^-)$
^{135}Te	0.000	$(7/2^-)$	0.0	(3)	$(7/2^-)$
S_n=3.34 MeV	0.659	$(3/2^-)$	≈0.66	(1)	$(3/2^-)$
	1.083	$(1/2^-)$	≈1.00	(1)	$(1/2^-)$
	1.837	$(3/2^-,5/2^-)$	≈1.80		

2. Experimental details

The ^{130,132}Sn and ^{134}Te(d,p) reactions were measured in inverse kinematics at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. Short-lived Sn and Te ions were produced from proton-induced fission of UC and mass separated. To maximize the purity of the Sn beams, sulfur was introduced into the ion source. SnS^+ ions were extracted and subsequently broke up in the charge exchange cell. Negative ^{132}Sn ions ($>$ 90% purity) were accelerated in the 25-MeV tandem Electrostatic Accelerator to energies of 630 MeV. Beam energies for the ^{130}Sn and ^{134}Te studies were 630 and 643 MeV, respectively. The Sn and Te beams interacted with CD_2 targets with effective areal density of $\approx 160\mu$g/cm^2.

Reaction protons were measured in an early implementation of the Oak Ridge Rutgers University Barrel Array (ORRUBA) [5] of position-sensitive silicon strip detectors. At forward angles, detector telescopes were deployed, with ΔE detectors of 65 or 140μm thickness backed by 1000μm E detectors. At backward angles 1000μm E detectors were used. Elastically scattered C ions were stopped in the ΔE detectors. Cross sections of elastically scattered deuterons were used to normalize the data. ORRUBA detectors were supplemented by part of the SIDAR array [6] of silicon strip detectors at back angles. Total angular coverage was 57-92, 90-130, and 143-167 degrees in the laboratory. A micro-channel plate detector was located downstream to provide a timing signal for beam-like recoil particles. To aid in elemental identification, a segmented ion chamber was located further downstream.

3. Results and Discussion

The $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$ and $2f_{5/2}$ orbitals are the low-spin configurations above the N=82 gap that are expected to be populated in (d,p) neutron transfer reactions on ^{132}Sn and ^{134}Te. The ^{130}Sn(d,p) reaction could also populate $3s_{1/2}$ or $2d_{3/2}$ excitations below the N=82 gap, as well as configurations above the N=82 gap at higher excitation energies.

Cross sections of reaction protons as a function of angle were measured and compared with distorted-wave Born approximation (DWBA) calculations using the code FRESCO [7]. Stroemich [8] optical potentials were used because they were deduced from extensive elastic scattering measurements on Sn nuclei. These potentials were also used in earlier studies [9] of the ^{124}Sn(d,p) reaction in inverse kinematics. Standard Woods-Saxon potential bound state parameters $R = r_0 A^{1/3}$ with $r_0 = 1.25$ fm and diffuseness $a = 0.65$ were adopted. Spectroscopic factors were deduced by comparing experimental to DWBA-calculated cross sections.

A summary of the preliminary energies and angular momentum transfers from the ^{130,132}Sn and ^{134}Te (d,p) reaction measurements is displayed in Table 1. The preliminary data are taken from [10, 11, 12] and compared to adopted values from [13].

The ^{133}Sn ground ($7/2^-$) and excited states at 854 ($3/2^-$) and 2005 keV ($5/2^-$) had been previously deduced by measuring gamma rays following prompt and beta decay of fission fragments [13]. Evidence for the expected $1/2^-$ state was at best highly tentative, since it was unlikely to have been populated in these studies that preferentially populate higher spin states. The present measurement provides the first clear evidence for a state at $\approx$1.4 MeV that is a candidate for the $3p_{1/2}$ excitation. Angular distributions to the ground and first excited states are consistent with ℓ=3 and ℓ=1 transfer, respectively. By comparing the magnitudes of measured and DWBA-predicted cross sections, all of the spectroscopic factors for ^{133}Sn are large, close to $S = 1$ [11], as expected for concentrated single-neutron strength in the respective states.

The ground-state region in ^{131}Sn was not significantly populated in the ^{130}Sn(d,p) measurement. However, strong population to states above 2 MeV in excitation was observed, with a pattern of Q-values and relative cross sections very similar to those observed in the ^{132}Sn(d,p) measurement. Preliminary angular distributions for the $\approx$2.7 and $\approx$3.4-MeV states agree with $\ell = 3$ and $\ell = 1$ transfer, respectively, to presumably $2f_{7/2}$ and $3p_{3/2}$ states.

There have also been extensive studies of ^{135}Te by prompt and beta decay of fission fragments. Previous studies [13] of excitations in ^{135}Te assigned $f_{5/2}$ character to the first ($5/2^-$) state at 1127 keV. Preliminary analysis of (d,p) angular distribution data supports $7/2^-$, $3/2^-$ and $1/2^-$ spin-parity assignments to the ^{135}Te ground, 659- and 1083-keV states, respectively. The $2f_{5/2}$ strength appears to be fragmented in ^{135}Te, compared to its isotone ^{133}Sn, with little, if any, population of the first $5/2^-$ state at 1127 keV.

Recently Beun and Surman and their colleagues [3, 4] have explored the impact that neutron capture cross sections have on r-process nucleosynthesis abundances. An example of the uncertainty of predictions in this region is ^{130}Sn for which the calculated direct (n,γ) cross section varies by almost 3 orders of magnitude, depending upon the mass model [14]. Beun et al. [3] found that the ^{130}Sn(n,γ) cross section can be especially sensitive to predictions of r-process abundances. By increasing the ^{130}Sn(n,γ) rate by a factor of 10 above standard calculations, r-process abundances of heavy elements can change by as much as 15%. In contrast, r-process abundances are relatively insensitive to the ^{132}Sn(n,γ) cross section [3].

Given sizeable population of candidates for $p_{3/2}$ and $p_{1/2}$ excitations in ^{131}Sn, direct neutron capture on ^{130}Sn could be larger than current estimates and therefore would impact r-process abundance calculations. We are in the process of finalizing confirmation of the $\ell = 1$ transfer to the $\approx$3.4 and $\approx$4.0-MeV states in ^{130}Sn and calculating direct neutron capture cross sections.

4. Summary and Future Prospects

Neutron transfer (d,p) reactions have been measured with rare isotope beams of ^{130,132}Sn and ^{134}Te. Neutron $\ell = 1$ and $\ell = 3$ excitations above the N=82 shell gap were populated. These measurements highlight ^{132}Sn as an excellent example of a doubly-closed shell nucleus with relatively pure single-neutron excitations in ^{133}Sn. Understanding $\ell = 1$ excitations also has important implications for predicting r-process abundances.

The prospects for future (d,p) reaction studies with neutron-rich rare isotope beams are bright. Experiments with ^{126,128}Sn beams are planned for HRIBF. A measurement of the ^{130}Sn(^{9}Be,^{8}Beγ) reaction is also planned at HRIBF, to confirm the excitation energies of the ^{131}Sn states above the N=82 gap that were populated in the (d,p) reaction. Later this year, the CARIBU facility [15] at Argonne National Laboratory will enable studies of heavier neutron-rich nuclei from the fission of ^{252}Cf. The Facility for Rare Isotope Beams (FRIB) [16], scheduled to come on line later in this decade, would provide beams of all nuclei along the r-process path up to N≈140.

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