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Neutron single particle structure in ^{131}Sn and the r-process

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Recent calculations suggest that, at late times in the r-process, the rate of neutron capture by ^{130}Sn has a significant impact on nucleosynthesis. Direct capture into low-lying bound states is likely the dominant reaction in the r-process near the N=82 closed shell, so reaction rates are strongly impacted by the properties of neutron single particle states in this region. In order to investigate these properties, we have acquired (d,p) reaction data in the A~132 region in inverse kinematics using ~630 MeV beams (4.85 MeV/u for ^{130}Sn) and CD_2 targets. An array of Si strip detectors, including SIDAR and an early implementation of the new Oak Ridge Rutgers University Barrel Array (ORRUBA), was used to detect reaction products. Preliminary results for the ^{130}Sn(d,p)^{131}Sn experiment are reported.

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1. Introduction

The rapid neutron capture process (r-process) is thought to be responsible for the synthesis of about half of the nuclear species heavier than Fe [1], but little experimental nuclear physics information is available for r-process studies. Recent r-process calculations by Beun *et al.* [2] and Surman *et al.* [3] suggest the ^{130}Sn(n,γ)^{131}Sn reaction rate plays a pivotal role in nucleosynthesis, engendering global effects on isotopic abundances over a wide mass range during the freeze-out epoch following (n,γ)⇋(γ,n) equilibrium. This is owing, in part, to the long β-decay half-life of ^{130}Sn (162 s). Direct neutron capture (DC) is likely the dominant reaction at late times in the r-process near the N=82 closed shell, and the reaction rate is thus strongly impacted by the properties of single particle states in this region. Indeed, calculated DC (n,γ) cross sections can vary by up to three orders of magnitude for ^{130}Sn, depending on the nuclear model selected [4]. Thus, neutron single particle data on neutron rich species in this region are crucial for evaluating the role of ^{130}Sn in the r-process and for constraining model parameters.

Yrast cascades in ^{131}Sn involving states with J≥11/2 have been studied by Bhattacharyya *et al.* [5], and some of the low-lying hole states have been assigned tentatively from β-decay experiments [6]. Since there are nominally two neutron holes in the (N=80) ^{130}Sn core, one or more low-lying, low angular momentum hole states of ^{131}Sn may be observed in a (d,p) experiment, depending on the complexity of the ^{130}Sn ground state wave function. However, from shell model considerations, one expects the strongest states to be ℓ=1 and ℓ=3 transfers coupled to the ^{130}Sn ground state, i. e., negative-parity 1p-2h states. No single-particle information for any of these states in ^{131}Sn has been reported previously. The ℓ=1, $3p_{3/2}$ and $3p_{1/2}$ single particle states are of particular importance for DC in the r-process, as this typically involves the capture of an s-wave neutron followed by an E1 γ-ray transition. In this paper, we report preliminary results from the first experiment to investigate directly the single particle properties of states in ^{131}Sn.

2. Experimental Procedure

A radioactive beam of 630-MeV ^{130}Sn ions (4.8 MeV/u), accelerated at the Holifield Radioactive Beam Facility (HRIBF), bombarded an 80 μg/cm^2-thick CD_2 foil. In order to detect protons near 90° in the laboratory, the target surface was placed at 30° with respect to the beam axis, so the effective thickness was ≈160 μg/cm^2. The beam intensity was ~2×10^5 ions/s.

Reaction products were detected with arrays of silicon strip detectors, including an early implementation of the Oak Ridge Rutgers University Barrel Array (ORRUBA) and the ORNL Silicon Detector Array (SIDAR) [7], as shown schematically in Fig. 1. ORRUBA consisted of ten 1000-μm-thick position sensitive silicon strip detectors, plus four thinner ΔE detectors that were used to form detector telescopes for the more forward angles. The ORRUBA system is described in more detail elsewhere [8, 9]. Downstream from these arrays were mounted (in order) an annular silicon strip detector, a carbon-foil-microchannel plate detector (MCP), and a segmented-anode ion counter. These were used for beam diagnostics and cross section normalization. Coincidence signals from particles detected in the silicon arrays and the beam-like recoils striking the MCP served to reduce the background from other, non-(d,p) processes. Proton loci from the inverse (d,p) reaction were identified in the energy-versus-angle event spectra by comparison to superimposed calculated kinematics lines.

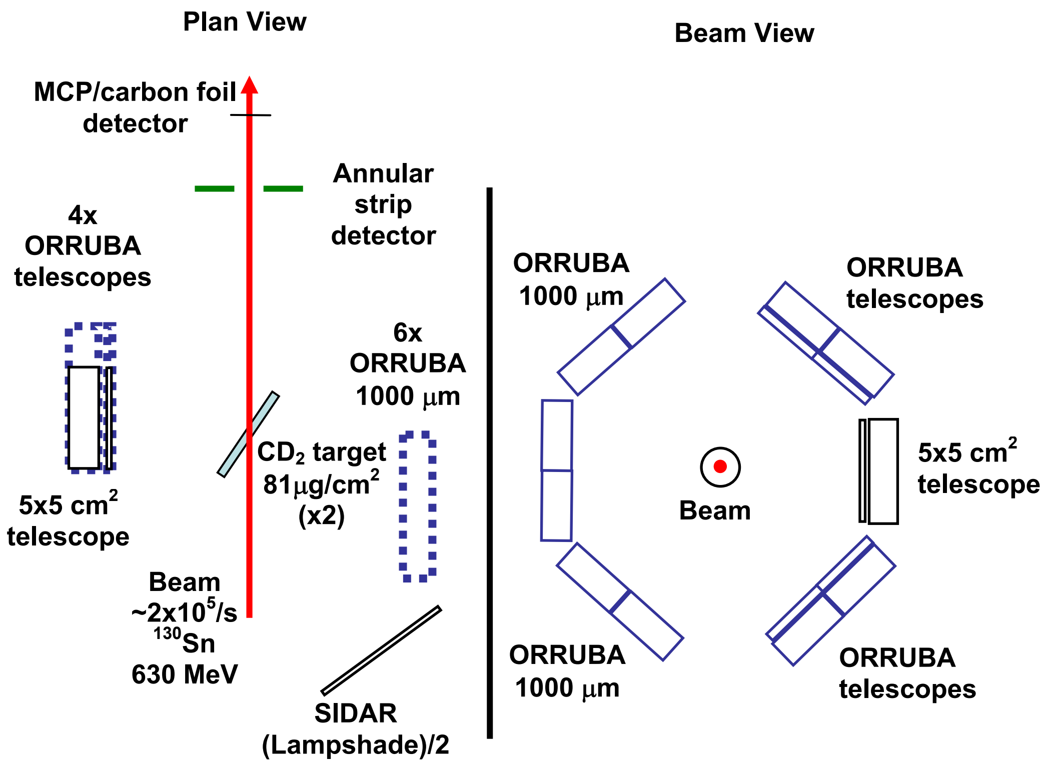

Figure 1. Schematic arrangement of target and detectors for the ^{2}H(^{130}Sn,p)^{131}Sn experiment. In addition, a segmented, gas-filled ion counter was placed downstream of this array for beam diagnostics.

3. Results and Discussion

A preliminary Q-value spectrum from one of the strip detectors is shown in Fig. 2. Four strong proton groups are observed, presumably corresponding to single-particle $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$, and $2f_{5/2}$ states, in the excitation energy range of ~2.7-4.7 MeV in ^{131}Sn. None of these levels has been reported previously. This spectrum is remarkably similar to that acquired in our (d,p) reaction study on doubly magic ^{132}Sn (see [9],[10]), in which the lowest strong state was the ^{133}Sn ground state, which presumably is the $2f_{7/2}$ single particle state. In fact, the lowest strong state in ^{131}Sn is precisely where the $2f_{7/2}$ single particle state should be expected, based on a simple weak coupling calculation [11], and our preliminary angular distribution data indicate the level at 2.7 MeV is indeed consistent with an ℓ=3 angular momentum transfer. Further, the angular distributions for the 3.4- and 4.0-MeV groups are both consistent with ℓ=1 transfers, suggesting the order of single particle levels may be similar to that in ^{133}Sn. A preliminary angular distribution for the 3.4-MeV level in ^{131}Sn is shown in Fig. 3. To date, our analysis shows no evidence for the excitation of low-lying hole states in ^{131}Sn.

4. Summary and Conclusions

The inverse ^{130}Sn(d,p)^{131}Sn reaction has been investigated at 4.8 MeV/u. An apparent single-particle spectrum is observed, similar to that observed in the (d,p) reaction on doubly magic ^{132}Sn. Preliminary measurements have been made of excitation energies and angular distributions, and ℓ assignments have been made. This information will help to constrain nuclear models and facilitate more realistic (n,γ) reaction rate calculations for r-process nucleosynthesis. The latter could have a significant impact on isotopic abundances over a wide mass range. Further analysis is ongoing, pursuant to extracting more precise energies and spectroscopic factors.

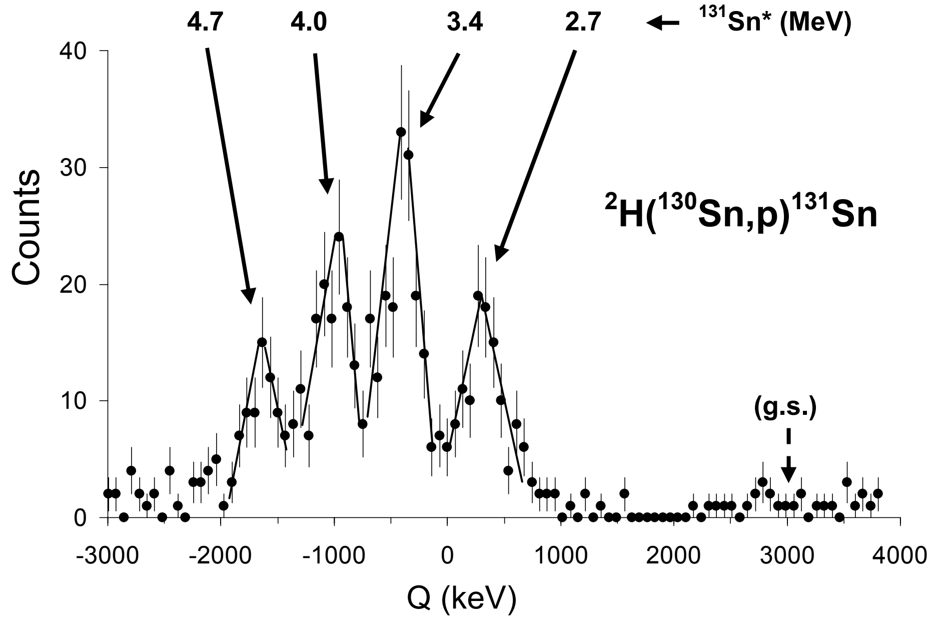

Figure 2. Preliminary Q-value spectrum of protons from one of the strip detectors of the ORRUBA. Approximate ^{131}Sn excitation energies are shown near the top of the figure. Solid lines are drawn to guide the eye.

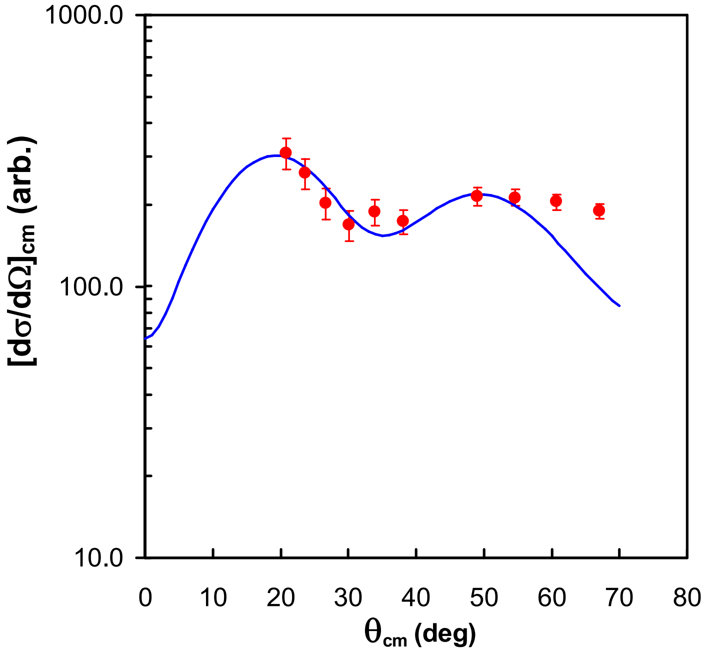

Figure 3. Preliminary angular distribution of protons from one of the strip detectors of the ORRUBA for the 3.4-MeV state. The solid curve is a distorted wave Born approximation (DWBA) calculation for a $3p_{3/2}$ neutron transfer.

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