Neutron Single Particle Structure in ^{131}Sn and Direct Neutron Capture Cross Sections

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(Received 29 May 2012; revised manuscript received 17 July 2012; published 24 October 2012)

Recent calculations suggest that the rate of neutron capture by ^{130}Sn has a significant impact on late-time nucleosynthesis in the *r* process. Direct capture into low-lying bound states is expected to be significant in neutron capture near the $N = 82$ closed shell, so *r*-process reaction rates may be strongly impacted by the properties of neutron single particle states in this region. In order to investigate these properties, the (d,p) reaction has been studied in inverse kinematics using a 630 MeV beam of ^{130}Sn (4.8 MeV/u) and a $(CD_2)_n$ target. An array of Si strip detectors, including the Silicon Detector Array and an early implementation of the Oak Ridge Rutgers University Barrel Array, was used to detect reaction products. Results for the ^{130}Sn$(d,p)^{131}$Sn reaction are found to be very similar to those from the previously reported ^{132}Sn$(d,p)^{133}$Sn reaction. Direct-semidirect (n,γ) cross section calculations, based for the first time on experimental data, are presented. The uncertainties in these cross sections are thus reduced by orders of magnitude from previous estimates.

DOI: 10.1103/PhysRevLett.109.172501 PACS numbers: 21.10.Jx, 25.45.Hi, 25.60.Je, 26.30.Hj

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$(n,\gamma)^{131}$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 $(n,\gamma) \rightleftharpoons (\gamma,n)$ equilibrium. This is owing, in part, to the long β-decay lifetime of the ^{130}Sn ground state (322 s). Direct neutron capture (DC) is expected to be significant at late times in the *r* process near the $N = 82$ closed shell, and the reaction rate may thus be strongly impacted by the properties of single particle states in this region. The most critical states for *s*-wave DC are the $3p_{3/2}$ and $3p_{1/2}$ single neutron states, which would be populated via $E1$ transitions. The DC cross section varies widely depending on whether or not these states are bound [4], and their excitation energies were not known before the present work. Indeed, theoretical DC (n,γ) cross sections can vary by nearly 3 orders of magnitude for ^{130}Sn, depending on the nuclear structure 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 $J \geq 11/2$ have been studied by Bhattacharyya *et al.* [5], and the spins and parities of some of the low-lying hole states have been assigned tentatively from β-decay experiments [6,7]. Since there are nominally two neutron holes in the ^{130}Sn core ($N = 80$), 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. From shell model considerations, the highest orbitals below the $N = 82$ shell gap are expected to be the (nearly degenerate) $2d_{3/2}$ and $1h_{11/2}$, plus the $3s_{1/2}$. From the recent ^{132}Sn$(d,p)^{133}$Sn work of Jones *et al.* [8], the lowest orbital above the $N = 82$ gap is expected to be the $2f_{7/2}$, followed by (in order) $3p_{3/2}$, $3p_{1/2}$, $1h_{9/2}$, and $2f_{5/2}$, all of which are vacant in ^{130}Sn. Since $\ell = 5$ transfers are very weak in the (d,p) reaction at the energy used here (4.8 MeV/u), one expects the strongest states to be $\ell = 1$ and $\ell = 3$ 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 from previous measurements.

As mentioned above, the $\ell = 1$, $3p_{3/2}$ and $3p_{1/2}$ single neutron 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 Letter, results from the first experiment to investigate directly the single particle properties of states in ^{131}Sn are reported, and direct-semidirect (n,γ) cross section calculations based on those data are presented.

The experimental technique has been described earlier [9] and is essentially identical to that used for the (d,p) study of doubly magic ^{132}Sn [8]. A radioactive beam of 630-MeV ^{130}Sn ions (4.8 MeV/u), accelerated at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory (ORNL), bombarded an 80 μg/cm^2-thick $(CD_2)_n$ 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 areal density was $\simeq 160$ μg/cm^2. The beam intensity was $\sim 2 \times 10^5$ 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) [10] and the ORNL Silicon Detector Array [11]. [The Silicon Detector Array was mounted at large laboratory angles (small center-of-mass angles) to detect protons from possible $\ell = 0$ transitions, but no evidence for such transitions was observed.] The 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. Mounted downstream from these arrays were (in order) an annular silicon strip detector, a carbon-foil-microchannel plate detector, and a segmented-anode ion counter. These detectors were used for beam diagnostics. Coincidence signals from particles detected in the silicon arrays and the beamlike recoils striking the microchannel plate detector 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 calculated kinematics lines. Cross section normalization was achieved by detecting elastically scattered deuterons with the ORRUBA at relatively small center-of-mass angles (33°–38°), where the ratio to Rutherford scattering is in the range 0.92–0.99, and comparing to optical model calculations. The estimated uncertainty in normalization is 10%. Corrections for energy loss in the target were made for both the beam and the emitted protons. Excitation energies in ^{131}Sn were deduced by using as a calibration known states excited via the ^{2}H(^{132}Sn, p)^{133}Sn reaction [8] with the same detectors and target. This worked quite well, as the ranges of reaction Q values overlap nicely for the two experiments. However, the absence of clear evidence for any previously known levels in ^{131}Sn necessitated the inclusion of uncertainties in the masses of all the isotopes involved in the calibration ($^{130-133}$Sn) in determining the errors for the ^{131}Sn excitation energies. This contribution is about 30 keV [12,13] and we estimate an excitation energy uncertainty of ± 50 keV.

A Q-value spectrum from a forward-angle strip detector is shown in Fig. 1. This spectrum is remarkably similar to that acquired in the (d,p) reaction study on doubly magic ^{132}Sn [8], in which the lowest strong state was the ^{133}Sn ground state, which has most of the $2f_{7/2}$ single particle strength. In both experiments, 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, and the level spacings are about the same in the two residual nuclei (Fig. 2). The excitation energy range is ~2.6–4.7 MeV in ^{131}Sn. Prior to the present work, none of these levels had been reported. It is interesting to note that the lowest strong state in ^{131}Sn is close to where the $2f_{7/2}$ single particle state is expected (~ 2.8 MeV), based on a simple weak coupling calculation [14]. The angular distribution data (Fig. 3) indicate the level at 2.6 MeV is indeed consistent with an $\ell = 3$ angular momentum transfer. Furthermore, the angular distributions for the 3.4- and 4.0-MeV groups are both consistent with $\ell = 1$ transfers, suggesting that the order of single particle levels is probably similar to that in ^{133}Sn. On this basis, the 4.7-MeV group is tentatively assigned $(5/2^-)$, even though the angular distribution is not sufficiently definitive to rule out other possibilities. The dotted curves in Fig. 3 are $2f_{7/2}$ and $2f_{5/2}$ calculations for the 3404- and 3986-keV levels, respectively (both with $S = 1.00$), to illustrate the strong preference at small angles for $\ell = 1$ assignments for these states. The experimental results for ^{131}Sn are summarized in Table I. The spectroscopic factors listed in Table I can be

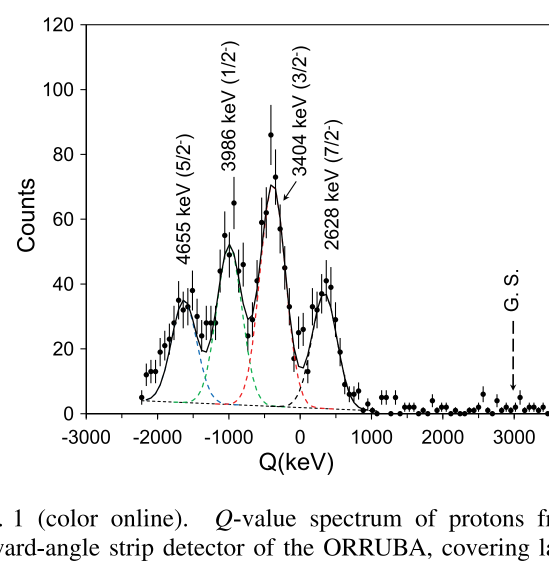

FIG. 1 (color online). Q-value spectrum of protons from a forward-angle strip detector of the ORRUBA, covering laboratory angles between about 69° and 90°. Approximate ^{131}Sn excitation energies, assumed spins and parities, and nominal position of the unobserved ground state are also shown. The strong peak region is fitted with four Gaussians of equal width, for which the χ^2 per degree of freedom is 1.46. The background in the low Q-value region (low proton energies) is owing mostly to setting analysis thresholds close to detector noise levels.

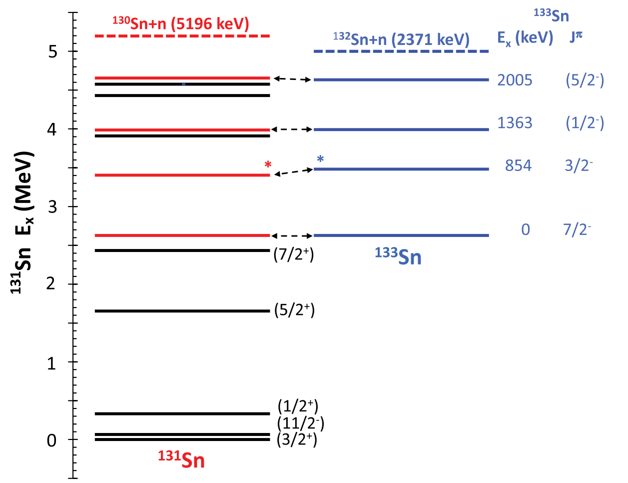

FIG. 2 (color online). The dashed arrows connect energy levels observed in the (d,p) reaction on ^{130}Sn (left) and ^{132}Sn (right) [8]. The energy corresponding to the ^{133}Sn ground state has been shifted to align with the lowest state observed in ^{131}Sn. (For a Q-value comparison, the energy levels of ^{133}Sn should be shifted upward by 197 keV, so neutron thresholds are aligned.) The states flagged with an asterisk (*) were the strongest in the respective experiments. Lower known states in ^{131}Sn [6] are also shown, but they were not observed in the present work.

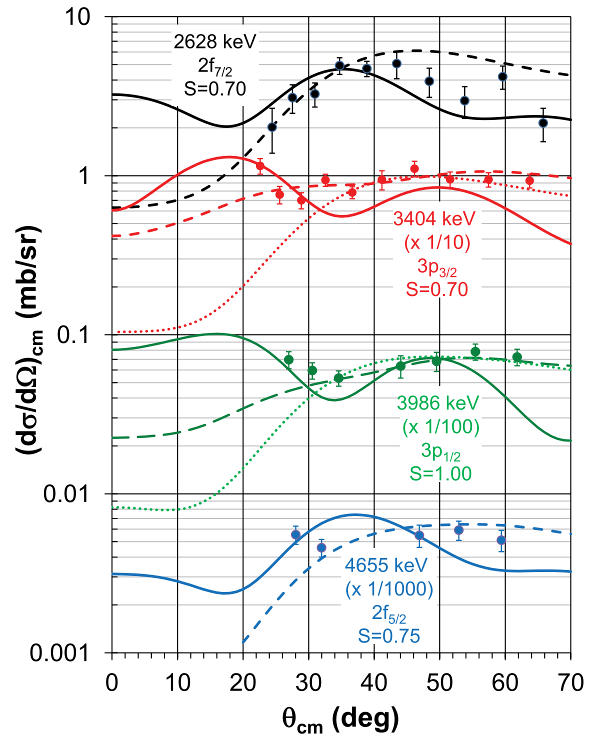

FIG. 3 (color online). Angular distributions of protons from ORRUBA detectors, extracted by using bins of 5° angular width in the laboratory. The 3986- and 4655-keV distributions have fewer points, owing to low proton energies being below detector thresholds at some angles. Dashed curves are distorted wave Born approximation calculations using the optical parameters of Strömich *et al.* [15], and the solid curves are the same calculations except for using the *BG* parameters of Sen, Riley, and Udagawa [27] in the proton channel [obtained by fitting ^{136}Xe$(p,p)^{136}$Xe elastic scattering data]. The "standard" bound state parameters of $r_0 = 1.25$ fm and $a = 0.65$ fm were used for all cases. For each level, the dashed and solid curves are shown for the same spectroscopic factor. Dotted curves are $2f_{7/2}$ and $2f_{5/2}$ calculations for the 3404- and 3986-keV levels, respectively (both with $S = 1.00$), to illustrate the strong preference at small angles for $\ell = 1$ assignments for these states. The exact finite range code DWUCK5 [28] was used for the calculations. See the text for discussion of tentative J^π assignments.

compared directly to the distorted wave Born approximation spectroscopic factors for ^{133}Sn [8], as they were obtained by using the same bound state potential parameters and the same source of optical model parameters [15].

It should be noted that a similar correspondence of single particle strength between ^{207}Pb and ^{209}Pb was observed by Mukherjee and Cohen [16], who studied the (d,p) reaction on ^{206}Pb and doubly magic ^{208}Pb. Even though a similar pattern was observed in the ^{206}Pb$(d,p)^{207}$Pb spectra of these authors, the apparent concentration of fp-shell single particle strength in only one main level for each orbital in ^{131}Sn is somewhat surprising, given that ^{130}Sn is only semimagic. This relative lack of fragmentation suggests that the $Z = 50$ proton core is intact and that the ^{130}Sn ground state has a simple neutron structure as well. In contrast, the semimagic nucleus ^{134}Te $(Z = 52,\ N = 82)$ is apparently not so simple, as the neutron single particle strength in ^{135}Te was found to be significantly fragmented in a (d,p) study, also performed at the Holifield Radioactive Ion Beam Facility [17].

The ^{131}Sn ground state is believed to be $3/2^+$, with the first excited state being the $1h_{11/2}$ hole state at about 65 keV excitation [18]. Neither of these states was observed in the present experiment. If the two neutron holes in the ^{130}Sn ground state were in the $2d_{3/2}$ orbital, the orbital would be half-empty and the spectroscopic factor S could be as large as 0.5. An upper limit of 0.3 is consistent with the data from the present experiment. Of course, from shell and pairing model considerations [19,20], the ground state wave function of ^{130}Sn is expected to be a linear combination of hole pairs in the $1h_{11/2}$, $2d_{3/2}$, $3s_{1/2}$, $2d_{5/2}$, and $1g_{7/2}$ orbitals, roughly in order of decreasing coefficients [14]. This suggests there is a significant probability that the two neutron holes in ^{130}Sn are in the $1h_{11/2}$ orbital, as it is nearly degenerate with the $2d_{3/2}$ [18], and $\ell = 5$ transfers would be very weak in the (d,p) reaction at our beam energy (4.8 MeV/u). Indeed, even with the hole pair only in the $1h_{11/2}$ orbital $(S = 0.17)$, the maximum differential cross section for $\ell = 5$ would be $\sim$0.1 mb/sr, a factor of 20 lower than the smallest measured in the present experiment. Also, from a purely statistical point of view, it is 3 times more likely for the holes to lie in the $1h_{11/2}$ than in the $2d_{3/2}$ orbital.

TABLE I. Properties of single particle states in ^{131}Sn from the inverse ^{130}Sn$(d,p)^{131}$Sn reaction. Estimated uncertainties in spectroscopic factors (S) are primarily owing to ambiguities in the direct reaction model.

E_x(keV) (± 50 keV)	J^π	S (± 30%)
2628	$(7/2^-)$	0.70
3404	$(3/2^-)$	0.70
3986	$(1/2^-)$	1.00
4655	$(5/2^-)$	0.75

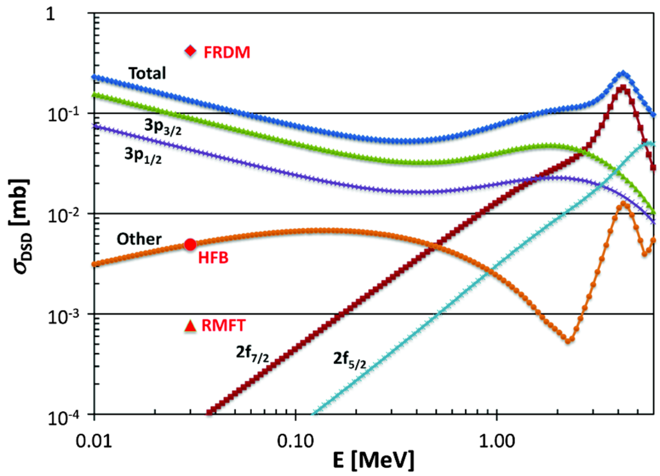

FIG. 4 (color online). Direct-semidirect capture cross sections for the ^{130}Sn$(n,\gamma)^{131}$Sn reaction computed by using the code CUPIDO [21] for real parts of a phenomenological Koning-Delaroche [22] optical model potential are plotted for levels in Table I. An upper limit for the combined DSD capture into the $1h_{11/2}$, $2d_{3/2}$, $3s_{1/2}$, $2d_{5/2}$, and $1g_{7/2}$ orbitals (labeled *other*) is not included in the total DSD. Shown for comparison (single points) are the calculations of Rauscher *et al.* [4] for 30 keV neutrons using the finite range droplet (FRDM), the Hartree-Fock-Bogoliubov (HFB), and relativistic mean field theory (RMFT) models. Of these, only the FRDM predicted both the $3p_{3/2}$ and $3p_{1/2}$ single-neutron states to be bound.

As mentioned earlier, the observation of $\ell = 1$ strength in ^{131}Sn is important for direct neutron capture and its potential impact on r-process nucleosynthesis. There is also a semidirect capture via the giant dipole resonance, which is accounted for by adding a giant dipole resonance term to the single particle electromagnetic operator. Direct-semidirect (DSD) neutron capture cross sections for ^{130}Sn were calculated by using the data in Table I and the code CUPIDO [21]. For low energy capture, the code implements a conventional potential model expressed in terms of single particle electromagnetic transition matrix elements computed in a first-order approximation. In the incident channel the real part of a phenomenological Koning-Delaroche potential [22] was used. The imaginary part of these potentials is dropped, because the loss of flux into other channels is expected to be small [23]. For the bound-state single-neutron wave functions the Bear-Hodgson potential [24] was used, where the depth was fitted to reproduce binding energies for each of the capturing bound states in Table I. The DSD capture cross sections are plotted in Fig. 4 between 0.01 and 6 MeV for computation of Maxwellian averages at astrophysical temperatures. At 30 keV the total computed DSD cross section is 0.14 mb for the real parts of the Koning-Delaroche potential with an uncertainty of $\approx 20\%$. A slight variance with a DSD capture computation of ≈ 0.22 mb reported by Chiba *et al.* [25] is likely due to using different single particle level energies or a different single particle bound-state potential [26].

Reaction rate and nucleosynthesis calculations require (n,γ) cross sections for both DSD capture and statistical capture. The latter depend heavily on the level density in the Gamow window, and while that is not yet well established for ^{131}Sn, there are reasons to believe that the level density so close to the $N = 82$ closed shell is too low for statistical capture to dominate. In any case, the results of the present work will be an absolutely necessary ingredient for reaction rate calculations that may be done in the future and are thus a critical component for determining the impact of the important ^{130}Sn$(n,\gamma)^{131}$Sn reaction on global isotopic abundances in the r process.

In summary, the inverse ^{130}Sn$(d,p)^{131}$Sn reaction has been investigated at 4.8 MeV/u. An apparent single particle spectrum is observed, very similar to that observed in the (d,p) reaction on doubly magic ^{132}Sn. Measurements have been made of excitation energies and angular distributions, and ℓ assignments are consistent with expected single particle states. In particular, the presumed $\ell = 1$ single particle states are both bound, which favors a relatively large DC cross section compared to those from models that predict one or both of these states to be unbound [4]. Using these experimental results, cross sections for ^{130}Sn$(n,\gamma)^{131}$Sn direct-semidirect capture have been calculated, and, for reasons stated earlier, the uncertainties are reduced by orders of magnitude from previous estimates, none of which was based on experimental data. This information will also help to constrain nuclear models and facilitate more realistic (n,γ) reaction rate calculations for r-process nucleosynthesis involving other isotopes. At present, we defer calculation of the ^{130}Sn$(n,\gamma)^{131}$Sn reaction rate and r-process nucleosynthesis, as contributions from statistical processes are not well understood at this time.

This work was supported by the U.S. Department of Energy under Contracts No. DE-FG02-96ER40955 (TTU), No. DE-FG52-03NA00143 (Rutgers, ORAU), No. DE-AC05-00OR22725 (ORNL), No. DE-FG02-96ER40990 (TTU), No. DE-FG03-93ER40789 (Mines), No. DE-FG02-96ER40983 (UTK), and No. DE-SC0001174 (UTK) and the National Science Foundation under Contract No. NSF-PHY-00-098800 (Rutgers). Computation of direct-semidirect capture was supported by Topical Collaboration on Theory for Reactions on Unstable iSotopes [29]. The authors also acknowledge useful discussions with R. Surman, J. Beun, and B. A. Brown.

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