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Developing techniques to study A $\sim$ 132 nuclei with (d, p) reactions in inverse kinematics

K.L. Jones[1,a], C. Baktash[2], D.W. Bardayan[2], J.C. Blackmon[2], W.N. Catford[3], J.A. Cizewski[1], R.P. Fitzgerald[4], U. Greife[5], M.S. Johnson[6], R.L. Kozub[7], R.J. Livesay[5], Z. Ma[8], C.D. Nesaraja[2,8], D. Shapira[2], M.S. Smith[2], J.S. Thomas[1], and D. Visser[4]

[1] Department of Physics and Astronomy, Rutgers University, New Brunswick, NJ 08903, USA
[2] Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[3] Department of Physics, University of Surrey, Guildford, Surrey, GU2 7XH, UK
[4] Department of Physics and Astronomy, University of NC, Chapel Hill, NC 27599, USA
[5] Department of Physics, Colorado School of Mines, Golden, CO 80401, USA
[6] Oak Ridge Associated Universities, Oak Ridge, P.O. Box 117, TN 37831, USA
[7] Physics Department, Tennessee Technological University, Cookeville, TN 38505, USA
[8] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA

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Abstract. A measurement of the (d, p) reaction in inverse kinematics at energies near the Coulomb barrier using a stable beam of ^{124}Sn has been performed at ORNL's Holifield Radioactive Ion Beam Facility (HRIBF). The sensitivity of proton angular distributions to the transferred angular momentum has been demonstrated. Spectroscopic factors have been extracted for three states and are in agreement with previous measurements made in normal kinematics.

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Neutron-transfer reactions on stable targets have been used extensively to study the spectroscopy of both ground and excited states of nuclei close to stability. By utilizing this technique in inverse kinematics with rare isotope beams (RIBs), it is possible to study the evolution of single-particle structure away from the valley of stability. This is of importance to the understanding of both effective interactions and the synthesis of heavy elements in the r-process. Of particular interest is the region close to the double shell closure at ^{132}Sn.

The first (d, p) measurement in inverse kinematics was made in GSI using stable Xe beams at 5.87 A MeV [1]. Reaction measurements with weak RIBs are technically challenging, and although (d, p) reactions in inverse kinematics have been performed with RIBs in the A $\sim$ 80 region [2,3] close to the Coulomb barrier, it was not clear that the technique would work well for heavier nuclei at these low bombardment energies. Hence it was decided to first make a test measurement using a stable beam of ^{124}Sn as the reaction has been well studied in normal kinematics [4,5,6,7,8]. In one study [8] the center of mass energies were similar to those which are available at the HRIBF, where a $^{132}\mathrm{Sn}(\mathrm{d}, \mathrm{p})$ measurement will be performed.

The single-neutron transfer reaction $^{2}\mathrm{H}(^{124}\mathrm{Sn}, \mathrm{p})$ has been measured at 4.5 A MeV using a deuterated polyethylene target with an effective thickness of $200\,\mu\mathrm{g/cm}^2$ [9]. Protons were detected in two position sensitive silicon telescopes and the silicon detector array SIDAR [10], covering angles $\theta_{\mathrm{lab}} = 70°\text{–}160°$ ($\theta_{\mathrm{C.M.}} = 7°\text{–}61°$). Particle identification was possible in the telescopes, where elastically scattered target constituents were detected as well as protons from the reaction. Data were collected for about 18 hours with a beam rate of 10^7 ^{124}Sn particles per second.

Angular distributions of elastically scattered deuterons were used to obtain absolute normalization of the cross sections. Comparisons of the data with calculations made with the DWUCK5 [11] code indicate that the deviations from Rutherford scattering for the measured deuterons were at most 5% for angles foward of 40° in the center-of-mass system owing to the close vicinity of the beam energy to the Coulomb barrier. This method allows normalization of the data independently of target thickness and beam fluctuation effects as it is a direct measure of the total number of beam ions incident on target atoms, and reduces the uncertainties to about 10%.

The angle and energy of reaction protons were measured and used to determine the excitation energies in ^{125}Sn. States populated in ^{125}Sn were measured with a

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[a] Conference presenter; e-mail: `kate@phy.ornl.gov`

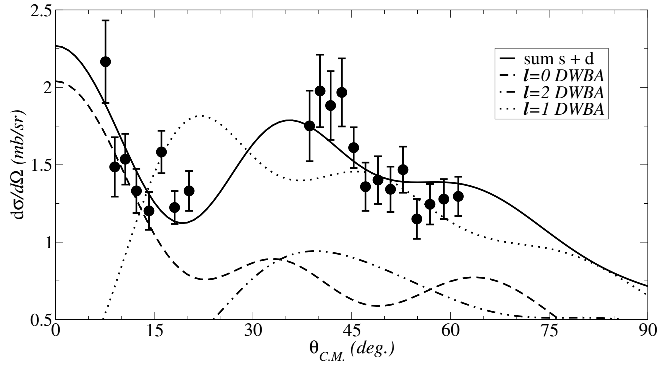

Fig. 1. Angular distribution for the group of states below $E_x = 300\,\text{keV}$ in ^{125}Sn. The solid curve is the combined DWBA calculation for the $3/2^+$ state (dot-dashed) and the $1/2^+$ state (dashed). A $3/2^-$ DWBA calculation (dotted) is shown for comparison.

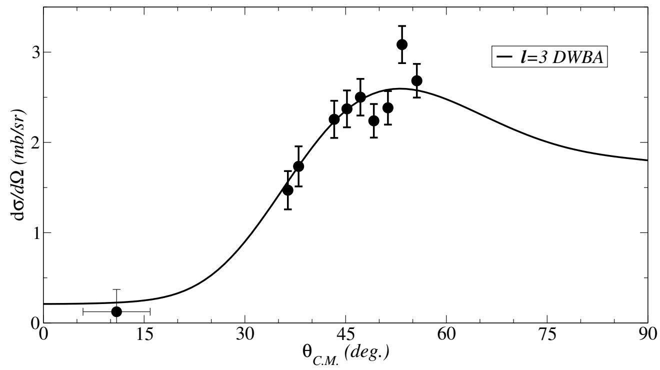

Fig. 2. Angular distribution for the 2.8 MeV in ^{125}Sn. The solid curve is the DWBA calculation for an $\ell = 3$ transfer. All the small angle data from SIDAR have been binned into one data point.

resolution $\varDelta E \approx 200\,\text{keV}$ FWHM, hence the $3/2^+$ state at 28 keV and the $1/2^+$ state at 215 keV could not be resolved in this measurement. The resolution was limited primarily by target thickness effects, specifically, the energy loss incurred by the heavy beam particle and the resulting uncertainty in the reaction energy. A slightly enlarged beam spot also affected the resolution.

The combined angular distribution for the two low-lying states populated in ^{125}Sn and the angular distribution for the 2.8 MeV state are shown in figs. 1 and 2, respectively. Distorted Wave Born Approximation (DWBA) calculations using the TWOFNR code [12] with the optical model parameters given in [8] were performed. The calculations were fitted to the data and it was found that for the states below $E_x = 300\,\text{keV}$ both the $3/2^+$ state (dot-dashed) and the $1/2^+$ state (dashed) were needed in order to reproduce the data. Calculations including either a $3/2^-$ state (as shown by the dotted line) or the $11/2^-$ ground state did not improve the fit. The state at 2.8 MeV shows a considerably different shape to any of the low angular momentum transfer calculations shown in fig. 1 and is well described by a calculation assuming $\ell = 3$ transfer, in agreement with the known $f_{7/2}$ assignment of this state.

Table 1. Spectroscopic factors from this work and previous works. The quoted uncertainties include statistical, DWBA fitting effects and systematic errors due to the normalization.

E_x (MeV)	J^π	This work	Ref. [8]	Ref. [7]
0.028	$3/2^+$	0.44(6)	0.53	0.44
0.215	$1/2^+$	0.33(4)	0.32	0.33
2.8	$7/2^-$	0.46(5)	0.52	0.54

Spectroscopic factors were extracted from the DWBA fits for $\ell = 2$ transfer to the $3/2^+$ state (dot-dashed) at 28 keV and the $\ell = 0$ transfer to the $1/2^+$ state (dashed) at 215 keV as well as for $f_{7/2}$ state at 2.8 MeV, as shown in table 1. These values are compared with those measured in normal kinematics at the same effective deuteron energy [8] and at a higher beam energy $E_\text{d} = 33\,\text{MeV}$ [7]. Considering the 15–30% uncertainty normally assigned to spectroscopic factors, our results are in good agreement with those made in normal kinematics.

In summary, the $^{124}\text{Sn(d, p)}$ reaction has been measured in inverse kinematics at 4.5 A MeV. The resolution in Q-value was found to be 200 keV, limited mostly by the target thickness, but also by a slightly enlarged beam spot. It should also be noted that level densities around ^{132}Sn are expected to be low due to the vicinity to the double shell closure, hence the resolution obtained here should be adequate. The data presented here show sensitivity of proton angular distributions to the ℓ-value of the transferred neutron in this mass region, with beam energies close to the Coulomb barrier. It is encouraging to note that even where states are not resolvable, it is still possible to extract both ℓ-values and spectroscopic factors, as for the $3/2^+$ and $1/2^+$ states in this work. Similar levels of statistics would be required to resolve ℓ-values with radioactive beams. With currently available beam intensities at the HRIBF, this equates to ten days of ^{132}Sn beam.

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