Study of the ^{124}Sn(d,p) reaction in inverse kinematics close to the Coulomb barrier

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The ^{2}H(^{124}Sn$,p$) reaction has been measured at 562 MeV (4.5 A MeV). Differential cross sections were measured from $\theta_{\mathrm{c.m}}=7°–61°$. Angular momentum transfers and spectroscopic factors determined using finite range DWBA calculations are in good agreement with earlier measurements performed in normal kinematics.

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The single-particle structure of nuclei close to the magic numbers is crucial for improving models of the nucleus and to understanding abundances resulting from the rapid neutron-capture (r) process. The properties of the few doubly-magic nuclei within the valley of stability and their neighbors have been well measured and serve as benchmarks for the nuclear shell model and parameterizations of effective interactions. However, much less is known for the nuclei neighboring the more neutron-rich double shell closures at ^{78}Ni and ^{132}Sn.

Neutron-capture rates on closed-shell nuclei are important during the cooling stage of the r process. The shape of the abundance peaks at $A=130$ and $A=195$ may be modified by the neutron-capture rates on nuclei close to the closed shells [1]. Nuclear structure data are particularly critical in regions where the level density is low and statistical models are unreliable.

Transfer reactions induced by light-ion beams on targets of stable isotopes provide a well-established technique for probing the single-particle structure of nuclei [2–4]. Following the pioneering experiment using stable Xe beams to measure (d,p) reactions [5], and with beam intensities greater than 10^4 particles/second at a number of facilities around the world, a number of (d,p) reactions have been performed in inverse kinematics using light radioactive ion beams (RIB's) [6–10]. Transfer reactions using a beam of ^{132}Sn have been the subject of recent attention and are often stated as prototype experiments [11–13] for next generation RIB facilities such as the Rare Isotope Accelerator (RIA) [14]. At the Holifield Radioactive Ion Beam Facility (HRIBF) of the Oak Ridge National Laboratory (ORNL) it has recently become possible to accelerate heavier RIBs (e.g., ^{132}Sn) to energies around the Coulomb barrier with sufficient intensity and resolution to perform transfer reactions.

The nucleon-transfer probability to low-lying, low-angular momentum states is higher at lower energies, due to kinematic matching conditions, and at the same time the reaction is cleaner as there are fewer reaction channels open. However, below the Coulomb barrier angular distributions become less distinctive and it was not clear that ℓ values and spectroscopic factors could be extracted under such conditions. The purpose of this Brief Report is to demonstrate that such information can indeed be extracted from (d,p) reaction data taken in inverse kinematics around the Coulomb barrier with heavy RIBs.

A ^{124}Sn beam was chosen for this purpose as ^{125}Sn has one of the lowest level densities in the region and has a similar Coulomb barrier to the neutron-rich isotopes of interest. Also, this nucleus has been studied via the (d,p) reaction in normal kinematics at several different beam energies [15–19], thereby creating a good benchmark. In particular, there exists a study at similar center of mass energies in which the elastic scattering was also measured and optical model parameters extracted [19].

A beam of ^{124}Sn was accelerated to 562 MeV by the tandem accelerator of the HRIBF and focused onto a 100 μg/cm^2 target of deuterated polyethylene (CD_2). The target was turned 30° to the beam, thus achieving an effective thickness of 200 μg/cm^2 and at the same time allowing emerging protons to be detected around $\theta_{lab}=90°$ without being shadowed. Protons were detected in two telescopes of silicon detectors. One telescope on the downstream side subtended $\theta_{lab}=70°–102°$. The other telescope on the upstream side subtended $\theta_{lab}=85°–110°$. The silicon detector array (SIDAR) [20] was mounted at more backward angles $\theta_{lab}=130°–160°$ (see Fig. 1). The telescopes consisted of a thin position-sensitive energy loss (ΔE) detector and a thicker stopping (E) detector (1000 μm). As the protons emitted from the (d,p) reaction at more forward angles in the laboratory frame have higher energies, the downstream telescope had a thicker ΔE detector (140 μm) compared to the upstream ΔE detector (65 μm). Both ΔE detectors had 16 position-sensitive strips allowing the angle of proton emission to be determined to a precision of ±0.5°. SIDAR was mounted in a half lampshade configuration with three 16-strip silicon wedges. The emission angle of each proton mea-

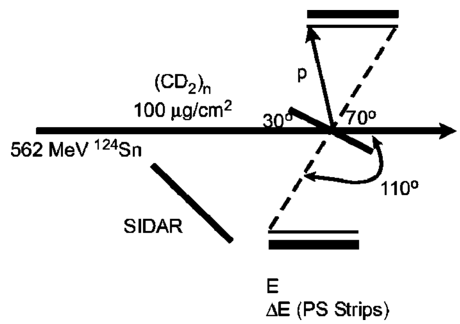

FIG. 1. Experimental setup with the ^{124}Sn beam impinging on a 100 μg/cm^2 CD_2 target rotated 30° with respect to the beam direction. Protons following a (d,p) reaction were measured in two detector telescopes that covered 70° to 110° in the laboratory and in SIDAR that covered 130° to 160°.

sured in SIDAR was determined from the strip that was hit. Proton energies were recorded from all the silicon detectors, with the total energy in the telescopes calculated from the sum of the ΔE and E energies.

Data were collected for about 18 hours with a beam rate of 10^7 ^{124}Sn particles per second. The angles of particles measured in the downstream telescope are shown as a function of their energy in Fig. 2. There are three clearly visible loci relating to elastically scattered carbon atoms, deuterons and protons from the target; additionally the distinctive loci resulting from the (d,p) reaction are discernible at larger angles. A break can be seen around channel 100 where protons following the (d,p) reaction have just enough energy to punch-through the ΔE detector, leaving only a subthreshold signal in the E detector. Two gates were used to identify protons resulting from the (d,p) reaction: (1) protons were identified using standard energy loss techniques with the ΔE and E detectors; and (2) kinematic cuts which exclude elastically scattered events were used for those protons which were too low in energy to be recorded in the E detector. The kinematic cuts ensured that all of the protons measured at angles greater than $\theta_{lab}=85°$ populating states with $2.6 < E_x < 4.2$ MeV in ^{125}Sn were accepted (see Fig. 3).

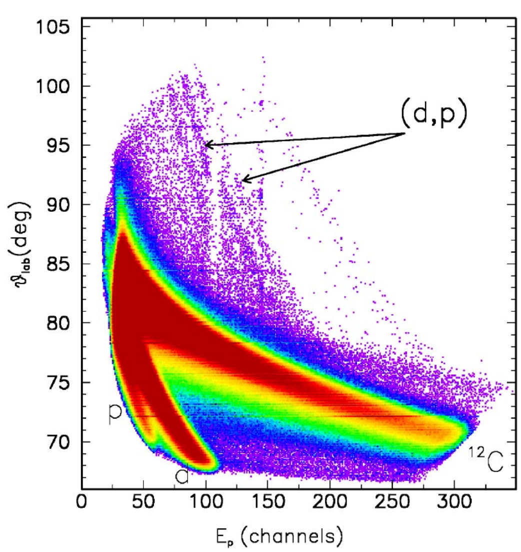

FIG. 2. (Color online) Angle of particles measured in the upstream telescope as a function of energy, without any gates imposed. Elastic scattering of carbon atoms, deuterons and protons from the target and reaction protons from the (d,p) reaction are indicated.

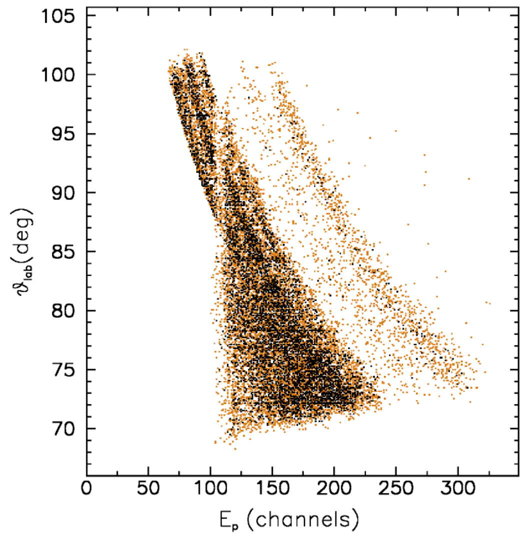

FIG. 3. (Color online) Angle of particles measured in the downstream telescope as a function of energy, with proton gates imposed. Proton identification was based on ΔE versus E characteristics for those particles passing through the ΔE detector and on the kinematics for the lower energy protons, i.e., those below channel 100 (see text).

At the very backward angles covered by SIDAR, the proton energies were very low, as dictated by the kinematics of the reaction. Hence, the protons could not punch through even thin silicon detectors and identification of protons was not possible via the ΔE-E method in this region. However, target constituents can not be elastically scattered into this region, drastically reducing the background. Data were also collected using a CH_2 target to identify contaminants from these spectra.

The data from each telescope were analyzed in 2-degree bins while the data from SIDAR were divided in 2-strip bins (1.6° to 2° angular intervals). The reaction Q value was calculated on an event-by-event basis. Figure 4 shows the data for the bin centered at 92° in the upstream telescope. The peak at low excitation energy is comprised of the first two excited states ($3/2^+$ at 28 keV and $1/2^+$ at 215 keV). The contribution from the $11/2^-$ ground state is minimal due to the large transfer of angular momentum required to populate this state. The resolution in Q value (excitation energy) is approximately 200 keV, as can be seen from the width of the $7/2^-$ state at 2.8 MeV; hence, the two low-lying excited states cannot be resolved in this measurement. The main contributions to this resolution were target thickness effects and kinematic dispersion owing to a slightly enlarged beam spot.

The absolute normalization of the cross sections was achieved using the angular distributions of elastically scattered deuterons. Calculations made with the DWUCK5 [21] code indicate that the deviations from Rutherford scattering for the measured deuterons were at most 5% for angles

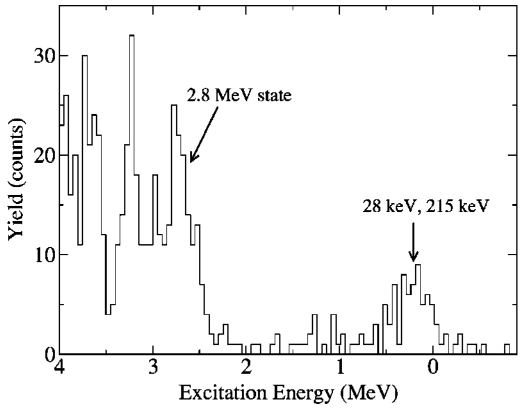

FIG. 4. *Q*-value spectrum measured in the downstream telescope at 92° in the laboratory frame. The low-lying $3/2^+$ (28 keV) and $1/2^+$ (215 keV) states and a higher-lying $7/2^-$ (2.8 MeV) state are indicated.

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%.

Angular distributions for the pair of low-lying excited states and for the $7/2^-$ state at 2.8 MeV are shown in Figs. 5 and 6, respectively. The distribution for the lower excited states shows a peak close to $\theta_{\mathrm{c.m}}=0°$, which is indicative of an $\ell=0$ transfer, and a second peak close to 40°. For the 2.8 MeV level, there is little cross section at forward center of mass angles with the cross section peaked at around 50°.

To understand these angular distributions and to make a comparison with existing data, DWBA calculations were performed using the TWOFNR code [22] with the optical model parameters given in [19] and a Hulthén finite-range factor of

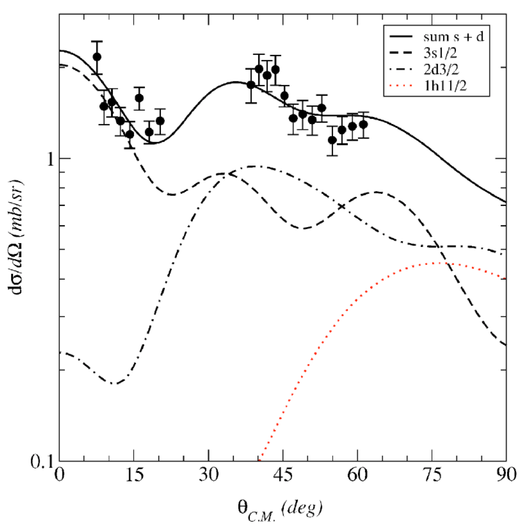

FIG. 5. (Color online) Angular distribution for the group of states below 300 keV in excitation. The solid line is a finite-range DWBA calculation (see text) for the known $3/2^+$ state (dot-dashed) at 28 keV and a $1/2^+$ state (dashed) at 215 keV. The dotted line is DWBA calculation for the $11/2^-$ ground state for comparison.

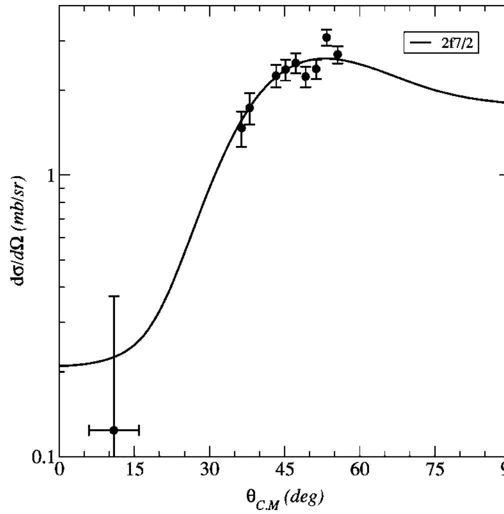

FIG. 6. Angular distribution for the $7/2^-$ state at 2.8 MeV in excitation. The solid line is a finite-range DWBA calculation (see text). The point at 10.9° represents all the data taken in SIDAR for this low cross section region.

0.746 [23]. The calculations were fitted to the data and spectroscopic factors were extracted as shown in Table I. For the lower excited states both the $3/2^+$ state (dot-dashed) at 28 keV and the $1/2^+$ state (dashed) at 215 keV needed to be included in order to reproduce the data. The $11/2^-$ ground state, contributes minimally to the angular distributions as shown by the dotted line, where a spectroscopic factor of 1 has been assumed. For the 2.8 MeV state, only an $\ell=3$ transfer, appropriate for the known $2f_{7/2}$ [24] contribution could reproduce the data, and lower values of transferred angular momentum showed distinguishably different characteristics. The values of the spectroscopic factors all agree well with those from the work of Strömich *et al.* [19], which were performed in normal kinematics at 5–8 MeV in deuteron energy (E_d) and those from the work of Bingham and Hillis [18] which were performed at $E_d=33.3$ MeV. It should be noted that a zero-range approximation was used in the DWBA analysis of [18,19].

In summary, the (d,p) reaction in inverse kinematics was studied using a stable beam of ^{124}Sn on a thin deuterated polyethylene target. The detection and identification of protons from the reaction enabled the study of single-neutron excitations in ^{125}Sn. The angular distributions of the protons

TABLE I. 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. [19]	Ref. [18]
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

from these states show distinctive structures which are characteristic of the angular momentum transfered in the reaction. Using optical model parameters obtained from elastic scattering measurements from previous work [19], DWBA calculations were performed and spectroscopic factors were extracted. The results are in good agreement with earlier measurements [18,19] performed in normal kinematics. These results demonstrate the effectiveness of these techniques to determine spectroscopic properties of nuclei in this mass region at beam energies close to the Coulomb barrier. This is encouraging news for the study of single-particle structure far from stability using RIBs.

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