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SINGLE NEUTRON TRANSFER EXPERIMENTS CLOSE TO THE r-PROCESS PATH*

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The first measurements using the (d,p) transfer reaction to study single-particle states in nuclei on the expected r-process path have been made at the Holifield Radioactive Ion Beam Facility. The shell closure at $N = 50$ has been crossed using the ^{82}Ge(d,p) and ^{84}Se(d,p) reactions. The properties of the lowest-lying states have been determined. Furthermore, the ^{132}Sn(d,p) reaction has been used for the first time to populate single-particle states in ^{133}Sn.

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1. Introduction

There is currently a paucity of knowledge of the single-particle spectroscopy of nuclei on, or close to, the r-process line. This is due mainly to the location of this nucleo-synthetic path far from stability; hence there are great technical challenges to producing enough ions of any nucleus to be able to make detailed studies using secondary reactions. Most of the experimental data available are from β-decay or from measuring γ-decay (typically from high-spin states) following spontaneous fission. However, opportunities to use reactions to study very neutron-rich nuclei at the Holifield Radioactive Ion Beam Facility (HRIBF) have arisen. At the HRIBF products of proton-induced fission of ^{238}U are accelerated in the tandem accelerator to around Coulomb barrier energies. Sulfur is bled into the ion source to produce molecular beams of SnS and GeS that have been shown to have greatly reduced contamination from the more stable isobars present in the mass analyzed atomic beams, making these experiments possible.

Our collaboration has seized this opportunity and performed experiments using radioactive beams of ^{82}Ge, ^{84}Se and ^{132}Sn on thin foil CD_2 targets to produce ^{83}Ge, ^{85}Se and ^{133}Sn[1]. In the case of ^{83}Ge, only the half-life of the ground state was known [1]. The measurement described below yielded the first mass measurement, the assignment of the ℓ-value and spectroscopic factors for the ground and first excited states and the energy of the first excited state. Data analysis for the ^{133}Sn measurement is in a preliminary stage (the experiment was still in progress at the time of the conference). Final analysis is expected to yield sufficient resolution and statistics to extract ℓ-values and spectroscopic factors for the lower spin states.

2. $N = 51$ studies

Two measurements using unstable neutron-rich $N = 50$ beams at around 4 MeV/nucleon were performed at the HRIBF. The combined information for the ground and first excited states from the two measurements presented here has been added to the systematics of the neutron-rich $N = 51$ isotones and are analyzed in a shell model framework.

2.1. ^{82}Ge(d, p)^{83}Ge

The first ever measurement using the (d, p) reaction on an exotic r-process nucleus was performed using a 4 MeV/nucleon beam of ^{82}Ge (15% ^{82}Ge, 85% ^{82}Se after sulfur purification). The total beam, having an intensity of 7×10^4 pps, impinged on a $430 \mu\mathrm{g/cm}^2$ foil CD_2 target. An ioniza-

[1] More recently this collaboration has measured states in ^{131}Sn using a RIB of ^{130}Sn, but no results will be presented here.

tion chamber was placed at zero degrees to monitor beam and beam-like recoil particles and to give identification of the charge of the particle. Protons emerging from the (d,p) reaction were measured in SIDAR [2], which was mounted in a lampshade of six detectors subtending $\theta_{\rm lab} = 105°–150°$ ($\theta_{\rm CM} = 11° - 36°$). The energies and angles of protons incident in SIDAR were measured in coincidence with either ^{83}Se or ^{83}Ge in the ionization chamber. In this way, the ^{82}Se$(d,p)^{83}$Se reaction, which was previously measured in normal kinematics [3], was used as a calibration for the ^{83}Ge measurement.

The ^{83}Se measurement gave an upper limit for the Q-value resolution of 300 keV, mostly from target thickness effects. The strongest group in the ^{83}Ge Q-value spectrum has a width of 460 keV, much larger than the measured resolution. This finding, along with the systematics for the other neutron-rich $N = 51$ isotones, suggests that there is more than one state present in the low-lying group. By fitting the group with two Gaussians, the widths being set by the resolution found for ^{83}Se, a ground state Q-value of Q_0=1.47 (±0.02 stat.,±0.07 sys.) MeV and the energy of the first excited state of E_x=280 (±20 stat.) keV were extracted. The ground state Q-value implies a neutron separation energy of $\mathrm{S}_n = 3.69$ (±0.07) MeV and a mass excess of $\mathit{\Delta} = -61.25$ (±0.26) MeV, which is in agreement with a mass measurement performed at GSI [4].

Angular distributions for these two states were compared with Distorted Wave Born Approximation (DWBA) calculations performed using TWOFNR [5] and global optical model parameters. The angular distributions are compatible with an ℓ transfer of 2 and 0 for the ground and first excited states respectively, which agrees with expectations from the $N = 51$ systematics of a $d_{5/2}$ ground state and $s_{1/2}$ first excited state. The normalization of the data relative to the DWBA results give a ground state and first excited state spectroscopic factor of $S = 0.48$ (±0.14) and 0.50 (±0.15), respectively. Further details can be found in [6].

2.2. ^{84}Se$(d,p)^{85}$Se

The measurement of ^{85}Se was performed in a similar way to that described above for ^{83}Ge, with improved resolution over the original experiment owing to a thinner target (200 μg/cm^2) and a slightly higher beam energy (4.5 MeV/nucleon). The average intensity was 10^5 pps for the $A = 84$ beam which was comprised of 92% Br and 8%Se, the isobars being separated in the ionization chamber as in the previous measurement. SIDAR was mounted at $\theta_{\rm lab} = 105° - 150°$ ($\theta_{\rm CM} = 12° - 38°$) with an additional annular detector covering $\theta_{\rm lab} = 160° - 170°$ ($\theta_{\rm CM} = 8° - 4°$).

The ground state of ^{85}Se was measured as well as three previously identified excited states [7] at 461.9 keV, 1114.9 keV and 1437.6 keV. Angular distributions for the ground and first excited states confirmed the orbital angular momentum to be $\ell = 2$ and $\ell = 0$, respectively, as expected for $5/2^+$ and $1/2^+$. The extracted spectroscopic factors were found to be smaller than for ^{83}Ge at $S = 0.33$ (± 0.09) for the ground state and $S = 0.304$ ($\pm$ 0.08) for the first excited state.

2.3. Comparisons with Shell Model

We compare our experimental results to shell model calculations using an effective two-body interaction in the model space starting from the free nucleon–nucleon interaction V that is appropriate for low-energy nuclear physics. We use the charge-dependent version of the Bonn potential as our starting point [8]. This typically has a strongly repulsive core that we renormalize by building a reaction G-matrix. The G-matrix is incomplete in the sense that it sums to all orders only for the particle–particle ladder diagrams. We must also include long-range effects represented by core-polarization terms. We included these into the theory by renormalizing the G-matrix elements by the $\hat{Q}$-box method. Non-folded, irreducible, and valence linked diagrams make up the $\hat{Q}$-box. We include all non-folded diagrams to third order in G. We then compute an effective interaction $\tilde{H}$ in terms of the $\hat{Q}$-box using the folded-diagram expansion method; see Ref. [9] for further details.

Our model space consists of the $0f_{5/2}$-$1p$-$0g_{9/2}$ proton and $0g_{7/2}$-$1d$-$2s$-$0h_{11/2}$ neutron spaces, where the core is taken as ^{78}Ni with a closed $0f_{7/2}$ proton orbital and a closed neutron shell at $N = 50$. The interaction is defined by both the single-particle energies (SPE) within the model space, taken from Ref. [10], and the effective two-body interaction in that space. It was found that better agreement with experimental results for the excitation energy of the 2^+ in the even–even $N = 50$ isotones could be made when the $0g_{9/2}$ SPE was set to a higher level of $\varepsilon(0g_{9/2}) = 4.5$ MeV (*c.f.* 3.3 MeV), and it is this value which is used in the calculations below. A comparison between the original set of SPE's and this modified set, as well as further details of the calculations and results thereof, will be presented in a longer article [11].

The shell-model problem is an eigenvalue problem, requiring the solution to $\tilde{H} \mid \Psi_k\rangle = E_k \mid \Psi_k\rangle$, with $k = 1, \ldots, K$. We employ the Lanczos algorithm to find the lowest (and highest) eigenvalues and eigenvectors (up to typically $K = 10$). The basic algorithm we use was first proposed in Ref. [12]. We performed calculations using the Strasbourg shell-model code Antoine [13]. The calculated spectroscopic factor is given by $S(j) = \mid \langle \Psi_f(J_f) \mid a_j^\dagger \mid \Psi_i(J_i)\rangle \mid^2$.

The comparison between experiment and theory is shown in Fig. 1. The length of the lines in Fig. 1 denotes the value of the spectroscopic factor. Generally, the calculations show good qualitative agreement; the $5/2^+$ state is always the ground state, the trend of reduced splitting between $5/2^+$ and $1/2^+$ states going from ^{89}Sr and ^{91}Zr to ^{83}Ge and ^{85}Se is reproduced as are the reductions in the spectroscopic factors. There is also some quantitative agreement for the spectroscopic factors compared to the experimentally measured values. However, the small excitation energy of the $1/2^+$ state in ^{83}Ge is not completely reproduced in these calculations. This could be due to the omission of correlations that come from the $0f_{7/2}$ orbital within our model space, and may indicate the need to open the $0f_{7/2}$ in the protons to include further configuration mixing.

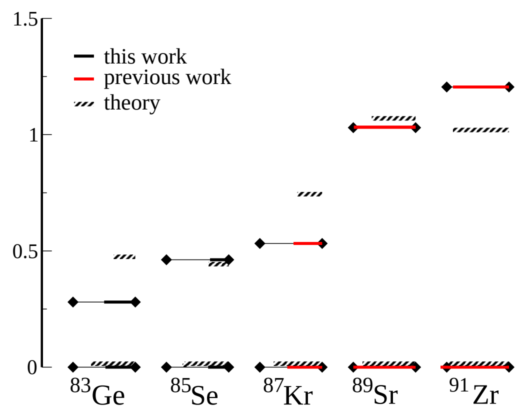

Fig. 1. Experimental and theoretical values for the excitation energy of the first excited state and spectroscopic factors for the first two states in the neutron-rich even-Z $N = 51$ systems. The spectroscopic factors are represented by the length of the bars.

3. ^{132}Sn$(d,p)^{133}$Sn

The nucleus ^{132}Sn is a rare case of an exotic doubly-magic nucleus, which can be made into a beam with enough intensity that it can be used for transfer reactions. The information known to date on ^{133}Sn has come from β-decay [14] and from the prompt γ-decay of fission fragments from ^{248}Cf [15]. The β-decay of ^{133}In is dominated by the $(\pi g_{9/2})^{-1}$ configuration, which predominantly populates $7/2^+$, $9/2^+$ and $11/2^+$ states in ^{133}Sn. Similarly with the β-delayed neutron decay from ^{134}In, it is higher spin states that are preferentially populated. Although most of the bound states in ^{133}Sn were identified via these methods, the $1/2^-$ state in particular has a paucity of knowledge, with its location only tentatively assigned [14]. The fission studies were only sensitive to the high spin states, due to preferred population of yrast states and multiple gating techniques. The (d,p) reaction is an ideal method for measuring low-spin states due to the selectivity of the reaction mechanism. States up to $\ell = 3$ can be populated strongly in this reaction.

In our (d,p) reaction study, a 630 MeV beam of ^{132}Sn (4.77 MeV/u) was used. The experimental setup incorporated twenty individual silicon detectors. As many of the important center of mass angles are located close to 90° in the laboratory frame in inverse kinematics, the target was turned 30° to the beam axis, allowing emerging protons to be measured perpendicular to the beam axis without being shadowed by the target frame. At backward angles, SIDAR was mounted in a half lampshade configuration covering $\theta_{\mathrm{lab}} = 143° - 167°$, and six position sensitive ORRUBA (Oak Ridge Rutgers University Barrel Array) detectors were mounted parallel to the beam subtending roughly $\theta_{\mathrm{lab}} = 90° - 130°$. Telescopes of silicon detectors with $\Delta E - E$ capabilities were required at forward angles due to the need to identify elastically scattered particles, including ^{12}C and ^{2}H particles from the target. Four of these telescopes consisted of 65 μm or 140 μm ORRUBA ΔE detectors backed by 1000 μm ORRUBA E detectors. The final telescope, centered on the beam axis vertically, comprised of a 5 cm $\times$ 5 cm 140 μm position sensitive silicon strip detector backed by a 1000 μm non-position sensitive detector of similar planar geometry. A small annular detector was mounted downstream to monitor elastic scattering as a measure of the beam current. Downstream from the target chamber, a multichannel plate (MCP) detector was mounted as an additional beam monitor and to provide a timing signal for the beam/recoil particle. Further downstream, the beam and beam-like recoils were measured in a segmented ionization chamber for elemental identification.

Protons emerging from the target following a (d,p) reaction were identified using kinematics and in energy versus angle spectra. For the ORRUBA telescopes this initial analysis used the residual energy deposited in the E detector, the energy loss in the ΔE being calculated knowing the thickness of the detector and the angle of the proton. These (d,p) events were used as gates for timing (TAC) spectra, where the time signal was taken between the MCP and the silicon detectors. The resulting spectra were used to set prompt timing gates to filter out background from fusion evaporation and other uncorrelated events.

A TAC-gated energy-angle plot for one $\Delta E - E$ telescope is shown in Fig. 2. Three distinctive loci are clearly observable, relating to the ground state and two excited states, presumably the $p_{3/2}$ and the $f_{5/2}$ excitations. Kinematics calculations can reproduce the locus of the ground state and the reported energies of these two excited states (853.7 keV and 2004.6 MeV) simultaneously, suggesting that our measurement is in agreement with the published data from [14]. Additionally, there is a weaker locus of counts between the excited states, which may be related to the $p_{1/2}$ state. Further analysis is required to obtain the excitation energy of this state and to extract ℓ-values and spectroscopic factors for all four observed states.

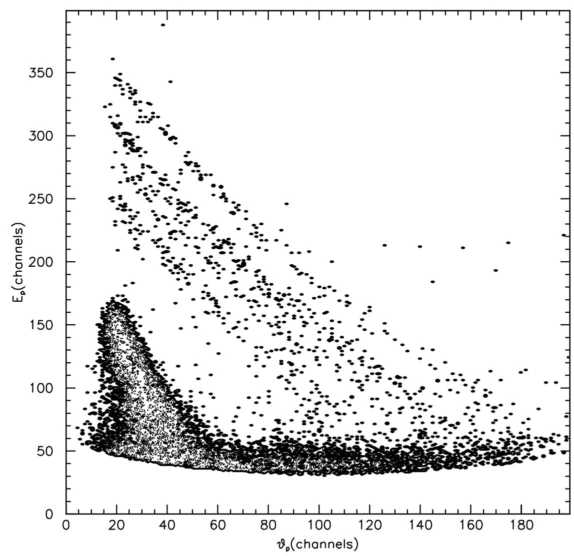

Fig. 2. Energy *versus* angle plot for one $\Delta E - E$ telescope in the ^{132}Sn(d,p) experiment.

4. Conclusions

Our collaboration is proceeding with a program to measure single-particle states using the (d,p) reaction in inverse kinematics for nuclei on, or close to, the predicted r-process path. Our focus thus far has been on the neutron shell closure at $N = 50$ and the area around doubly-magic ^{132}Sn. This work includes the first mass measurement of ^{83}Ge, an r-process nucleus. The angular distributions of protons resulting from population of the ground and first excited states in ^{83}Ge were found to be compatible with spin-parity assignments of $5/2^+$ and $1/2^+$, as would be expected from the systematics of the even-Z $N = 51$ nuclei. A similar measurement of ^{85}Se supports the assignments of $5/2^+$ and $1/2^+$ for the ground and first excited states. Extracted spectroscopic factors show a weakening for ^{85}Se compared with the stable even-Z $N = 51$ isotones followed by a slight strengthening in ^{83}Ge.

The experimental results were compared with shell model calculations using the G-matrix formalism and built on a ^{78}Ni core. The calculations show qualitative and quantitative agreement although the low excitation energy of the first excited state in ^{83}Ge is not completely reproduced.

The first data from our recent ^{132}Sn(d,p) measurement are reported. Four states are observed, presumably including the $p_{1/2}$ excitation. Further analysis will include angular distributions of protons to help verify spin-parity assignments and to extract spectroscopic factors.

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