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Single-neutron excitations in neutron-rich N = 51 nuclei

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Abstract. Single-neutron transfer reactions have been measured on two $N = 50$ isotones at the Holifield Radioactive Ion Beam Facility (HRIBF). The single-particle-like states of ^{83}Ge and ^{85}Se have been populated using radioactive ion beams of ^{82}Ge and ^{84}Se and the (d, p) reaction in inverse kinematics. The properties of the lowest-lying states —including excitation energies, orbital angular momenta, and spectroscopic factors— have been determined for these $N = 51$ nuclei.

PACS. 25.60.Je Transfer reactions – 21.10.Dr Binding energies and masses – 21.10.Pc Single-particle levels and strength functions – 26.50.+x Nuclear physics aspects of novae, supernovae, and other explosive environments

1 Introduction

The single-particle properties of nuclei near closed shells are important probes of nuclear structure. With the growing availability of beams of radioactive ions, these properties can be investigated in exotic, neutron-rich nuclei. Very few experimental data exist for the thousands of neutron-rich nuclei for which nuclear shell structure is expected to change. It has been suggested that the shift of single-particle orbitals, leading to non-traditional "magic numbers", is the result of the spin-isospin part of the monopole proton-neutron interaction [1,2]. This argument has been used to explain the emergence of a new sub-shell closure at $N = 32$ near neutron-rich ^{56}Cr [3,4]. Alternatively, extremely neutron-rich nuclei are predicted to exhibit more uniformly spaced single-particle spectra, similar to a harmonic oscillator with a spin-orbit interaction as a result of pairing interactions [5]. For both of these scenarios the single-particle structure of neutron-rich nuclei determines the extent to which the shell structure has changed.

The same low-lying structure near the closed shells may also affect the synthesis of elements in the rapid neutron capture (r-) process. In some r-process scenarios the final abundance pattern may be modified by neutron capture reactions on near-closed-shell nuclei after the fall out from nuclear statistical equilibrium [6]. But in weakly bound nuclei with small neutron separation energies, the level density of the final compound nucleus near the neutron threshold is low and neutron capture is more likely to proceed through the direct radiative capture mechanism. Without measurements of these reactions, the neutron capture rates and their influence on the final abundance must be estimated. For the direct capture component, these rates depend on specific nuclear structure data including energy levels, spins, parities, electromagnetic transition probabilities, and single-particle spectroscopic factors [7]. All of these quantities, with the exception of electromagnetic transition probabilities, can be determined from measurements of (d, p) reactions on neutron-rich nuclei.

Two (d, p) transfer measurements on $N = 50$ isotones were performed at the Holifield Radioactive Ion Beam Facility (HRIBF) to investigate the single-particle structure of the neutron-rich, $N = 51$ nuclei ^{83}Ge and ^{85}Se.

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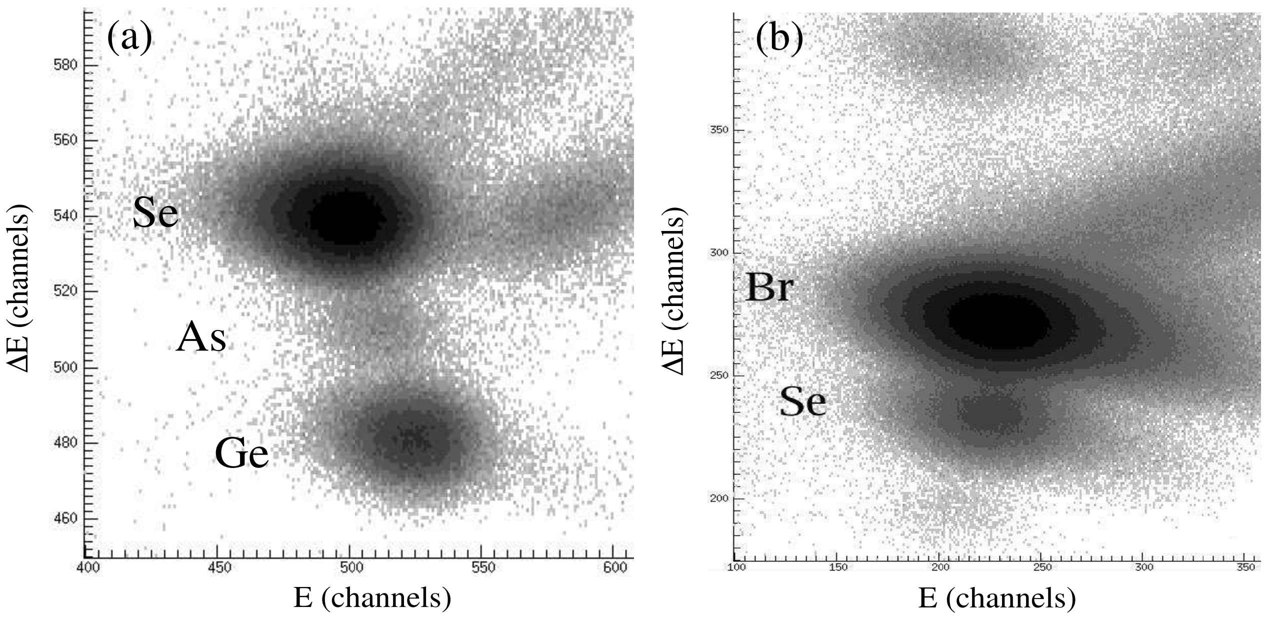

Fig. 1. Energy loss *vs.* total energy as measured by the ionization chamber for incoming beams of a) $A = 82$ and b) $A = 84$ isobars.

2 The measurements

Radioactive ion beams at the HRIBF at Oak Ridge National Laboratory are produced using the isotope separation on-line (ISOL) technique [8]. Proton bombardment of a UC target induces fission of the uranium. The resultant neutron-rich fission fragments are then transported to an ion source. It has been shown that for some group 4A elements of the periodic table (*e.g.* Sn, Ge) transport of the isotope of interest as a sulfide molecule through the ion source enhances the relative isobaric purity of the beam [8]. After mass analysis, the ions are injected into the 25 MV tandem accelerator.

2.1 ^{2}H(^{82}Ge, p)^{83}Ge

An isobaric $A = 82$ beam, accelerated to 4 MeV/nucleon, bombarded a 430 μg/cm^2 deuterated polyethylene (CD_2) target for 4 days at an average intensity of 7×10^4 pps. The beam was highly contaminated, even with the sulfur technique to enhance the relative fraction of ^{82}Ge: 85% was stable ^{82}Se, 15% was ^{82}Ge, and $< 1\%$ ^{82}As. The beam and beam-like recoils exited the target in a narrow cone with an opening angle $< 1°$, and were stopped, counted, and identified in a segmented, gas-filled ionization chamber downstream of the target. An elemental resolution of $\Delta Z = 1$ was achieved with energy loss measurements from the anodes of the ionization chamber (fig. 1a).

Protons from the reaction were detected in a large area silicon detector array (SIDAR) [9] covering the laboratory angular range of $\theta_{lab} = 105°–150°$ ($\theta_{cm} = 36°–11°$) in 16 strips. Coincidences between these protons and recoils in the ionization chamber indicate the states populated in the $A = 83$ nuclei.

The concurrent measurement of the ^{2}H(^{82}Se, p)^{83}Se reaction was a source of internal calibration as this reaction has been studied previously in normal kinematics [10]. The ^{83}Se data provided an upper limit of the excitation energy resolution that was achievable ($\Delta E_x \approx 300$ keV). Further details of the analysis of this measurement are presented in [11].

The Q-value for the ^{2}H(^{82}Ge, p)^{83}Ge reaction is $Q = 1.47 \pm 0.02$ stat. ± 0.07 sys. MeV; the first-excited state is populated at an excitation energy $E_x = 280 \pm 20$ keV. Proton angular distributions are consistent with $\ell = 2$ transfer to the ground state and $\ell = 0$ transfer to the first-excited state (fig. 2). Spin-parity assignments of $J^\pi = 5/2^+$ and $J^\pi = 1/2^+$ were made for the ground and first-excited states, respectively, based on the ℓ transfer and energy level systematics of other even-Z, $N = 51$ isotones. Spectroscopic factors were also deduced for these two states from a DWBA analysis using global optical model parameters (see [11]). The values $S = 0.48 \pm 0.14$ for the ground state and $S = 0.50 \pm 0.15$ for the first-excited state have been reported [11], with the quoted uncertainties reflecting both statistical and systematic effects. The largest of the latter are a result of the ambiguities of the DWBA parameters used to describe the bound state of ^{83}Ge, a contribution to the uncertainty 25% of the value of S.

2.2 ^{2}H(^{84}Se, p)^{85}Se

The measurement of ^{85}Se was performed with a similar arrangement of beam conditions and detector positions as the ^{83}Ge measurement. One of the largest contributions to the overall energy resolution of final states is the energy lost by the beam as it passes through the target [11]. For

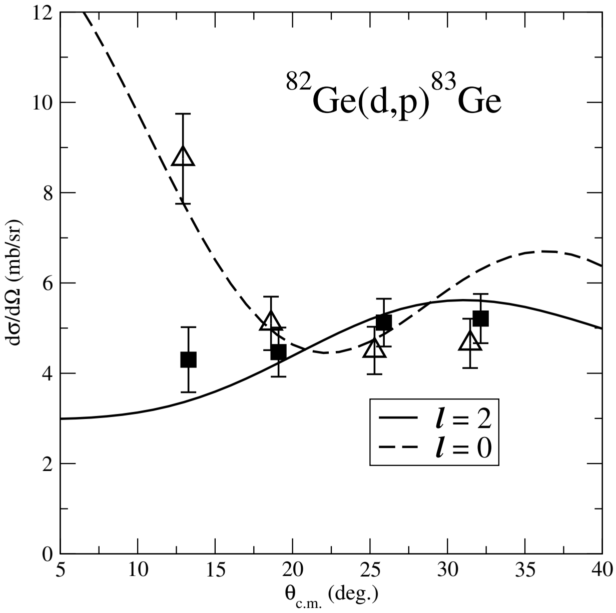

Fig. 2. Proton angular distributions for the $^2H(^{82}Ge, p)^{83}Ge$ reaction. Filled squares represent the ground state (populated with $\ell = 2$), open triangles represent the first-excited state (populated with $\ell = 0$). The curves are DWBA calculations fit to the data yielding the spectroscopic factors (see text).

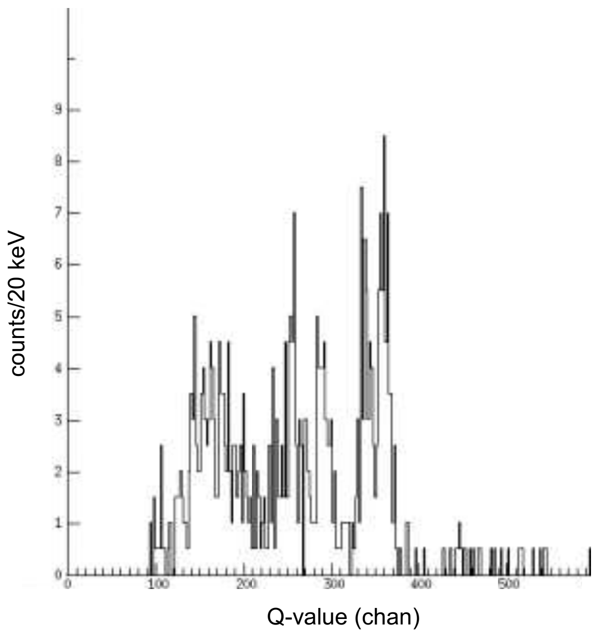

Fig. 3. The $^2H(^{84}Se, p)^{85}Se$ reaction Q-value spectrum.

the ^{85}Se measurement, a higher beam energy and thinner target were used to reduce this effect. A 380 MeV (4.5 MeV/nucleon), isobaric $A = 84$ beam bombarded a $200\,\mu g/cm^2$ CD_2 target with an average intensity of 10^5 pps. Sulfur was not introduced in the beam production because Se is one of the elements that is reduced with the technique. The beam was composed of 92% Br, 8% Se, and a trace of other elements, as determined from energy loss measurements in the ionization chamber (fig. 1b).

Protons were detected in SIDAR at backward laboratory angles ($\theta_{lab} = 105°$–$150°$ or $\theta_{cm} = 38°$–$12°$) and in an additional annular silicon detector covering $\theta_{lab} = 160°$–$170°$ ($\theta_{cm} = 8°$–$4°$). Coincidences between the protons and recoils in the ionization chamber, once again, determined the states populated in ^{85}Se. Figure 3 is a preliminary Q-value spectrum for the $^2H(^{84}Se, p)^{85}Se$ reaction showing at least 4 populated groups ($\Delta E_x \approx 220$ keV) in ^{85}Se, including the ground and first-excited states.

3 Discussion

The measurement of ^{83}Ge is the first study of the low-lying level structure of this nucleus. Previously, the half-life ($t_{1/2} = 1.85$ s) was the only measured property [12]. The Q-value for the (d, p) reaction, when corrected for the binding energy of the deuteron, yields the neutron separation energy $S_n(^{83}Ge) = 3.69 \pm 0.07$ MeV. The separation energy is also the Q-value for the (n, γ) reaction involving the same initial and final nuclei. The small Q-value for neutron capture on ^{82}Ge is actually lower than for any stable nucleus heavier than ^{15}N, suggesting direct neutron capture is a significant component to the $^{82}Ge(n, \gamma)^{83}Ge$ reaction rate. Since the mass of ^{82}Ge has been measured, the Q-value for the (d, p) reaction corresponds to an indirect measurement of the mass of ^{83}Ge, quoted first in [11] as a mass excess $\Delta(^{83}Ge) = -61.25\,\text{MeV} \pm 0.26\,\text{MeV}$. The large uncertainty in the measured ^{82}Ge mass (244 keV) leads to the large uncertainty of the derived mass.

The energy levels of ^{85}Se have been identified in a previous study of gamma transitions following β decay of ^{85}As [13]. Tentative level assignments were made in that study based on log ft values and energy level systematics. Preliminary proton angular distributions from the present study support the $J^\pi = 5/2^+$ and $J^\pi = 1/2^+$ assignments to the ground and first-excited states, respectively [14]. The distributions also yield preliminary spectroscopic factors of $S = 0.30$ for the ground state and $S = 0.35$

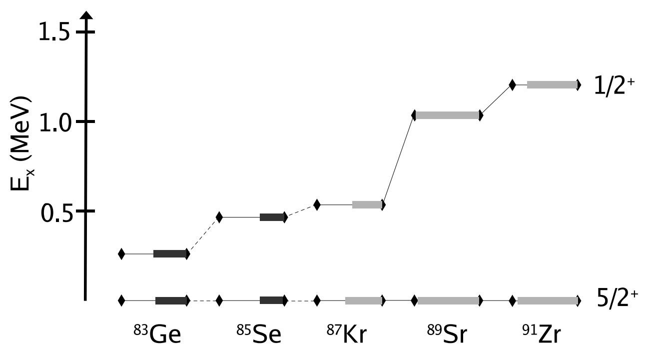

Fig. 4. Energy level systematics for even Z, $N = 51$ isotones. The length of the shaded bars represents the fraction of the single-particle strength observed in a (d, p) reaction. (Dark gray: present work; light gray: from [15].)

for the first-excited state with estimated uncertainties of 30% for each.

Figure 4 is a summary of the single-particle properties of the first two states of the $N = 51$ isotones measured in this work, compared with other even Z, $N = 51$ isotones [15]. The striking decrease of the first $1/2^+$ state with respect to the $5/2^+$ state as protons are removed from the $Z = 40$ nucleus ^{91}Zr could be evidence of a significant monopole drift: as protons are removed from the $2f_{5/2}$ orbital beginning at ^{89}Sr, any attractive monopole residual interaction between the spin-flip, $\Delta\ell = 1$ pair of $\pi f_{5/2}$ and $\nu d_{5/2}$ orbitals would weaken, raising the $\nu d_{5/2}$ relative to the $\nu s_{1/2}$. However, as fig. 4 shows, only about half of the single-particle strength was observed in the first two states for the most neutron-rich of these isotones. It is not clear that the *effective* single-particle energies (see, *e.g.*, [2]) follow the same trend as the observed energy levels.

In summary, these first (d, p) transfer measurements on two neutron-rich $N = 50$ nuclei inform the single-particle structure "northeast" of doubly-magic ^{78}Ni. The ground and first-excited states of ^{83}Ge were observed for the first time, and level assignments were made based on proton angular distributions and energy level systematics. The mass of ^{83}Ge was measured indirectly through the reaction Q-value. The related neutron separation energy is low enough to suggest a strong direct capture component to the overall neutron capture reaction rate. The preliminary analysis of the populated states of ^{85}Se lends support to the tentative level assignments made in [13]. Together, the two measurements show a continued trend of a decreasing $1/2^+$ state relative to the ground state in nuclei with increasing neutron-richness; however, additional theoretical work is needed to interpret this result.

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