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First study of the level structure of the *r*-process nucleus ^{83}Ge

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The first (d, p) neutron transfer reaction on a neutron-rich *r*-process nucleus has been measured at the Holifield Radioactive Ion Beam Facility. The ^{2}H(^{82}Ge, p)^{83}Ge reaction was studied by bombarding a 430-μg/cm^2 $(CD_2)_n$ target with a 330-MeV beam of radioactive ^{82}Ge. The reaction Q value ($Q = 1.47 \pm 0.02$ stat. ± 0.07 sys. MeV) has been measured leading to the first determination of the mass of the $N = 51$ nucleus ^{83}Ge. Excitation energies, angular distributions, and spectroscopic factors for the first two states of ^{83}Ge have also been determined.

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The properties of low-lying states in nuclei near the closed shells serve as key benchmarks for nuclear structure studies and can impact the synthesis of heavy elements in supernova explosions. Effective nuclear Hamiltonians are usually tuned in large part to reproduce experimentally determined energies, spins, and parities of single-particle and single-hole states around the closed nuclear shells. However, the available data are limited mostly to nuclei near the valley of beta stability. There are little or no experimental data for the thousands of nuclei away from stability, particularly on the neutron-rich side, where changes in the shell structure are expected. The spin-isospin part of the monopole proton-neutron interaction has been shown to cause the migration of single-particle orbitals [1,2], possibly leading to new shell closures in exotic nuclei. Examples include the disappearance of the shell gap at $N = 20$ [3] and the emergence of a new subshell closure at $N = 32$ near neutron-rich ^{56}Cr [4,5]. Hartree-Fock-Bogoliubov mean-field calculations for diffuse, neutron-rich nuclei also show that with pairing these weakly bound systems should exhibit more uniformly spaced single-particle spectra similar to a harmonic oscillator with a spin-orbit interaction [6]. Furthermore, the solar abundances attributed to the rapid neutron capture (r) process show patterns that are better explained in calculations that include a mass model with a quenched shell structure [7,8]. In all these studies, the single-particle excitation energies and strengths help determine the extent of shell structure changes.

The low-lying single-particle structure of neutron-rich nuclei near closed shells is also important for understanding how, in stellar explosions such as core-collapse supernovae, the synthesis of elements in the r process may be modified by neutron capture reactions following the fallout from nuclear statistical equilibrium [9]. The r process is believed to occur at very high temperatures. The distribution of nuclei concentrates in tightly-bound isotopes near closed shells. As the material cools, neutron captures and β decays of these near-closed-shell nuclei alter the abundance pattern. Neutron capture reactions on neutron-rich, closed-shell nuclei are expected to be dominated by direct capture to bound states because of the small Q values for neutron capture and the low-level density in the compound nucleus. Direct capture rates on these nuclei depend sensitively on the structure of low-energy states—such as energy levels (neutron separation energies), spins, parities, electromagnetic transition probabilities, and single-particle spectroscopic factors—and typically cannot be accurately estimated in the absence of experimental data [10]. It is, therefore, critical that direct capture rate calculations be supplemented with experimental data near closed shells where the r-process abundances peak.

Low-lying single-neutron excitations in ^{83}Ge have been studied for the first time using the ^{2}H(^{82}Ge, p)^{83}Ge reaction in inverse kinematics. Previously, only the half-life ($t_{1/2} = 1.85$ s) of this $N = 51$ nucleus had been measured [11]. The $A = 83$ isotope of Ge has seven neutrons more than the last stable Ge nucleus, but it is only one neutron past a closed shell. It is far enough from stability to lie on the path in some r-process models, but its low-lying spectrum is still expected to exhibit the simple characteristics of single-particle structure. With the (d, p) transfer reaction, neutron single-particle states are selectively populated, and proton angular distributions reveal orbital angular momenta and single-particle strengths of final states [12]. Because the mass of ^{82}Ge has been measured, a measurement of the Q value of the reaction also determines the mass of ^{83}Ge. Preliminary results of the ^{2}H(^{82}Ge, p) reaction measurement have been reported elsewhere [13].

The measurement was performed at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory using a radioactive ^{82}Ge ($t_{1/2} = 4.6$ s) beam. Neutron-rich radioactive ion beams were produced with the isotope separation on-line method [14]. A primary proton beam from the Oak Ridge Isochronous Cyclotron bombarded a UC target, inducing fission of the uranium. The $A = 82$ fragments were transported to an electron-beam-plasma ion source, and ^{82}Ge

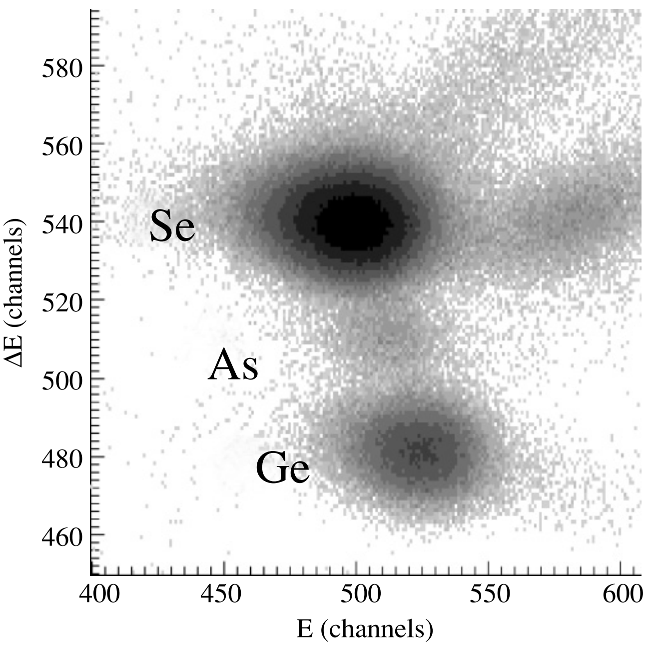

FIG. 1. Energy loss ΔE vs. total energy E spectrum for the ionization chamber for the $A = 82$ beam.

was extracted in a sulfide molecule to enhance its fraction of the mixture. The $^{82}GeS^{+}$ ions were dissociated in the Cs-vapor charge-exchange cell, and $^{82}Ge^{-}$ ions were injected into the 25-MV tandem and accelerated to 330 MeV.

The isobarically mixed $A = 82$ beam bombarded a 430 μg/cm^2 deuterated-polyethylene $(CD_2)_n$ target. The beam and beamlike recoils were highly forward focused ($\theta_{\rm lab} \leqslant 1^\circ$) and were stopped, counted, and identified according to atomic number in a gas-filled, segmented ionization chamber. With a fill gas of carbon tetrafluoride (CF_4), good Z separation was achieved for total rates up to 10^5 particles per second (Fig. 1). Even with the sulfur-enhancement technique, the $A = 82$ beam was composed of several isotopes: stable ^{82}Se (85%), ^{82}Ge (15%), and a trace of ^{82}As (<1%). The average ^{82}Ge beam rate was 10^4 particles per second.

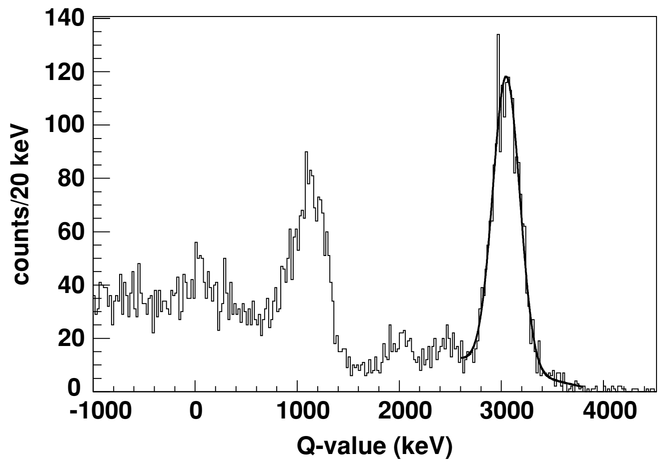

FIG. 2. ^{2}H(^{82}Se, p)^{83}Se Q-value spectrum (all angles). The solid line is the fit for the doublet of excited states of ^{83}Se at $E_x = 540$ keV and $E_x = 582$ keV.

Protons from the (d,p) transfer reaction were detected in a large area silicon detector array (SIDAR) [15] in coincidence with recoils in the ionization chamber. The array consists of 6 wedges of 16 annular strips per wedge, subtending $\theta_{\rm lab} = 105^\circ - 150^\circ$ ($\theta_{\rm c.m.} = 36^\circ - 11^\circ$). The time between SIDAR and ionization chamber events was measured for all coincident events, and true "proton-recoil" coincidences were concentrated in a time window $\Delta t = 80$ ns wide.

The concurrent measurement of the (d,p) reaction with the stable ^{82}Se beam facilitated the calibration of the ^{82}Ge rare isotope measurement. The ^{82}Se(d,p) reaction had been previously studied in normal kinematics and excitations up to 3.83 MeV were identified in ^{83}Se [16]. The measured energies of the Se-coincident protons, together with the known kinematics and relative strengths of the states populated in ^{83}Se, provided an independent calibration. The strongest populated group in ^{83}Se was a doublet of nearly equal strength states centered at $E_x = 560$ keV and separated by 42 keV—much less than the expected resolution considering target thickness effects (~200 keV). The width of this peak gave

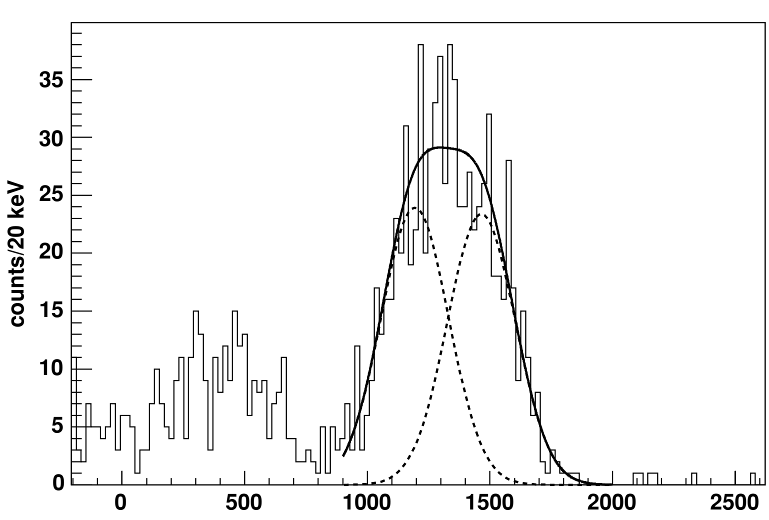

FIG. 3. ^{2}H(^{82}Ge, p)^{83}Ge Q-value spectrum (all angles). The solid line is the two-state fit for the ground and first-excited states of ^{83}Ge.

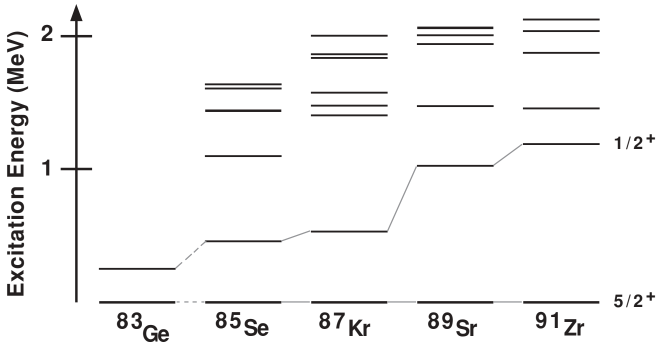

FIG. 4. The even Z, $N = 51$ energy level systematics taken from Refs. [17,18] and the present results.

an upper limit on the empirical excitation energy resolution of $\Delta E_x \approx 300$ keV (Fig. 2).

The Q-value spectrum for the ^{2}H(^{82}Ge, p)^{83}Ge reaction is shown in Fig. 3. There are two strong groups in the spectrum centered about $Q = 1.3$ MeV and $Q = 0.5$ MeV. The width of the highest-Q group, $\Delta E_x = 460$ keV, is 1.5 times the width of the ^{83}Se calibration line. The energy level systematics of the even $Z \leqslant 40$, $N = 51$ isotones [17], summarized in Fig. 4, suggest the first-excited state should exist below $E_x \approx 1$ MeV in ^{83}Ge. The width of the highest-Q group, the large separation between the first two groups, and the systematics of the even Z, $N = 51$ isotones suggest that the first two states of ^{83}Ge are unresolved in the present measurement. Figure 3 shows a fit of the unresolved group using the peak shape parameters from the ^{83}Se data. The values $Q = 1.47 \pm 0.02$ MeV and $E_x = 280 \pm 20$ keV have been extracted for the ground-state reaction Q value and the excitation energy of the first-excited state, respectively. The quoted uncertainties are statistical. The main contributions to the estimated systematic uncertainty of 70 keV are the target thickness, the excitation energy of the ^{83}Se calibration doublet, and the ^{82,83}Se masses—quantities that affect the calculated kinematics used to calibrate the measurement.

The measured Q value corresponds to a mass excess $\Delta(^{83}\text{Ge}) = -61.25 \pm 0.26$ MeV. The uncertainty propagates from the large uncertainty in the measured ^{82}Ge mass (244 keV). The neutron separation energy of ^{83}Ge can be determined more precisely by adding the well-known deuteron binding energy to the reaction Q value, yielding $S_n(^{83}\text{Ge}) = 3.69 \pm 0.07$ MeV.

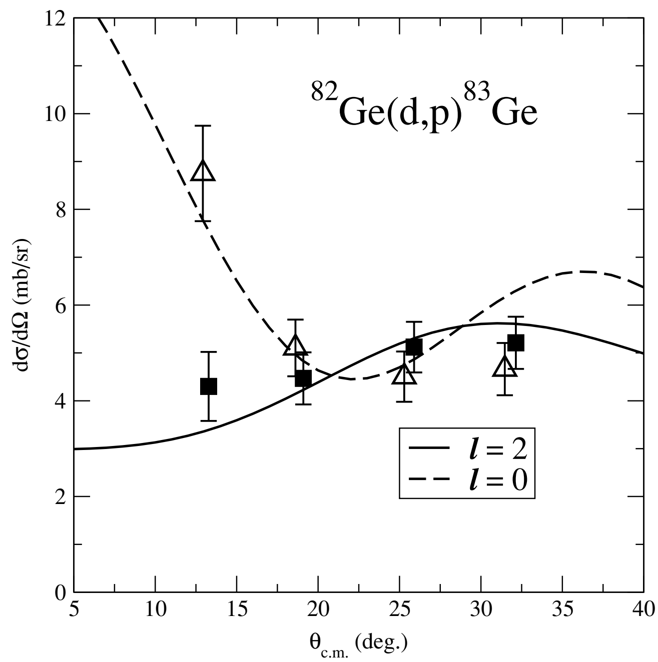

FIG. 5. Proton angular distributions as functions of c.m. angle for ^{83}Ge. Ground-state data (filled squares) fitted by $\ell = 2$ (solid curve); $E_x = 280$ keV data (open triangles) fitted by $\ell = 0$ (dashed curve).

In the study of the ^{82}Se(d, p)^{83}Se reaction by Montestruque *et al.* [16], the optical model parameters used in the distorted-waves Born approximation (DWBA) analysis were tuned to the nuclei and energies of interest by fitting to elastic scattering data. In the present inverse kinematics study, with the silicon array covering angles backwards of $\theta_{\text{lab}} = 90^\circ$, elastic scattering could not be measured. Even so, the global optical model parameters as deduced by Lohr and Haeberli [19] (deuterons) and Varner *et al.* [20] (protons) are well suited for this mass and energy region. A DWBA analysis of the Montestruque *et al.* data using these global parameters is consistent with Ref. [16]: the fits to the $E_x = 540$ keV ($J^\pi = 1/2^+$) and $E_x = 582$ keV ($J^\pi = 5/2^+$) distributions are qualitatively similar and the extracted spectroscopic factors are within 5% of those of the original work. Therefore, all subsequent DWBA analyses of the distributions of the current measurement have used the global parameter sets for the optical model potentials from Refs. [19,20]. Table I summarizes the model parameters used in the DWBA calculations with the code TWOFNR [21].

TABLE I. Global optical model parameters of Lohr and Haeberli [19] (deuteron) and Varner *et al.* [20] (proton) as input into the DWBA code TWOFNR [21]. The reader is referred to the original works for the functional forms of the optical model potentials and their dependencies on energy, atomic number, and atomic mass.

	V[a] (MeV)	r_0 (fm)	a_0 (fm)	W (MeV)	W_D (MeV)	r_W (fm)	a_W (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_c (fm)
d	107.33	1.05	0.86	0.0	11.55	1.43	0.745	7.0	0.75	0.5	1.3
p (g.s.)	56.16	1.192	0.69	0.75	10.31	1.234	0.69	5.9	1.065	0.63	1.268
n	—[b]	1.25	0.65	0.0	0.0	—	—	6.0	1.25	0.65	1.25

[a]The parameter definitions here follow the normal conventions and correspond to those found in Ref. [22].
[b]Fit to reproduce binding energy of neutron.

TABLE II. The measured Q value and excitation energy for the first two states of ^{83}Ge. Spectroscopic factors are listed assuming the given J^{π}.

Q value (MeV)	E_x (keV)	ℓ	J^{π}	$S_{\ell j}$
1.47 ± 0.02 (stat.) ± 0.07 (sys.)	0	2	$5/2^+$	0.48 ± 0.14
1.19 ± 0.02 (stat.) ± 0.07 (sys.)	280 ± 20 (stat.)	0	$1/2^+$	0.50 ± 0.15

The angular distributions for the ground and first-excited states of ^{83}Ge are shown in Fig. 5. Because of limited statistics, the data have been divided into fewer angular bins. Each bin subtends $\sim 12^{\circ}$ in the laboratory, but only 6° after the conversion to c.m. coordinates. The DWBA fits to the distributions—consistent with $\ell = 2$ for the ground state and $\ell = 0$ for the first-excited state—and the energy level systematics in Fig. 4 support a $J^{\pi} = 5/2^+$ assignment for the ground state and $J^{\pi} = 1/2^+$ for the first-excited state. Spectroscopic factors are extracted from the distributions assuming these J^{π} assignments. A Woods-Saxon form factor has been used for the neutron bound-state potential with radius and diffuseness parameters of $r_0 = 1.25$ fm and $a_0 = 0.65$ fm, respectively. A variation of these parameters within the usual range ($1.15 \leqslant r_0 \leqslant 1.35$; $0.55 \leqslant a_0 \leqslant 0.75$) leads to a 30% uncertainty in the spectroscopic factor. The results for the two lowest lying states of ^{83}Ge are summarized in Table II.

In summary, this is the first spectroscopic study of the $N = 51$ nucleus ^{83}Ge. The low-lying levels of ^{83}Ge were populated via the inverse kinematics ^{2}H(^{82}Ge, p) reaction. The measured reaction Q value, 1.47 MeV, leads to an indirect determination of the mass and neutron separation energy of ^{83}Ge. The deduced value of $S_n(^{83}\mathrm{Ge}) = 3.69$ MeV is much less than the ~ 8 MeV typically observed in nuclei nearer to stability. In fact, the Q value for neutron capture on ^{82}Ge is 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. From the shapes of the angular distributions, the ground state is populated with $\ell = 2$ and the first-excited state at $E_x = 280$ keV is populated with $\ell = 0$. Higher lying states are above $E_x \approx 1$ MeV. The extracted excitation energy of the first $1/2^+$ state in ^{83}Ge continues the decreasing trend observed in the other even $Z, N = 51$ nuclei approaching the $Z = 28$ closed proton shell of ^{79}Ni (Fig. 4). However, the spectroscopic factors—extracted from the normalizations of DWBA calculations to the data—account for only half of the single-particle strength expected in both the ground state ($\nu d_{5/2}$) and first-excited state ($\nu s_{1/2}$).

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