Properties of excited states in ^{77}Ge

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The nucleus ^{77}Ge was studied through the ^{76}Ge(^{13}C,^{12}C)^{77}Ge reaction at a sub-Coulomb energy. The angular distributions of γ rays depopulating excited states in ^{77}Ge were measured in order to constrain spin and parity assignments. Some of these assignments are of use in connection with neutrinoless double beta decay, where the population of states near the Fermi surface of ^{76}Ge was recently explored using transfer reactions.

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Introduction. Recently, measurements of neutron-adding transfer reactions on ^{76}Ge were performed to determine the population of its valence orbitals. This work was part of a series of experiments to characterize this nucleus in connection with its potential for undergoing neutrinoless double beta decay [1]. The analysis of the transfer data requires knowledge of the final-state spins and parities which, in several cases, are unknown or ambiguous [2]. In particular, no $5/2^-$ state was known in ^{77}Ge, though a level with this spin and parity was assumed to occur at 492 keV [1]. This energy had been previously reported in an abstract [3].

Most of the excited states in ^{77}Ge are known from transfer-reaction data: the most quantitative information is provided by the ^{76}Ge$(d,p)^{77}$Ge reaction using a polarized deuteron beam [4], where the vector analyzing powers and angular distributions of outgoing protons yield spin and parity information. From this study the following excited states had been assigned spin and parity: 159.70($1/2^-$), 224.9($9/2^+$), 504.8($5/2^+$), 629.4($3/2^-$), 884.3($5/2^+$), 1250.4($1/2^+$), 1385.0($5/2^+$), 1536($1/2^+$), 1777($1/2^+$), and 1804($3/2^+$) keV. No sign was seen of the 492-keV level, which could not be resolved next to the strongly populated 505-keV state, in that experiment. This represents all the states of known spin and parity; there are many other states reported with unknown spins. Beta-decay studies [5] of ^{77}Ga show some agreement with the transfer data. The state assumed to be $5/2^-$ in [1] at 492 keV, of principal interest for transfer in valence orbitals, was the one reported at 491.9 keV from studies with the (^{13}C,^{12}C) reaction with particle-γ coincidence [3].

Measurement. In the present experiment, we also used the ^{76}Ge(^{13}C,^{12}C)^{77}Ge reaction in order to reproduce the results of Ref. [3], and to attempt to measure angular distributions. We used a ^{13}C beam provided by the Argonne Tandem Linear Accelerator System (ATLAS). The yield was explored for beam energies between 27 and 36 MeV whilst monitoring Coulomb excitation, fusion-evaporation, and single-neutron transfer yields—29 MeV was found to be optimal, considerably lower than the 40 MeV used in the earlier work. The experiment was performed in two modes: the first, used a target of $\sim$400 μg/cm^2 of isotopically-enriched ^{76}Ge deposited on $\sim$10 mg/cm^2 of ^{208}Pb, ensuring that all recoiling ^{77}Ge ions were stopped in the backing. The reaction site was at the center of Gammasphere (GS) [6], comprised of 99 Compton-suppressed high-purity Ge detectors. The entire data stream was recorded, with no requirement on γ-ray multiplicity. The second mode utilized the Fragment Mass Analyzer (FMA) [7] in conjunction with GS to allow recoil-γ coincidences to be measured. For this phase, a similar layer of ^{76}Ge was deposited on a carbon foil $\sim$20 μg/cm^2 thick, with the carbon facing the beam, to allow recoiling ions to enter into the FMA. This instrument was tuned to accept ions of $A/Q = 77/10$ at the focal plane, where a parallel-grid avalanche counter was placed. The γ rays were required to be in coincidence with the detected ^{77}Ge ions. The efficiency of the FMA was $\sim$5%—limited by both solid angle and the fact that only one charge state was detected.

The data from GS operating alone were used to create a γ-γ coincidence matrix of prompt γ rays (selected by a narrow time gate centered on the prompt time peak), whereby gating on known transition energies in ^{77}Ge allows for identification of coincident γ rays. Examples of this are provided in Figs. 1(a) and 1(b) and are discussed below. The recoil-γ coincidence data were used to extract angular distributions, $W(\theta)$, where θ is the angle relative to the beam direction. Examples of these are given in Fig. 2, plotted as a function of $\cos^2\theta$. The measured angular distributions were fitted with the standard form

$$W(\theta) = A_0[1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)], \qquad (1)$$

where $P_L(\cos\theta)$ are Legendre polynomials and the coefficients, a_2 and a_4, can be found in Table I. A total spectrum of the recoil-γ coincidence data is shown in Fig. 1(c). The assignments made from the present measurement, resulting in the level scheme in Fig. 3, are as follows.

492 keV. The high efficiency of GS allows for the identification of previously unobserved γ-ray transitions in coincidence with the 492-keV transition. Gating on this transition yields the spectrum seen in Fig. 1(a): peaks at 127, 419, 561, 783, 794, 893, and 916 keV have been established as transitions feeding the 492-keV state. (Only the 127-, 419-, and 893-keV γ rays are shown in the partial level scheme of Fig. 3.) In turn, gating on the 419-keV transition identifies the 332- and 492-keV transitions, both assigned to depopulate the 492-keV

TABLE I. Energies, spins, and parities of excited states in ^{77}Ge. Relative intensities, I_γ, are given as a percentage of the 225-keV transition. The angular distribution coefficients, a_2 and a_4 (extracted from a least-squares fit of the angular distributions, with the form of Eq. (1)) and multipolarity (where square brackets indicate the multipolarity inferred from the level scheme), as derived from the recoil-γ coincidence data, are presented. All energies E_γ are as measured in the γ-γ coincidence data. For E_{level}, the energy is a weighted average based on the multiple decay paths. The uncertainties in energy are 0.1 keV for transitions with $I_\gamma > 5\%$ and 0.2 keV for the rest. The uncertainties in the intensities are statistical; there is an estimated 5% systematic uncertainty. Underlined values of $I^\pi_{\text{i,f}}$ were assigned in the present analysis.

E_{level} (keV)	I^π_{i}	E_γ (keV)	I_γ (%)	a_2	a_4	γ multipolarity	I^π_{f}
224.9	$9/2^+$	224.9	≡100	−0.39(6)	+0.12(7)	$M1/E2$	$7/2^+$
421.4	$\underline{(5/2)^+}$	421.4	124(3)	−0.01(6)	−0.03(7)	$(M1/E2)$	$7/2^+$
492.0	$\underline{5/2^{(-)}}$	332.4	1.3(9)[a]			$[E2]$	$1/2^-$
		492.0	23(1)	−0.42(15)	−0.16(19)	$(E1)$	$7/2^+$
504.8	$5/2^+$	83.5	37(2)	−0.03(10)	+0.19(12)	$[M1/E2]$	$\underline{(5/2)^+}$
		279.9	4.3(9)[a]			$[E2]$	$9/2^+$
		504.8	96(3)	−0.20(6)	−0.01(8)	$M1/E2$	$7/2^+$
618.9	$\underline{3/2^+}$	114.0	0.14(3)[a]			$[M1/E2]$	$5/2^+$
		126.8	0.36(5)[a]			$[E1]$	$\underline{5/2^{(-)}}$
		197.5	6.3(7)[a]			$[M1/E2]$	$\underline{(5/2)^+}$
		459.2	32(2)	−0.08(11)	−0.10(14)	$E1$	$1/2^-$
		618.9	8(2)[a]			$[E2]$	$7/2^+$
629.7	$3/2^-$	470.0	61(2)	−0.10(8)	+0.01(10)	$M1/E2$	$1/2^-$
760.6	$\underline{7/2^+}$	255.7	14(1)	−0.3(2)	+0.2(3)	$M1/E2$	$5/2^+$
		535.6	24(1)	−0.53(13)	+0.17(16)	$M1/E2$	$9/2^+$
		760.6	8.1(10)	−0.0(3)	−0.2(3)	$M1/E2$	$7/2^+$
884.3	$5/2^+$	884.3	33(2)	−0.07(19)	+0.5(3)	$M1/E2$	$7/2^+$
910.6	$\underline{(5/2,7/2)^+}$	291.8	3.0(4)[a]				$\underline{3/2^+}$
		418.5	8.4(8)[a]			$[E1]$	$\underline{5/2^{(-)}}$
		685.6	3.8(5)[a]				$9/2^+$
1385.3	$5/2^+$	624.7	39(2)	−0.69(17)	+0.2(2)	$M1/E2$	$\underline{7/2^+}$
		755.6	30(2)	−1.1(1)	−0.14(15)	$[E1]$	$3/2^-$
		766.5	17(1)	+0.3(2)	−0.5(3)	$[M1/E2]$	$\underline{3/2^+}$
		880.5	36(2)	+0.5(2)	−0.2(2)	$M1/E2$	$5/2^+$
		893.3	5.2(6)[a]			$[E1]$	$\underline{5/2^{(-)}}$
		963.9	11(1)[a]			$[M1/E2]$	$\underline{(5/2)^+}$

[a]Intensities too weak to analyze angular distribution.

state, see Fig. 1(b). The known spins and parities of the ground state, the 160-keV isomeric state, and the shape of the angular distribution of the 492-keV γ ray (see Fig. 2) favor the assignment of $I = 5/2$ and a tentative negative parity based on the following. The angular distribution immediately rules out the possibility of $I = 3/2$, as this would require a positive a_2 coefficient. If the 492-keV transition were $9/2 \rightarrow 7/2$, it would mean that the competing 332-keV transition was of $E4$ or $M4$ character. Similarly, if the 492-keV transition were $7/2 \rightarrow 7/2$, it would imply competition with an $E3$ or $M3$ transition. The observed branching ratio makes both of these scenarios unlikely. The tentative negative-parity assignment of the 492-keV level arises from the same argument.

581 and 778 keV. In the present analysis, no evidence was found for the existence of the 581- and 778-keV states reported in the β-decay study of Ref. [5], nor was any seen in the previous (^{13}C,^{12}C) reaction data [3]. The 778-keV state was reported to decay via the emission of 197- and 619-keV γ rays, populating the 581- and 160-keV states, respectively. The 581-keV level, in turn, was reported to feed the 160-keV state via emission of a 421-keV γ ray—this is in disagreement with current findings. The present analysis shows that the 619-keV state is depopulated by a 459-keV γ-ray transition to the 160-keV state (see Fig. 3), and four less intense transitions of 114, 127, 197, and 619 keV, as shown by the spectrum gated on 767 keV in Fig. 1(d). The 421-keV transition is seen to populate the ground state exclusively. Arguments for describing the 197-keV γ ray as depopulating the 619-keV state are based on observing its coincidence with the 421-keV γ ray. Similar coincidence relationships show the newly observed 127-keV transition to populate the 492-keV state, and the 114-keV transition to feed the 505-keV state.

421 keV. This state is tentatively assigned spin 5/2 in this analysis. Previously measured to be $\ell = 2$ from the (d,p) work of Ref. [8], its parity is known to be positive. The angular distribution of the 421-keV γ ray, presented in Fig. 2, is consistent with $M1/E2$ character, where the best fit was found for a mixing ratio $\delta = -0.10$. The angular distribution for a quadrupole transition, $3/2 \rightarrow 7/2$, shows a poorer fit to the data and so we assign $(5/2)^+$ on this basis.

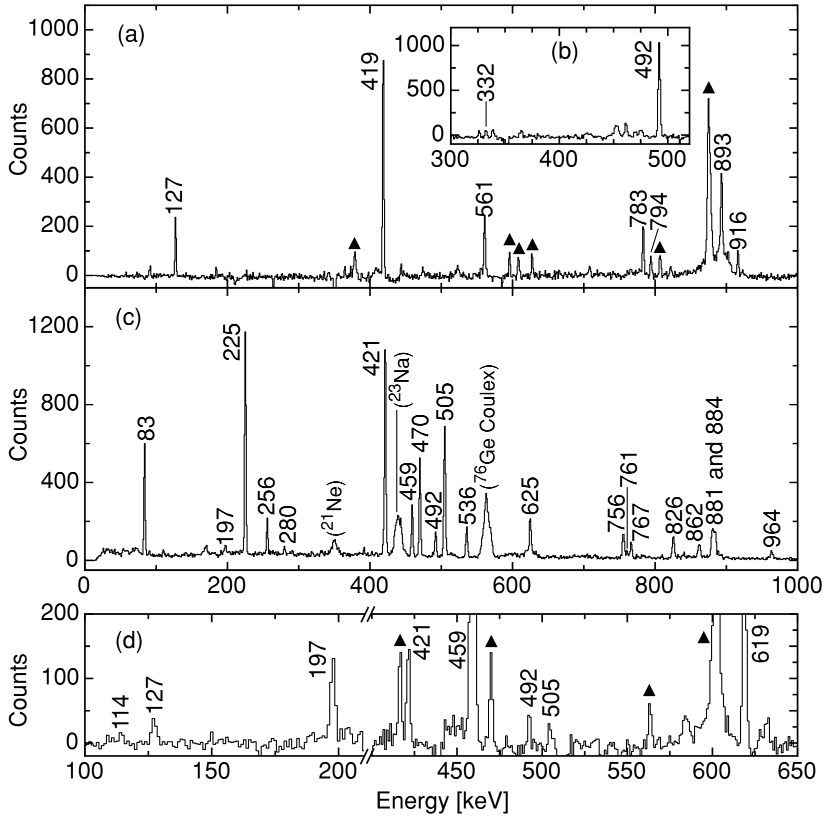

FIG. 1. (a) Spectrum produced by gating on the 492-keV transition in the GS data, showing coincidences with transitions deexciting levels located above the 492-keV state; (b) spectrum produced by gating on the 419-keV transition in the GS data, where both the 332- and 492-keV γ rays, assigned to depopulate the level at 492-keV, are seen; (c) spectrum recorded by GS in coincidence with mass $A = 77$ detected at the focal plane of the FMA; (d) spectrum produced by gating on the 767-keV transition in the GS data, showing the transitions depopulating the 619-keV state. In all spectra, peaks are labeled according to their energy to the nearest keV; those marked with a ▲ are from known contaminants.

619 keV. The spin of the 619-keV state, previously restricted to $1/2, 3/2$, or $5/2$ [2], is assigned as $3/2$ with positive parity in the present work. The angular distribution of the 459-keV γ ray is not consistent with a stretched-quadrupole assignment (see Fig. 2) making a spin of $1/2$ or $3/2$ plausible in view of it feeding the $1/2^-$ state; however, the 619-keV transition to the $7/2^+$ ground state disfavors a spin $1/2$ assignment and also suggests positive parity. (The 114- and 127-keV transitions populate states with spin 5/2, with positive and tentatively negative parity, respectively, further strengthening the assignment.)

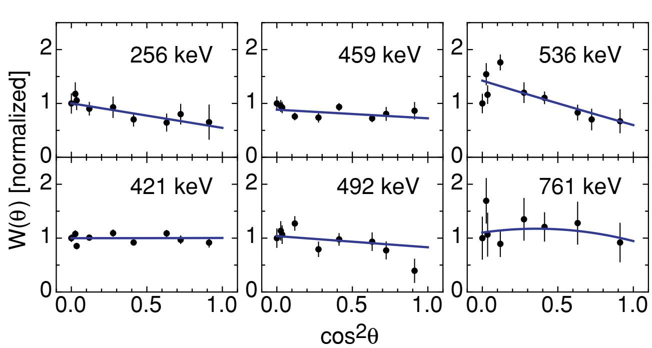

FIG. 2. (Color online) Angular distributions for γ-ray transitions in ^{77}Ge, labeled by their energy to the nearest keV, that are relevant to the discussion. The fitted lines are theoretical curves (for fully aligned states) based on the assigned multipolarities of Table I. Mixing ratios of $\delta \sim 0.0, -0.1, 0.2$, and -0.55 were obtained by fitting the 256-, 421-, 536-, and 761-keV mixed $M1/E2$ transitions, respectively. The error bars represent the statistical uncertainty.

761 keV. This state was reported in Ref. [3] to deexcite via γ-ray emissions of energies 256, 536, and 761 keV. The present work confirms this. The spin and parity of this state were

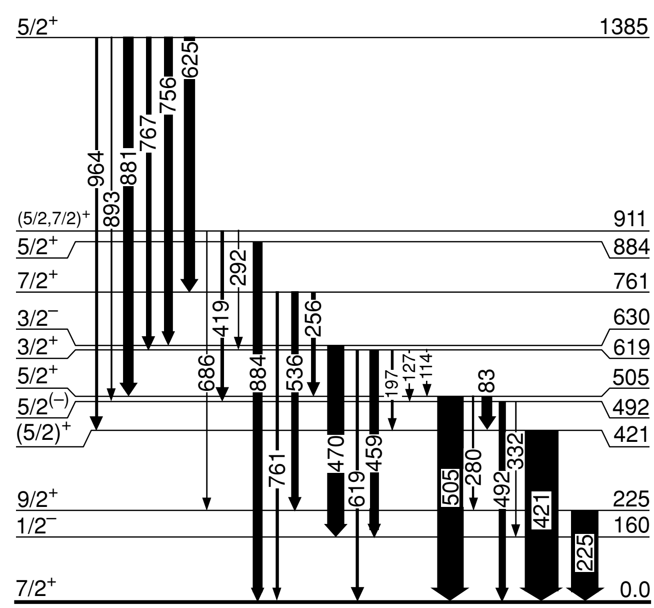

FIG. 3. Partial level scheme of ^{77}Ge deduced from the γ-γ coincidence data (with the exception of the 884-keV state, seen only in the recoil-γ coincidence data). Levels are labeled by their spin and parity. Energies of the levels and transitions are given to the nearest keV. The thickness of the arrows is in proportion to the intensity of the transition.

previously constrained to $5/2^+, 7/2$, or $9/2^+$: in this work we assign $7/2^+$. The 536-keV transition to the 225-keV, $9/2^+$ state has an angular distribution consistent with an $M1/E2$ transition (see Fig. 2) as does the 761-keV transition to the $7/2^+$ ground state, and the 256-keV transition to the 505-keV, $5/2^+$ state.

911 keV. A newly observed state at 911 keV is reported, though its spin cannot be fixed in this work—it is tentatively assigned $(5/2, 7/2)^+$. The 292-keV transition from this state to the 619-keV level, which we assigned as spin and parity $3/2^+$, suggests an upper limit of 7/2 for the spin of the 911-keV state. Likewise, the 686-keV transition to the 225-keV, $9/2^+$ state suggests a lower limit of 5/2 for the spin. Under the assumption that multipolarities higher than $E2$ are unlikely, positive parity is thus assigned.

Reaction mechanism. An additional check is provided by comparing the observed intensities with cross sections calculated with previously observed spectroscopic factors. The relative cross sections for the single-neutron transfer from (^{13}C,^{12}C) can be deduced by evaluating the γ-ray intensities: the observed feeding from higher-lying states being subtracted. This allows for a comparison with distorted-wave Born approximation (DWBA) calculations, the results of which are found in Table II. The DWBA calculations were done with the finite-range PTOLEMY [9] code. Several sets of optical-model and bound-state parameters [10] were used to explore the sensitivity of the relative cross sections to the parameters (the average values are given in Table II): the rms variation in the calculations due to the choice of parameters is $<5\%$. The FMA-selected ^{77}Ge recoils correspond to the transfer reaction at backward angles—its angular acceptance ($\pm 0.96^\circ$ horizontally, $\pm 1.69^\circ$ vertically) corresponds to center-of-mass angles between ~ 170 and 180°. The spectroscopic factors were those of Refs. [1,11], and the relative cross sections are normalized to the 225-keV, $9/2^+$ state. For the $5/2^+$ strength, the sum of the strength for all observed states with this assignment is compared to the single-particle strength. Though this is a crude comparison, it appears that about 40% of the $d_{5/2}$ strength is in the identified states. The measured cross section for transfer to the 492-keV, $5/2^{(-)}$ state in (^{13}C,^{12}C) appears to be a factor of approximately two higher than the DWBA estimate, though the uncertainties are large here. Overall, the agreement in the relative intensities is consistent with what is expected from simple transfer.

TABLE II. Measured relative cross sections, $\sigma_{\text{exp.}}$, compared to DWBA calculations, σ_{DWBA}, and previously determined spectroscopic factors, S [1]. The uncertainties in $S\sigma_{\text{DWBA}}$ arise from the experimental uncertainties in S. All results are presented relative to $\ell = 4$ transfer to the 225-keV state.

E_{level} (keV)	I_f^π (or ℓ transfer)	$\sigma_{\text{exp.}}$	$S\sigma_{\text{DWBA}}$	Ratio
225	$9/2^+$	≡1.00	≡1.00	≡1.00
492	$5/2^-$	0.13(4)	0.061(14)	2.07(82)
630	$3/2^-$	0.34(10)	0.38(7)	0.89(31)
1022	($\ell = 1$)	0.34(10)	0.32(6)	1.06(37)
1053	($\ell = 1$)	0.04(2)	0.11(2)	0.35(20)
–	$5/2^+$	4.2(12)[a]	10.47[b]	0.40(11)

[a]Summation of the 421-, 505-, 884-, and 1385-keV strength.
[b]Full sum-rule value, $S = 1$, used in the calculation for $5/2^+$.

The present report focuses on the states relating to the "active orbitals" in ^{77}Ge. The full level scheme extracted from this work is not shown, nor are all measured states and transitions presented in Table I. A complete summary of these data are available online in the XUNDL database [11].

Conclusion. γ rays depopulating states in ^{77}Ge were measured and γ-γ coincidences were used to construct a level scheme which provides some agreement with previous observations [2]. Additional information, provided by γ-ray angular distributions, was used to fix, or constrain, the spins and parities of several states. The spin and parity of the 492-keV state is found to be $5/2^{(-)}$, in line with the assumption made in Ref. [1].

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