Collectivity in ^{66}Ge and ^{68}Ge via lifetime measurements

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Lifetimes of the 2_1^+ states in ^{66,68}Ge were measured using the recoil distance Doppler shift method. Excited states in ^{66}Ge and ^{68}Ge were populated using the ^{58}Ni(^{10}B, $p2n$) and ^{58}Ni(^{12}C, $2p$) reactions, respectively. Lifetimes were extracted from coincidence data using the differential decay curve method. The resulting $B(E2;\ 2_1^+ \rightarrow 0_1^+)$ transition strengths are compared with large-scale shell-model calculations.

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Understanding the structure of germanium isotopes has always been difficult; they have sufficient valence particles in the fpg shell to be a real challenge to the shell model, are not amenable to bosonic approaches due to the underlying single-particle states, and are not sufficiently collective to be easily described by traditional collective models. Nonetheless, considerable new effort, both experimental and theoretical, is leading to rapid progress in understanding these nuclides. From the experimental side, the main thrust is to expand the data on a wider range of isotopes, with measurements of $B(E2;\ 2_1^+ \rightarrow 0_1^+)$ values being extended to both extremes of the Ge isotopic chain. The $N = Z$ nucleus, ^{64}Ge, has been studied [1] using knockout reactions, and the very neutron-rich Ge, up to $N = 50$, have been investigated [2] via Coulomb excitation. From the theory side, very-large-basis shell-model calculations [3,4] are state of the art, while refinements of "beyond mean field" Hartree-Fock-like approaches are becoming more reliable [5].

One experimental curiosity that has emerged from the data is the very low $B(E2;\ 2_1^+ \rightarrow 0_1^+)$ transition strength in ^{66}Ge ($N = 34$). The systematics of the $B(E2;\ 2_1^+ \rightarrow 0_1^+)$ values in the Ge isotopes are given in Fig. 1(b). Despite being located away from any major shell closure, the reported value [7] of $B(E2;\ 2_1^+ \rightarrow 0_1^+) = 12.0(23)$ W.u. for ^{66}Ge is nearly as low as that of the spherical, $N = 50$, ^{82}Ge. Further, while both the adjacent even-even isotopes ^{64}Ge and ^{68}Ge are reported to be quite collective, with $B(E2;\ 2_1^+ \rightarrow 0_1^+) \sim 20$ W.u., ^{66}Ge appears anomalously low, almost half of this value, and it is difficult to account for this finding in any modern theory. The apparent decrease in collectivity for ^{66}Ge is not reflected in the first 2^+ energy, $E(2_1^+)$, which remains rather constant across the light Ge isotopes, as shown in Fig. 1(a).

This paper reports on new recoil distance Doppler shift (RDDS) measurements of lifetimes in ^{66}Ge and ^{68}Ge using a modern coincidence plunger technique to try to resolve this anomaly and to determine if this is due to an experimental or a theoretical issue. The RDDS method applied in coincidence mode eliminates the issues of side feeding and therefore provides more reliable values compared with earlier singles measurements [7–12]. Resulting $B(E2)$ values are compared with the predictions of different large-scale shell-model calculations.

Lifetimes in ^{66,68}Ge were measured with the RDDS method in coincidence mode. Excited states in ^{66}Ge were populated by using the ^{58}Ni(^{10}B, $p2n$) reaction at a beam energy of 28 MeV, while excited states in ^{68}Ge were populated via the ^{58}Ni(^{12}C, $2p$) reaction at a beam energy of 38 MeV. The ^{10}B and ^{12}C beams were provided by the Extended Stretched TransUranium (ESTU) tandem accelerator at the Wright Nuclear Structure Laboratory at Yale University. Beam currents were limited to ~1 pnA to avoid damaging the stretched target foils. In both experiments, a 0.6 mg/cm^2 self-supporting ^{58}Ni target and a 12 mg/cm^2 Au stopper foil were used. The target and stopper foil were mounted in the new Yale plunger device (NYPD) [13]. The measured recoil velocities in these reactions were $v/c = 0.78(2)\%$ for ^{66}Ge and $v/c = 1.03(5)\%$ for ^{68}Ge.

Data were collected for 14 target-to-stopper distances ranging from 2 to 1500 μm for time intervals between 2 and 8 h. Longer runs were used for the shorter distances. To correct for thermal deformation of the target and stopper foils induced by beam heating, the plunger was run with an automatic feedback system. The capacitance between the two foils was continuously monitored, and fluctuations were corrected. The error of the relative target-to-stopper distances was ~0.2 μm for the range from electrical contact to 10 μm and ~2% the target-to-stopper separation for distances of 20–500 μm.

γ rays were detected by the SPEctrometer for Experiments for Doppler shifts at Yale (SPEEDY) array [14], with eight Compton-suppressed HPGe Clover detectors arranged in two rings located at angles of 41.5° and 138.5° relative to the beam axis. Data were collected with a doubles trigger and, for each distance, sorted into four γ-γ matrices that relate to all combinations (forward/forward, forward/backward, backward/forward, backward/backward) of the two detector rings. For each experiment, $\sim 1 \times 10^9$ events with multiplicity

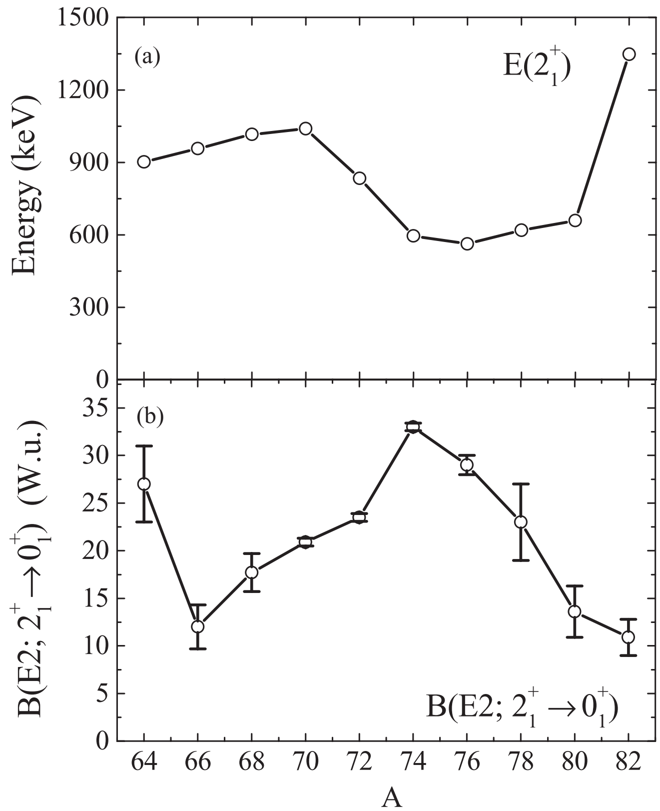

FIG. 1. Systematics of observables in the Ge isotopes as a function of mass number including (a) the first 2^+ level energy (in keV) and (b) literature $B(E2; 2_1^+ \to 0_1^+)$ values (in Weisskopf units). Data on $B(E2)$ values are taken from the evaluated data [6], except for ^{64}Ge [1] and ^{82}Ge [2].

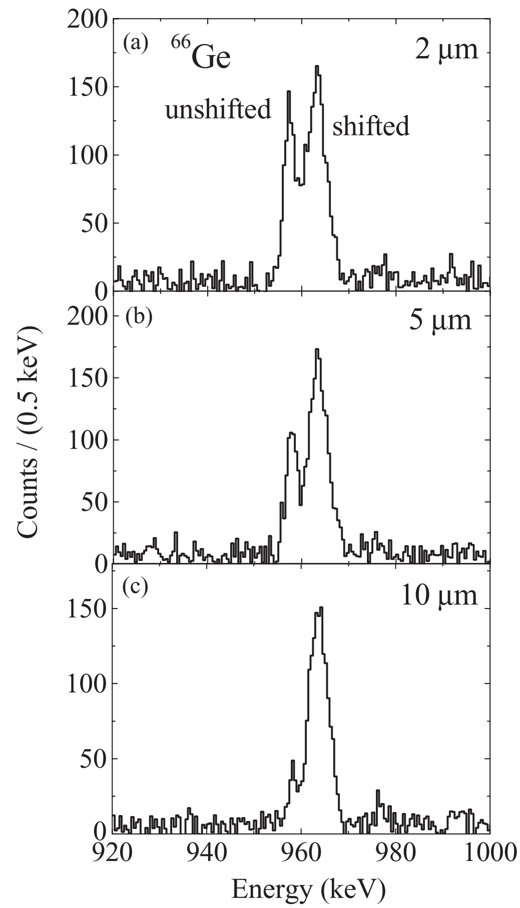

FIG. 2. Sample gated spectra for ^{66}Ge from the forward (38.5°) ring of detectors at three target-to-stopper distances. Spectra were obtained by gating on the shifted component of the $4_1^+ \to 2_1^+$ transition and show the shifted and unshifted components of the $2_1^+ \to 0_1^+$ transition.

$\geqslant 2$ were recorded. The spectra for different target-to-stopper distances were normalized by gating on the shifted and unshifted components of several different γ-ray transitions and requiring that the sum of the shifted and unshifted components of the higher lying γ-ray transitions remained constant for all distances. The quality of the gated spectra for ^{66}Ge and ^{68}Ge is illustrated in Figs. 2 and 3, respectively.

Lifetimes of excited levels were determined using the differential decay curve method (DDCM) [15,16] in coincidence mode. Gates were placed on the shifted component of a transition directly feeding the level of interest, and the intensities of the shifted and unshifted components of the γ-ray transition, depopulating the level of interest, were measured for each target-to-stopper distance. Directly gating on feeding transitions eliminates contributions from known or unknown side feeding. For a level directly populated by transition B and depopulated by transition A, the lifetime was determined using [15,16]

$$\tau(x) = \frac{I_{su}^{BA}(x)}{v \frac{d}{dx} I_{ss}^{BA}(x)}, \tag{1}$$

where v is the recoil velocity, x is the target to stopper distance, and I_{ss}^{BA}, I_{su}^{BA} are the number of coincidences between the shifted (s) component of the feeding transition B and the shifted or unshifted (u) component of the depopulating transition A, respectively.

The lifetime of the ^{66}Ge 2_1^+ level at 957 keV was determined through a direct gate on the 1217-keV, $4_1^+ \to 2_1^+$ transition. Sample spectra for three target-to-stopper distances are given in Fig. 2. Figure 4 shows the shifted and unshifted intensities of the depopulating transitions along with the measured τ curve for the forward angle detectors. Analysis of the forward and backward rings yielded consistent values of $\tau = 3.9(4)$ ps and $\tau = 3.6(5)$ ps, respectively. The resulting weighted average gives a lifetime of $\tau = 3.8(5)$ ps. This new result is ~30% smaller than the previously measured value of 5.3(10) ps [7] and provides a reduction in error.

The lifetime of the ^{68}Ge 2_1^+ level at 1016 keV was determined through a direct gate on the 1252-keV, $4_1^+ \to 2_1^+$ transition. Sample spectra for three different target-to-stopper distances are given in Fig. 3. The measured intensities of the shifted and unshifted depopulating transitions along with the extracted τ curve are given in Fig. 5. Analysis of the forward and backward rings gave τ values of 3.1(4) ps and 3.0(3) ps, respectively, resulting in a weighted average of 3.1(3) ps. There are several literature values for this lifetime, including 5^{+3}_{-2} ps [9], 2.0(10) ps [10], 3.0(10) ps [12], 2.6(3) ps [11], all from singles measurements using RDDS. In addition, a precise

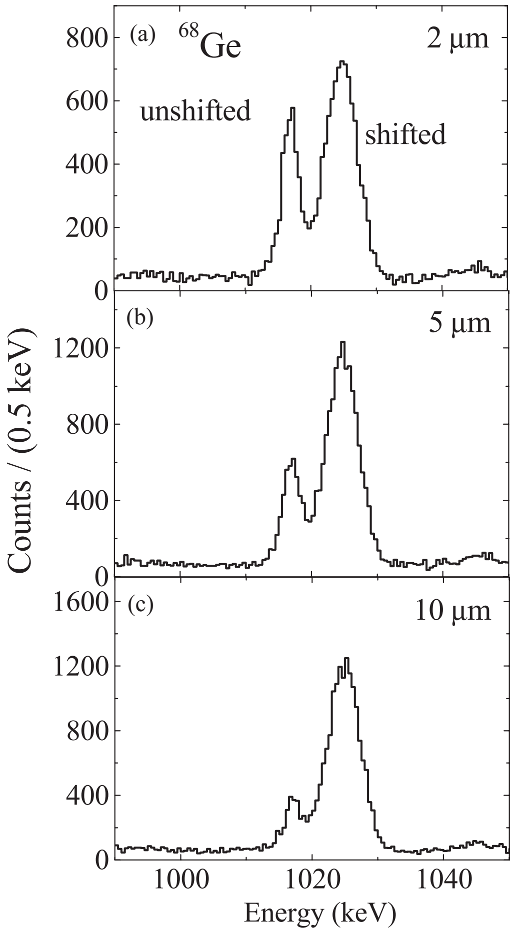

FIG. 3. Same as Fig. 2, but for the $2_1^+ \rightarrow 0_1^+$ transition in ^{68}Ge.

measurement has been reported in Ref. [17] of $\tau = 3.1(2)$ ps using the Doppler shift attenuation method, which the present result is in very good agreement with.

The $B(E2)$ transition strengths determined from the present measurements are plotted in Fig. 6. As mentioned previously, there have been several measurements of the 2_1^+ lifetime in ^{68}Ge ranging from 2 to 5 ps [18], with an adopted τ of 2.6(3) ps and an adopted $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of 17.7(20) W.u. As the present lifetime is in excellent agreement with a recent measurement [17], the value of $\tau = 3.1(2)$ is adopted here, giving $B(E2; 2_1^+ \rightarrow 0_1^+) = 14.8(14)$ W.u. In ^{66}Ge, the lifetime of the 2_1^+ state measured in the present work is ∼30% smaller than the one prior measurement [7], increasing the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value to 16.9(22) W.u. This resolves the prior anomaly in ^{66}Ge, placing it just as, or slightly more, collective than ^{68}Ge, in good agreement with the known level energies.

The experimental $B(E2; 2_1^+ \rightarrow 0_1^+)$ strengths are compared to modern shell-model calculations in Fig. 6. The GXPF1 results [19] consider only the pf shell-model orbits. They provide a good description of the transition strengths in the lighter Ge isotopes but significantly underpredict the $B(E2)$ strength for $N = 38$. This can be attributed to the necessity of including the $g_{9/2}$ orbit for the heavier Ge isotopes. In Ref. [4], the extended pairing plus quadrupole ($P + QQ$) model was applied to the Ge isotopes, including the $g_{9/2}$ orbit. These calculations nicely reproduce the transition strengths in $^{66-70}$Ge. While the $g_{9/2}$ orbit is important for describing ^{70}Ge, Ref. [4] notes that in ^{66,68}Ge, the configurations are dominated by the fp shell orbits. In Ref. [3], the shell-model space was extended to include the $g_{9/2}$ orbit using the new JUN45 effective interaction. As seen in Fig. 6, relatively good

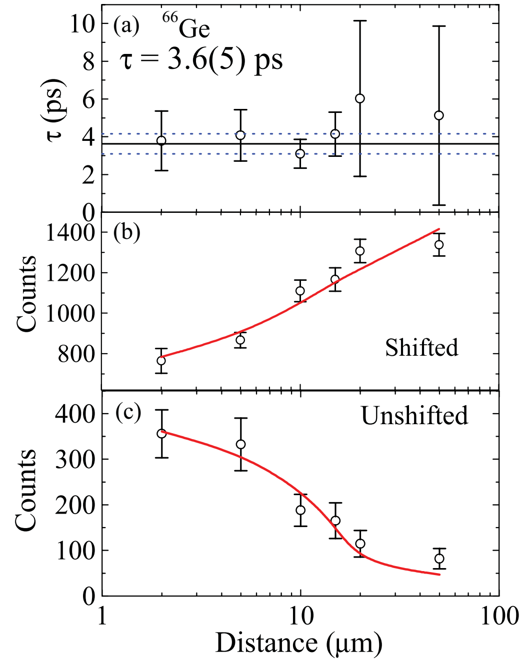

FIG. 4. (Color online) DDCM analysis of the 2_1^+ state lifetime in ^{66}Ge. Panels (b) and (c) show the shifted and unshifted intensities, respectively. The continuous curves are fits to the data and are used to extract the lifetime given in panel (a).

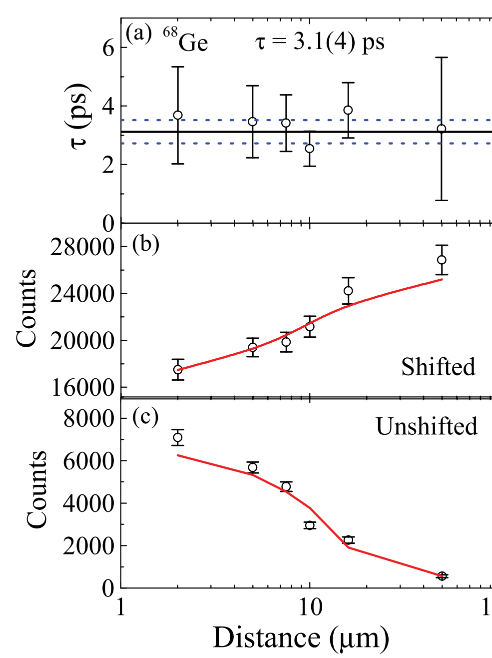

FIG. 5. (Color online) Same as Fig. 4, but for the 2_1^+ state in ^{68}Ge.

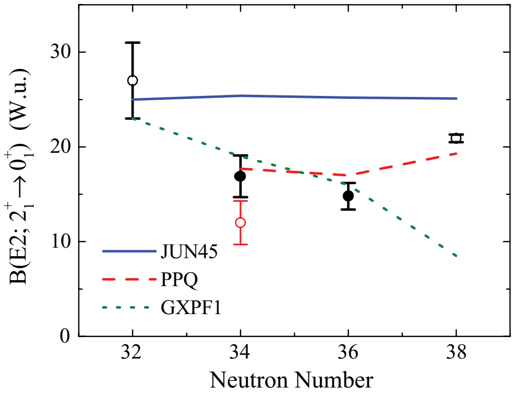

FIG. 6. (Color online) Experimental $B(E2;2_1^+ \rightarrow 0_1^+)$ values in the Ge isotopes compared with the shell-model predictions of Ref. [3] (JUN45), Ref. [4] (PPQ), and Ref. [19] (GXPF1). Solid symbols correspond to values measured in the present work.

agreement is obtained for ^{64}Ge as well as ^{70}Ge; however, the strength in ^{66,68}Ge is substantially overpredicted. These comparisons suggest that while the $g_{9/2}$ orbit is important for describing the heavier Ge isotopes, it does not play a significant role in the low-lying structure of ^{66,68}Ge.

We note that the most straightforward difference between the JUN45 calculations and the PPQ predictions is in the effective charges. In JUN45, a rather large neutron effective charge is used ($e_\nu = 1.1$), whereas in the PPQ calculations, the neutron effective charge was taken as 0.50. The PPQ calculations investigated the influence of the neutron effective charge and found significant overprediction of the $B(E2)$ strengths in ^{66,68}Ge when the neutron effective charge was increased to 0.97. These results could perhaps provide some guidance in determining effective charges in subsequent shell-model calculations.

In conclusion, lifetimes of the 2_1^+ states in ^{66,68}Ge were measured using the recoil distance Doppler shift method. The analysis was performed on coincidence data using the differential decay curve method. Lifetimes of $\tau = 3.8(5)$ ps in ^{66}Ge and $\tau = 3.1(3)$ ps in ^{68}Ge were obtained for the 2_1^+ states. Comparison of the resulting $B(E2; 2_1^+ \rightarrow 0_1^+)$ transition strengths with the predictions of large-scale shell-model calculations suggests that the $g_{9/2}$ orbit is not significantly involved in the low-energy structure of ^{66,68}Ge.

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