Low-level structure of ^{70}Ge from lifetime and g-factor measurements following α transfer to a ^{66}Zn ion beam

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The g factor of the 2_1^+ state in ^{70}Ge was remeasured using a different experimental approach. Furthermore, for the first time an experimental value (although with a large uncertainty) was obtained for the g factor of the 2_2^+ state in ^{70}Ge. All this was accomplished by employing the technique of α transfer to an energetic ^{66}Zn ion beam in inverse kinematics combined with transient magnetic fields in ferromagnetic gadolinium. The value of the $g(2_1^+)$ factor obtained ranges from +0.32(11) to +0.43(12), subject to certain assumptions. This range of values is in general agreement with the range of values in the literature, where Coulomb excitation and different IMPAC techniques were used. Lifetimes of several low-lying states were redetermined using the Doppler-Shift-Attenuation-Method. The deduced $B(E2)$ values and the $g(2_1^+)$ factor are discussed within the framework of large-scale full *fp* shell model calculations with a closed ^{40}Ca core and including excitations from the $f_{7/2}$ orbital. The results are compared with recent data for ^{68}Ge and ^{68}Zn.

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I. INTRODUCTION

Our recent investigations of the low-level nuclear structure of ^{68}Ge [1] involved measurements of g factors and lifetimes. Our results provided evidence that its nuclear properties (excitation energies, g factors, and $B(E2)$'s) can be well explained within the framework of the spherical shell model [2]. These calculations used the effective *NN* interactions FPD6 [3] and GXPF1 [4,5], which are commonly utilized for *fp* shell nuclei. For ^{68}Ge it was sufficient to consider a valence space for both protons and neutrons consisting of the $0f_{7/2}$, $1p_{3/2}$, $0f_{5/2}$, and $1p_{1/2}$ orbitals; the intruder $0g_{9/2}$ orbital was not included in the calculations for the levels in question. Good agreement with the experimental data was achieved by the excitation of no more than four particles of the $0f_{7/2}$ orbital to the upper *fp* subshells.

Only with the inclusion of such excitations from the $f_{7/2}$ orbital to the rest of the *fp* shell could the $B(E2)$'s of the yrast $(2_1^+ \to 0_1^+)$, $(4_1^+ \to 2_1^+)$, and $(6_1^+ \to 4_1^+)$ transitions in ^{68}Ge be well accounted for. The same ^{56}Ni core excitation phenomenon is also compatible with observations for some Ni [6,7] and Zn [8] isotopes, for which the same calculational assumptions were needed to account for the data for these nuclei. That ^{56}Ni is soft against nucleon excitations and is therefore less well-suited to serve as an inert core has been emphasized in many recent theoretical papers (see, e.g., Ref. [9]).

For the radioactive ^{68}Ge, the $g(2_1^+)$ factor and several lifetimes were determined in [1] for the first time. In contrast, for the stable ^{70}Ge the lifetimes of some excited states and the g factor of the 2_1^+ state were known from previous experiments (see [10,11]). Hence, the present investigations essentially provided redeterminations and confirmations of these properties using a different experimental technique. Our work aims to enhance the reliability of the spectroscopic information for ^{70}Ge and to provide a deeper insight into its nuclear structure on the basis of extensive new shell model calculations.

The ^{70}Ge nucleus has two more neutrons than ^{68}Ge and is isotonic to ^{68}Zn. Interestingly, despite the differing proton numbers, there are strong similarities (noted in [12]) between the observed excitation energies ^{70}Ge and ^{68}Zn of the 2_1^+, 4_1^+, and 3_1^- levels. Hence, an interesting question is whether other properties of these levels in ^{70}Ge can be attributed, predominantly, to neutron excitations. Such a picture was utilized in the early work of Bruandet *et al.* [12] and Morand *et al.* [13]. These authors suggested that, in general, the $I^\pi = 4^+, 6^+$, and 8^+ states for several isotonic Zn and Ge nuclei (with neutron numbers $N = 34$, 36, and 38) could be associated with neutron excited states, including excitations to the $g_{9/2}$ subshell. In this context, on the basis of the observation of a negative g factor for the 4_1^+ state in ^{68}Zn [14,15], it has been suggested that the neutron $g_{9/2}$ configuration must play an important role in the 4_1^+ nuclear wave function. From the perspective of this picture of a neutron-dominated structure one might expect for the 4_1^+ state of ^{70}Ge to have a single-particle structure, and hence a comparable g factor, similar to that of the 4_1^+ state in ^{68}Zn. This interesting issue has yet to be experimentally investigated by measuring the $g(4_1^+)$ in ^{70}Ge. Another interesting question is what role is played by the proton excitations in ^{70}Ge.

Another point of interest was whether full *fp* shell model calculations would be as successful for ^{70}Ge as they have proved to be for ^{68}Ge in explaining specific properties [1]. On the one hand, in comparing these two nuclei, the collective behavior of ^{70}Ge might be expected to be enhanced because of the presence of the two additional neutrons which could result in relatively larger $B(E2)$'s for the yrast transitions in ^{70}Ge. On the other hand, a relative reduction in collectivity for ^{70}Ge could also be possible, in view of the findings of a $B(E2)$ minimum (as function of neutron number N) for the $(2_1^+ \rightarrow 0_1^+)$ transition in its isotone ^{68}Zn, which was related to the neutron $0f_{5/2}$ subshell closure (see also [14]). Whether this shell closure also exists in ^{70}Ge needs to be studied by careful and accurate measurements. However, for the $(4_1^+ \rightarrow 2_1^+)$ transition in the Zn isotopes the $B(E2)$ minimum with N occurs for ^{66}Zn, i.e., for $N = 36$.

II. EXPERIMENTAL DETAILS

In the experiment, excited states of ^{70}Ge were populated in an α-transfer reaction to energetic ^{66}Zn nuclei. The latter were extracted from an ion source as isotopically pure ZnO$^-$ ions and then accelerated as ^{66}Zn ions to an energy of 180 MeV at the Munich tandem accelerator, delivering intensities of ~25–30 *e*nA to a multilayered target.

The target consisted of 0.44 mg/cm^2 of natural carbon deposited on 3.34 mg/cm^2 Gd that was evaporated on a 1.4 mg/cm^2 Ta foil backed by a 4.49 mg/cm^2 Cu layer. Good adherence between the C and Gd layers as well as between the Ta and Cu layers, was achieved by having thin layers of natural titanium of 0.005 mg/cm^2 thickness sandwiched between those layers. This preparation technique was previously successfully applied to other targets used in heavy ion beam experiments [16]. In the collisions of the 180 MeV ^{66}Zn ions with carbon nuclei, close to the Coulomb barrier, the α-transfer reaction ^{12}C(^{66}Zn,^{8}Be)^{70}Ge produced the ^{70}Ge nuclei. In addition, Coulomb excitation of the ^{66}Zn projectiles also occurred. Reliable discrimination between the two resulting nuclei ^{70}Ge and ^{66}Zn was absolutely necessary since the γ-ray energies of the $(2_1^+ \rightarrow 0_1^+)$ transitions in these nuclei were identical to within less than 1 keV. Because of the inverse kinematics of both of the above reactions, such a separation was indeed achieved. This was accomplished via the detection of the particles emitted in the respective reactions—the 2α particles from the decay of ^{8}Be, associated with ^{70}Ge formation, and the forward-recoiling ^{12}C ions from the inelastic scattering of

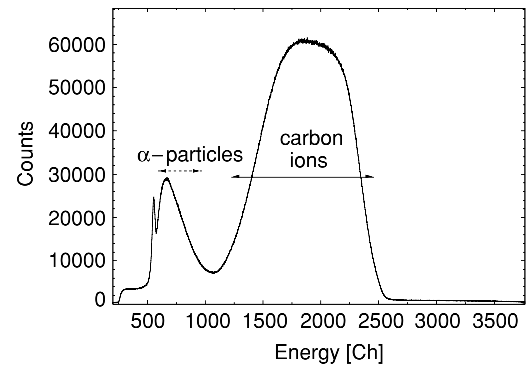

FIG. 1. Particle spectrum obtained with a low-biased 100-μm Si detector in coincidence with all the γ rays for a ^{66}Zn beam. The α particles from the decay of ^{8}Be, associated with ^{70}Ge, are shown to be well separated from the carbon ions corresponding to projectile Coulomb excitation (see text).

the Coulomb-excited ^{66}Zn projectiles. These particles were well distinguished in the energy spectrum of the Si detector, located at 0° relative to the beam direction. The detector was shielded against the beam ions by a 5 μm thick Ta stopper foil, which was still thin enough for the target ions and the light particles to pass through to the Si detector. The Si detector, of nominal 100 μm thickness, was operated at an unusually low bias of ≃3–5 V to reduce the depletion layer thickness. Only then, as shown in the spectrum of Fig. 1, could the α particles and the ^{12}C ions be separated in pulse-height because of their different stopping powers in the reduced sensitive layer of the detector. The results of the simultaneously measured ^{66}Zn events are reported in a separate article [17]. In the measurements the target was cooled to liquid nitrogen temperature and magnetized to saturation in an external field of 0.06 T. The excited ^{70}Ge nuclei moved with a mean velocity of ~6.6 v_0 ($v_0 = e^2/\hbar$) through the Gd layer, experiencing spin precessions in the transient field (TF), and were ultimately stopped in the hyperfine-interaction-free environment of the Cu backing.

The de-excitation γ rays of ^{70}Ge were measured in coincidence with the 2α particles using four 12.7 × 12.7 cm NaI(Tl) scintillators, located in pairs symmetric to the beam direction. Figure 2 shows the level scheme relevant to the transitions observed in the present work. An intrinsic Ge detector with a relative efficiency of 40% served as a monitor for contaminant lines in the energy regions of interest and enabled the measurement of the nuclear lifetimes via the Doppler-Shift-Attenuation-Method (DSAM). For this purpose, the detector was placed at 0° relative to the beam axis, a position where the lines have maximal Doppler shifts and well-pronounced lineshapes. Typical coincidence spectra obtained with the two detector types that were used are displayed in Figs. 3 and 4.

The line intensities in the γ spectra allowed the determination of the spin precessions with sufficient accuracy only for the 2_1^+ state. This spin-selective population of the excited states is a clear signature of the transfer reaction mechanism that has been observed in all the other nuclei studied with this same technique (see e.g., Ref. [1]). The precession angles $\Phi^{\rm exp}$ were derived from the coincident counting-rate ratios R for the "up"

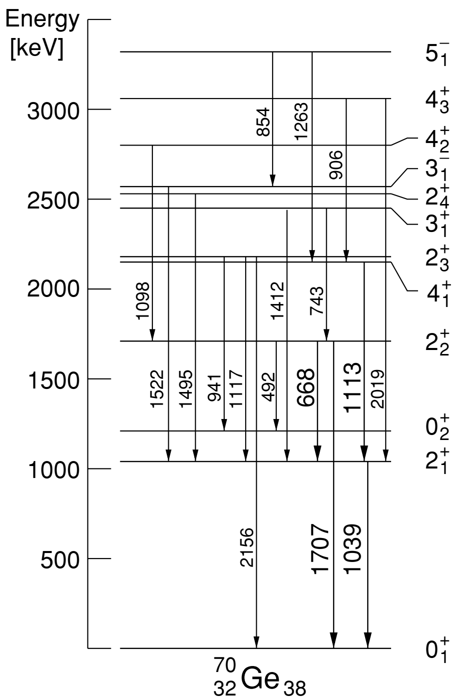

FIG. 2. Level scheme of ^{70}Ge with the relevant γ transitions.

and "down" directions of the external magnetizing field. [1]

$$\Phi^{\rm exp} = \frac{1}{S}\cdot\frac{\sqrt{R}-1}{\sqrt{R}+1} = g\frac{\mu_N}{\hbar}\int_{t_{\rm in}}^{t_{\rm out}} B_{\rm TF}(v_{\rm ion}(t))e^{-\frac{t}{\tau}}dt, \quad (1)$$

where g is the g factor of the 2_1^+ state and $B_{\rm TF}$ is the transient field acting for the time interval ($t_{\rm out}$-$t_{\rm in}$) that the ions spend in the Gd layer; the exponential accounts for the decay of the excited state during its lifetime τ while the ions pass through the Gd layer. The logarithmic slope

$$|S| = [1/W(\Theta_\gamma)]\cdot[dW(\Theta_\gamma)/d\Theta_\gamma], \quad (2)$$

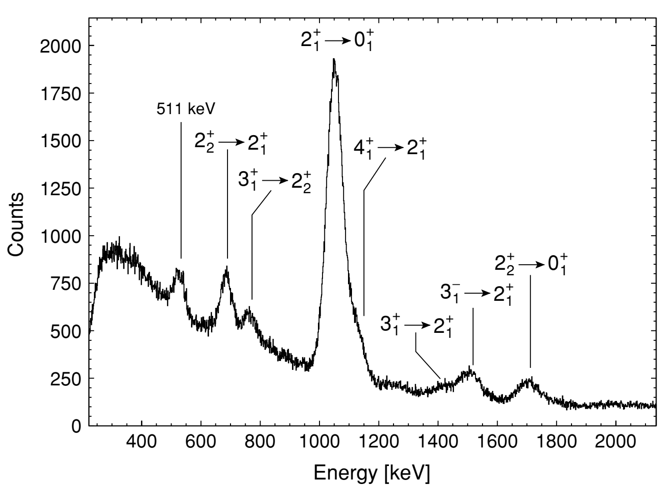

FIG. 3. The γ-coincidence spectrum for ^{70}Ge observed with a large-volume NaI(Tl) scintillator located at $\Theta_\gamma = 65^\circ$. The assigned transitions refer to the present investigations (see text).

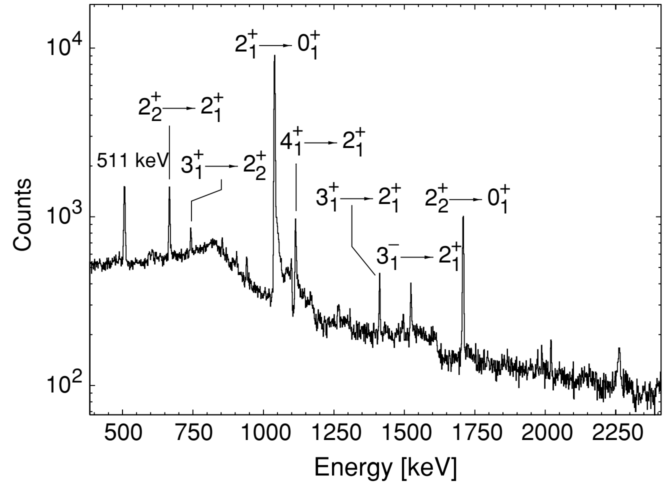

FIG. 4. The same γ-coincidence spectrum as shown in Fig. 3, observed with a Ge detector located at $\Theta_\gamma = 0^\circ$. The assigned γ lines are identified according to the level scheme shown in Fig. 2. The Doppler-broadened lineshapes reflect the nuclear lifetimes.

which determines the sensitivity to the nuclear precession, has been evaluated from the measured angular correlation $W(\Theta_\gamma)$ of the ($2_1^+ \rightarrow 0_1^+$) γ transition.

The lifetimes of several excited states in ^{70}Ge were determined in those cases where the emitted γ lines, observed with the 0° Ge detector, exhibit pronounced Doppler-broadened line shapes. In this analysis the computer code LINESHAPE [18] was used in applying stopping powers [19] to Monte Carlo simulations, which included the second-order Doppler effect as well as the finite size and the energy resolution of the Ge detector. Corrections because of substantial feeding from higher states were considered and are responsible for the relatively large errors in the lifetime values for the 2_1^+ and the 4_1^+ states (see Table I).

III. RESULTS AND DISCUSSION

The g factor of the 2_1^+ state was derived from the precession angle $\Phi^{\rm exp}$ (see Table I). This was done by determining the effective transient field on the basis of the empirical linear parametrization [1,20]

$$B_{\rm TF}(v_{\rm ion}) = G_{\rm beam}\cdot B_{\rm lin}, \quad (3)$$

with

$$B_{\rm lin} = a({\rm Gd})\cdot Z_{\rm ion}\cdot v_{\rm ion}/v_0. \quad (4)$$

Here the strength parameter $a({\rm Gd}) = 17(1)$ T, $v_0 = e^2/\hbar$, and $G_{\rm beam} = 0.61(6)$ is the empirical attenuation factor of the transient field induced by the Zn beam in the Gd layer. The $G_{\rm beam}$ value quoted above refers to the present experimental conditions in terms of the energy loss of the beam ions and the mean velocity of the Ge ions in the Gd layer (see also [20]).

It should be noted that the observed precession of the 2_1^+ state had to be corrected for contributions from the precession of the 4_1^+ state because of a 15(3)% feeding fraction to the 2_1^+ state. Without this correction, the measured precession angle would imply a g factor, $g(2_1^+) = +0.32(11)$. Clearly

TABLE I. Summary for ^{70}Ge of the slopes of the measured angular correlations, the experimental precession angles (corrected for feeding), and the deduced g factors and lifetimes. The $\Phi^{\rm lin}/g$ values were calculated using Eqs. (1), (3), and (4). Comparisons are made to earlier data.

I^{π}:	E_x (MeV)	τ (ps)			$\|S(65^{\circ})\|$	$\Phi^{\rm exp}$ (mrad)	$\Phi^{\rm lin}g$ (mrad)	$g(I^{\pi})$
		[11]	Present	Average				
2_1^+:	1.039	1.88(3)	1.9(2)	1.88(3)	0.455(38)	12(3)	27.8(2.7)	+0.43(12)
2_2^+:	1.707	$1.6^{+1.4}_{-0.6}$	2.8(4)	2.6(4)	0.38(19)	11(16)	28.6(2.8)	+0.4(6)
4_1^+:	2.153	1.2(3)	1.1(2)	1.1(2)	–	–	–	–
3_1^-:	2.562	0.6(2)	0.8(1)	0.76(9)	–	–	–	–

a direct measurement of the $g(4_1^+)$ in ^{70}Ge would be valuable. However, the 4_1^+ precession could not be extracted from the present data, mainly because of the insufficient energy resolution of the scintillators that were used (see Fig. 3), but also because of the low intensity of the $(4_1^+ \rightarrow 2_1^+)$ γ line. Therefore to correct the observed precession of the 2_1^+ state, one would have to make assumptions about the value (sign and magnitude) of the unmeasured $g(4_1^+)$. These assumptions would affect the deduced value for the $g(2_1^+)$. The correction procedure utilizes the approach that is discussed in detail in Refs. [21,22].

If we assume $g(4_1^+) \simeq g(2_1^+) = +0.32(11)$ the correction to the $g(2_1^+)$ will be very small and the corrected value will remain at $g(2_1^+) = +0.32(11)$. This is because, with the 2_1^+ and 4_1^+ g factors being about the same, it then essentially does not matter whether the precession takes place in the 2_1^+ or the 4_1^+ state. A more positive $g(4_1^+)$ value will generally result in a negative correction to the $g(2_1^+)$, whereas a less positive $g(4_1^+)$ value will bring about a positive correction.

For another interesting example of correcting the $g(2_1^+)$, let us assume that $g(4_1^+) = -0.37(17)$, using the experimental value recently obtained for the $g(4_1^+)$ in ^{68}Zn [15]. We assume this value although large negative $g(4_1^+)$ values are not very common and in ^{68}Zn the $g(4_1^+)$ is probably due to dominating $g_{9/2}$ neutron effects. This assumption for the $g(4_1^+)$ in ^{70}Ge can be justified by noting that the two nuclei, ^{70}Ge and ^{68}Zn, both have 38 neutrons and also very similar excitation energy patterns that have been attributed to dominant neutron excitations [12,13]. The g value in Table I, $g(2_1^+) = +0.43(12)$, was finally obtained by using this negative $g(4_1^+)$ value and a slope value for the relevant γ angular correlation with an unobserved $(4_1^+ \rightarrow 2_1^+)$ transition, $|S(4_1^+ \not\rightarrow 2_1^+ \rightarrow 0_1^+)| = |S(2_1^+ \rightarrow 0_1^+)|$. A larger slope value of the $(4_1^+ \not\rightarrow 2_1^+ \rightarrow 0_1^+)$ angular correlation, which is not unlikely in view of the observations for ^{52}Ti [23], would lead to an even larger g factor for the 2_1^+ state in ^{70}Ge, but one which would still be consistent with the literature values. It should be noted that the rather large error of the $g(4_1^+)$ value leads only to a small increase in the error of the corrected $g(2_1^+)$ value because the feeding $(4_1^+ \rightarrow 2_1^+)$ γ intensity fraction is small. Additional corrections to the $g(2_1^+)$ from the other higher states would fit within the error quoted for the $g(2_1^+)$.

By assuming in our correction procedure two specific, and rather different, values for the unmeasured $g(4_1^+)$ in ^{70}Ge, two corresponding values of +0.32(11) and +0.43(12), respectively, were obtained for the $g(2_1^+)$; the latter value was adopted in Tables I and II. It is noted that both values are in general agreement with results of former measurements that are compiled in [10]. Lampard *et al.* [24] obtained +0.37(9) using Coulomb excitation and the transient field method; in Ref. [25] an IMPAC approach led to +0.38(8) and re-evaluation there of an earlier result yielded +0.47(10). The most accurate result by Pakou *et al.* [26] of +0.47(3) is, however, in better agreement with the value we quote in Tables I and II.

The newly determined lifetimes are summarized in Table I. It is encouraging that these values are in good agreement with those of the literature [11]. The errors reflect the relatively large feeding fractions contributing to the stopped components of the respective γ lines. The new lifetime value of the 2_2^+ state at 1.707 MeV was determined with a precision that is much higher than that of the literature value.

The measured g factors of the 2_1^+- and 2_2^+- states and the deduced $B(E2)$ values of several transitions in ^{70}Ge are compared in Table II with the results of spherical shell model calculations that were carried out within the same space that was used for explaining our previous results for ^{68}Ge [1]. These calculations were based on an inert ^{40}Ca core plus valence protons and neutrons in the full *fp* shell model space and utilized the shell model codes OXBASH [27] and ANTOINE [28,29]. The four effective interactions that were used—KB3 [2], FPD6 [3], GXPF1 [4], and GXPF1A [5]—are commonly applied to *fp* shell nuclei. All these interactions except KB3 involve A scaling for the two-body matrix elements. The calculations utilized the free nucleon g factors and the effective charges $e_{\pi} = 1.5\ e$ and $e_{\nu} = 0.5\ e$ for protons and neutrons, respectively (see also [1]).

In Table II we see that, overall, the GXPF1A interaction accounts the best (and the KB3 accounts the worst) for the experimental excitation energies. The GXPF1A results are always within 270 keV or less, except for the $E(0_2^+)$ which is significantly overestimated by all the interactions; this latter level may be an intruder state. The excitation energies of the yrast 2_1^+ and 4_1^+ are accounted for to within 60 keV by GXPF1A.

The newly determined $g(2_2^+)$ value has a big uncertainty so that the predictions of all the interactions fall within the experimental error. As Table II indicates, the more precisely measured $g(2_1^+)$ is explained, within our experimental error, by the full *fp* shell calculations with GXPF1A, GXPF1, and KB3, but not with FPD6. Calculations with our four interactions for the $g(2_1^+)$ of ^{70}Ge, in a smaller space, with closed $f_{7/2}$ and $p_{3/2}$

TABLE II. Experimental excitation energies, $B(E2)$'s, and g factors for ^{70}Ge in comparison with the results from full *fp* shell model calculations using the effective interactions KB3 [2], FPD6 [3], GXPF1 [4], and GXPF1A [5]. The symmetrized errors of the $B(E2)$'s include the uncertainties of the measured lifetimes and branching ratios as well as mixing ratios taken from [11]. The collective model predicts $g(2_1^+) = Z/A = 0.46$ (see text).

Quantity	Experimental	KB3	FPD6	GXPF1	GXPF1A
$E(2_1^+)$ [MeV]	1.039	1.470	1.050	1.337	1.097
$E(2_2^+)$ [MeV]	1.707	2.745	2.229	2.387	1.976
$E(0_2^+)$ [MeV]	1.212	3.926	2.416	2.301	1.909
$E(2_3^+)$ [MeV]	2.156	4.127	2.745	2.661	2.339
$E(4_1^+)$ [MeV]	2.153	2.413	2.218	2.256	2.093
$g(2_1^+)$	+0.47(3)[a] +0.43(12)	+0.528	+0.769	+0.397	+0.343
$g(2_2^+)$	+0.4(6)	+0.678	+0.880	+0.745	+0.896
$B(E2; 0_1^+ \to 2_1^+)$ (e^2b^2)	0.179(3)	0.0501	0.1776	0.0789	0.0673
$B(E2; 0_1^+ \to 2_2^+)$ (e^2b^2)	0.0047(8)	0.0138	0.0110	0.0022	0.0081
$B(E2; 2_1^+ \to 2_2^+)$ (e^2b^2)	0.118(21)	0.0115	0.0394	0.0105	0.0067
$B(E2; 2_1^+ \to 4_1^+)$ (e^2b^2)	0.078(14)	0.0135	0.0665	0.0234	0.0216

[a]Reference [26].

subshells for both protons and neutrons and with two neutron holes in the $f_{5/2}$, $p_{1/2}$ space, yielded results for this simplified picture ranging from +0.42 to +0.547, in agreement with the experimental data.

The yrast $B(E2)$'s of the $(0_1^+ \to 2_1^+)$ and $(2_1^+ \to 4_1^+)$ transitions, on the other hand, are very well accounted for by FPD6 interaction but not by the KB3, GXPF1, or GXPF1A interactions. The non-yrast $B(E2; 2_1^+ \to 2_2^+)$ is underestimated by factors of at least three by all the interactions. The $B(E2; 0_1^+ \to 2_2^+)$ is significantly underestimated by GXPF1 and significantly overestimated by the other three interactions.

Thus, overall, the interactions (KB3, GXPF1, GXPF1A) that explain the $g(2_1^+)$, significantly underestimate the yrast $B(E2)$'s. On the other hand, the FPD6 interaction, which accounts for the yrast $B(E2)$'s so well, greatly overpredicts the $g(2_1^+)$. Hence no single interaction seems to be able to account for the complete low-energy structure of ^{70}Ge. One possible explanation for these deficiencies is that we may need to enlarge the full *fp* shell model space by including also the intruder $g_{9/2}$ orbital. This was done in Ref. [8] for all the even-A Zn isotopes, in [15] for ^{68}Zn, and in [30] for the Ni isotopes. There, however, an inert ^{56}Ni core was assumed (instead of a ^{40}Ca core as in the present work), thus excluding the possibility of particle excitations from the $f_{7/2}$ subshell to the rest of the *fp* shell. The absence of such $f_{7/2}$ excitations could perhaps account for some of the disagreements between theory and experiment for ^{68}Zn in [14]. The expansion of our full *fp* shell model space for ^{70}Ge to include the opposite parity $g_{9/2}$ orbital would also make it possible to explain the 3_1^- level data. However, at present, such an expansion is beyond our computational means.

In [1], for ^{68}Ge (with four *fp* shell neutron holes), especially with GXPF1, some of the yrast $B(E2)$'s were underpredicted in the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ space. These $B(E2)$ values increased when excitations were permitted from the closed $f_{7/2}$ orbit to the higher *fp* shell orbits. In our present article for ^{70}Ge (with two *fp* shell neutron holes), although such $f_{7/2}$ excitations are permitted they play only a more minor role; the yrast $B(E2)$'s with GXPF1 (but not with FPD6) are still substantially underestimated. It may be that the inclusion of possible excitations to the $g_{9/2}$ subshell would again increase the $B(E2)$'s.

For all four interactions, in the 2_1^+ wave function of ^{70}Ge, the intensity of the largest component that involves excitations from the $f_{7/2}$ subshell is under 2%. For the FPD6 interaction, exciting no more than two $f_{7/2}$ nucleons (to the rest of the *fp* shell) yields results in excellent agreement with the full *fp* shell FPD6 results in Table II. Specifically, this yields results within 4% for the five excitation energies, within 1% for the two g factors, and within 8% for the four $B(E2)$'s. On the other hand, FPD6 results with *no* $f_{7/2}$ excitations differ from the full *fp* shell FPD6 results by 5%–20% for the excitation energies and by under 4% in the g factors, and they underestimate the $B(E2)$'s by 20%–45%. Thus within our picture, limiting to two the number of $f_{7/2}$ nucleon excitations provides a good approximation to the full *fp* shell calculational results. Such excitations are most important for the $B(E2)$'s and least important for the g factors.

A study of the ^{70}Ge wave functions that are obtained utilizing ANTOINE elucidates why the FPD6 results differ from those of the other three interactions. Crudely and approximately speaking, with FPD6 two protons are excited from the $p_{3/2}$ orbit to the $f_{5/2}$ orbit and the two neutron holes are in the $p_{1/2}$ orbit. With KB3, GXPF1, and GXPF1A the proton $p_{3/2}$ orbit is closed and the two neutron holes are in the $f_{5/2}$ orbit.

All four interactions give positive quadrupole moments for the 2_1^+ state, indicating, from a collective perspective, an oblate shape. Such a positive value was indeed measured in [31].

IV. SUMMARY AND CONCLUSIONS

Using a different experimental approach, remeasurements were made of the $g(2_1^+)$ and of the lifetimes of several low-lying states in the ^{70}Ge nucleus. The technique utilized was α transfer to an energetic ^{66}Zn ion beam in inverse kinematics combined with transient magnetic fields in ferromagnetic gadolinium. The values obtained, utilizing certain assumptions, were in general agreement with earlier data obtained using Coulomb excitation and IMPAC techniques. The lifetime of the 2_2^+ state was determined with much greater precision than hitherto. The $g(2_2^+)$ was measured (with a large uncertainty) for the first time.

The excitation energies, $g(2_1^+)$, $g(2_2^+)$, and several $B(E2)$'s were compared with the results of full *fp* shell calculations. The KB3, GXPF1, and GXPF1A interactions did better on the $g(2_1^+)$ but worse on the yrast $B(E2)$'s than did the FPD6 interaction. No single interaction could account for the complete low-energy structure of ^{70}Ge. This would seem to indicate that it is important to try to add the $g_{9/2}$ orbital to our shell model space; such was not the situation in the case of ^{68}Ge [1], where excitations from the $f_{7/2}$ orbit to higher *fp* orbits sufficed. Our results for ^{70}Ge suggest that exciting up to two nucleons from the $f_{7/2}$ subshell provides a good approximation to full *fp* shell model calculations. The impact of such excitations is largest for the $B(E2)$'s and smallest for the $g(2^+)$ factors. Finally, the results of the present work and of Ref. [15] for ^{68}Zn strongly request a direct measurement of the $g(4_1^+)$ in ^{70}Ge.

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