This, obviously, does not reproduce the experimentally observed decay branching of the 3.68-MeV level. (Only an upper limit for this lifetime is known.) A more realistic estimate of the expected lifetime of the 3.68-MeV level could perhaps be obtained by using the experimentally determined $E1$ width of the 2.64-MeV level to estimate the expected $E1$ widths of the 3.68-MeV level by taking account of the different Wigner coefficients in Eq. (1). This results in

$$\Gamma(E1,\ 3.68\to 0)=3.62\ \text{meV},$$

$$\Gamma(E1,\ 3.68\to 0.44)=3.70\ \text{meV},$$

and, as before,

$$\Gamma(M1,\ 3.68\to 2.64)=3.14\ \text{meV}.$$

The corresponding percentage branchings are 35, 35, and 30%, respectively, compared to the experimentally observed branchings of 2, 77, and 19% (there is also a 2% branch to the 2.39-MeV level), while the predicted lifetime for the 3.68-MeV level is 6.2×10^{-14} sec. Experimentally only an upper limit $\tau_m<17\times10^{-14}$ sec is known.

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Directional Correlation of Gamma Rays in ^{72}Ge*

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The γ rays of ^{72} Ge following the β decay of 14.1-h ^{72}Ga have been studied using a 20-cm^3 Ge(Li) detector in coincidence with a 2×2-in. NaI(Tl) crystal. Directional-correlation measurements have been carried out on the cascades involving 630-, 894-, 1231-, 2202-, 2491-, and 2508-keV γ rays with the 834-keV ground-state transition from the first excited 2+ state. 1-3 directional-correlation measurements (with the intermediate γ ray unobserved) have been made between γ rays of energy 601, 786, 1000, 1051, 1215, 1597, and 1861 keV and the 834-keV transition. Spin assignments of 2 for the 1464- and the 3036-keV levels have been confirmed. The 630- and 2202-keV transitions are nearly pure $E2$ and $E1$, respectively. The level at 2065 keV has been assigned a spin of 3. The 601-keV transition has a maximum $M1$ admixture of 10%. Assuming that the 2515-keV level is a 3− state, the following spin and mixing assignments can be made. The level at 1728 keV is found to have a spin of 4, which requires 0.4–1.3% octupole mixture in the 894-keV transition. The levels at 3325 and 3342 keV have been assigned spins of 3 and 2, respectively. The 786-, 1597-, 2491-, and 2508-keV transitions are all nearly pure $E1$.

I. INTRODUCTION

THE nuclear level structure of ^{72}Ge was first studied in detail by Kraushaar, Brun, and Meyerhof.[1,2] They examined the levels in ^{72}Ge from both the β^- decay of ^{72}Ga and the β^+ and electron-capture decay of ^{72}As. Their decay scheme was based on conversion-electron and β spectra, γ-ray spectra using scintillation detectors, and β-γ and γ-γ coincidence measurements. Except for the first excited state, their spin and parity assignments were based on log*ft* values.

The first direct measurement of the spins of several of the excited states was made by Arns and Wiedenbeck.[3] Some other spin assignments have been made from proton inelastic-scattering experiments.[4–6] Recently, the γ-ray relative intensities have been measured with high-resolution Ge(Li) detectors.[7–9] The decay scheme proposed by Camp[9] has been checked by Ge(Li)-Ge(Li) coincidence measurements.[10] These measurements have confirmed major features of the level structure originally proposed by Kraushaar *et al.*, and,

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* Work supported in part by the National Science Foundation.

[1] J. J. Kraushaar, E. Brun, and W. E. Meyerhof, Phys. Rev. **101**, 139 (1956).

[2] E. Brun, J. J. Kraushaar, and W. E. Meyerhof, Phys. Rev. **102**, 808 (1956).

[3] R. G. Arns and M. L. Wiedenbeck, Phys. Rev. **112**, 229 (1958).

[4] D. M. Van Patter, R. Rikmenspol, and P. N. Trehan, Nucl. Phys. **27**, 467 (1961).

[5] W. Darcey, in *Proceedings of the International Conference on Nuclear Physics, Paris, 1964* (Editions du Centre National de la Recherche Scientifique, Paris, 1965), Vol. II, p. 456.

[6] J. K. Dickens, R. G. Perry, and R. J. Silva, Oak Ridge National Laboratory Report No. ORNL 3499, Vol. 1, p. 20, 1963 (unpublished).

[7] D. C. Camp, Bull. Am. Phys. Soc. **12**, 492 (1967).

[8] H. Ottmar, Z. Physik **209**, 44 (1968).

[9] D. C. Camp, University of California Lawrence Radiation Laboratory Report No. UCRL-71099, 1968 (unpublished); Nucl. Phys. **A121**, 561 (1968).

[10] A. C. Rester, A. V. Ramayya, and J. H. Hamilton, Bull. Am. Phys. Soc. **13**, 1427 (1968).

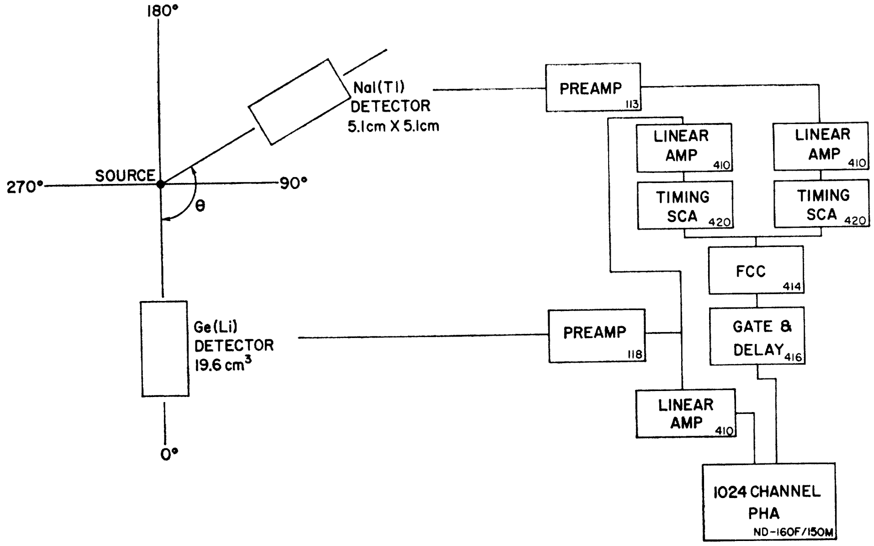

FIG. 1. Schematic diagram of the directional-correlation apparatus. An 80-keV window was set on the 834-keV line in the NaI(Tl)-detector channel and the Ge(Li)-detector channel was set on integral above the noise. Coincidence counts were accumulated during 20-min intervals at 10 angles between 90° and 270°. SCA = single-channel analyzer; PHA = pulse-height analyzer; FCC = fast-coincidence circuit.

in addition, have shown the existence of many weak transitions and weakly excited levels in the decay of ^{72}Ga and ^{72}As.

The richness of the level structure of ^{72}Ge, and the ease with which these levels may be excited, suggests that this nuclide may be especially valuable as a test for nuclear structural models. The present experiment[11] has involved coincidence and directional-correlation measurements between a NaI(Tl) detector and a Ge(Li) detector. The purpose was to make a direct measurement of the spins of as many as possible of the ^{72}Ge levels and to determine the properties of the transitions connecting these levels.

II. EXPERIMENTAL METHOD

Sources of ^{72}Ga, which undergoes β^- decay to levels in ^{72}Ge with a half-life of 14.1 h, were prepared by irradiating 500-mg samples of 99.99% pure gallium metal in the Ohio State University reactor for 1 h at 10 kW. The gallium was dissolved in 10 cm^3 of aqua regia and evaporated to about 1 cm^3. Several directional-correlation sources were prepared at one time by adding different amounts of this solution to thin-walled polyethylene cylinders, 2.5 mm in diam and 10 mm in height. Liquid sources were used throughout the directional-correlation experiment in order to minimize extra-nuclear effects.

A block diagram of the apparatus used in the experiment is shown in Fig. 1. The Ge(Li) detector was made by Ortec, Inc. and had an active volume of 19.6 cm^3 and resolution of 3.9 keV for the 1333-keV line of ^{30}Co. The NaI detector was a 5.1×5.1 cm crystal integrally mounted on a 6342 A photomultiplier tube. The coincidence measurements were made in 180° geometry and the results were in complete agreement with those reported by Camp,[9] and Rester *et al.*[10]

For the directional-correlation measurements, the Ge(Li) detector was held fixed and the NaI detector was moved through the sequence of angles 90°, 115°, 135°, 160°, 180°, and their supplementary angles in the 180°–270° quadrant. The NaI-detector channel was gated on the 834-keV line and the Ge(Li)-detector channel was set on integral above the noise. Data for all of the directional-correlation measurements were collected simultaneously and recorded in a 1024-channel analyzer. The coincidence requirement was determined by crossover timing with a resolving time of 5.0×10^{-8} sec. The coincidence spectra were accumulated during 20 min live-time at each angle until 1% statistics were reached for the stronger correlations.

The correlation data were obtained by adding the total number of coincidence counts in the peaks of the Ge(Li) spectrum for a particular angle. The background subtraction was made from a linear interpolation of the background to the left and right of a peak. The data were then corrected for accidental coincidences. The number of accidental coincidences was determined by measuring the real to accidental ratio during each run. The average ratio was 10:1. The corrections due to the source half-life and electronic pileup[12] were also considered. However, when the data from supplementary angles were added together, these corrections amounted to only 0.4% over all angles.

A least-squares fit of the data was made to a series of even Legendre polynomials up to order 4:

$$W'(\theta)=\alpha_0+\alpha_2P_2(\cos\theta)+\alpha_4P_4(\cos\theta).$$

The resultant expansion coefficients were normalized

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[11] A preliminary report of this work was made by W. G. Monahan and R. G. Arns, Bull. Am. Phys. Soc. **13**, 582 (1968).

[12] S. L. Blatt, Nucl. Instr. Methods **49**, 235 (1967).

TABLE I. Summary of directional-correlation measurements and level and transition assignments. The possible spin sequences have been limited to the assignments shown by the present measurements and other available experimental information. All measurements involve the known $2(E2)0$ 834-keV transition.

Energies (keV)	A_2	A_4	Assigned sequences	2^{L+1} Fraction
		Direct cascades		
630–834	-0.075 ± 0.012	0.225 ± 0.018	$2(D,Q)2(E2)0$	$Q\geq0.99$
894–834	0.046 ± 0.016	-0.012 ± 0.030	$4(Q,O)2(E2)0$	$0.004<O<0.013$
1231–834	-0.50 ± 0.13	-0.16 ± 0.19	$3(D,Q)2(E2)0$	$0.15<Q<0.95$
2202–834	0.283 ± 0.028	0.002 ± 0.042	$2(D,Q)2(E2)0$	$Q\leq0.01$
2491–834	0.040 ± 0.032	-0.003 ± 0.049	$3(D,Q)2(E2)0$	$0.01<Q<0.04$
2508–834	0.181 ± 0.021	-0.057 ± 0.033	$2(D,Q)2(E2)0$	$0.0<Q<0.02$
		1-3 Correlations with 894-keV transition unobserved		
786–834	-0.165 ± 0.043	-0.076 ± 0.066	$3(D,Q)4$	$Q\leq0.01$
1215–834	-0.28 ± 0.19	-0.06 ± 0.28	$3(D,Q)4$	$0<Q<1.0$
			$4(D,Q)4$	$0.3<Q<1.0$
1597–834	-0.182 ± 0.050	0.081 ± 0.076	$3(D,Q)4$	$Q\leq0.01$
		1-3 Correlations with 630-keV transition unobserved		
601–834	0.045 ± 0.050	-0.092 ± 0.075	$3(D,Q)2$	$0.9<Q<1.0$
1000–834	-0.19 ± 0.17	-0.22 ± 0.25	$2(D,Q)2$	$0.0<Q<0.7$
			$3(D,Q)2$	$0.05<Q<0.85$
			$4(Q)2$	
1051–834	-0.039 ± 0.055	-0.069 ± 0.084	$3(D,Q)2$	$0<Q<1.0$
1861–834	0.058 ± 0.091	0.14 ± 0.14	$3(D,Q)2$	$0<Q<1.0$

and corrected for the finite source size and detector solid angles. The geometrical corrections for the Ge(Li) and NaI(Tl) detectors were determined by a collimated-beam method.[13] This yielded a correlation function of the form

$$W(\theta)=1+(A_2\pm\sigma_2)P_2(\cos\theta)+(A_4\pm\sigma_4)P_4(\cos\theta).$$

The σ_2 and σ_4 are the rms errors as defined by Eq. (30) of Ref. 14.

III. RESULTS

Two types of directional-correlation data were analyzed; the direct cascade correlation, and the 1-3 correlation in which the intermediate γ ray is unobserved. The 834-keV level has previously been shown by β-γ directional correlation[15] and by Coulomb excitation[16] measurements to be a 2+ level. Since ^{72}Ge is an even-even nucleus, its ground state is 0+ and therefore the 834-keV transition is pure electric quadrupole ($E2$).

The directional-correlation expansion coefficients, corrected in the manner described in Sec. II, are listed in Table I. This table also summarizes the spin assignments which were made on the basis of the directional-correlation data and other experimental information. The spin sequence is given for each cascade. Only the spin sequence of the first γ ray is given for the 1-3 correlations. In each case, the fraction of higher multipole order is given for the first γ ray in the sequence.

Arns and Wiedenbeck[3] were able to limit the quadrupole content (Q) of the 630-keV transition between the 1464- and 834-keV levels to the value of $Q\geq0.90$. However, in that measurement, the 630-keV γ ray could not be resolved from the 601-keV γ ray, so that its effect on the correlation had to be estimated. The present results, in which the 630-keV γ ray is clearly resolved, limit the quadrupole content for this transition to $Q\geq0.99$.

The coefficients obtained by Arns and Wiedenbeck for the 2202–834-keV correlation are consistent with either a $2(D)2(E2)0$ or a $3(D,Q)2(E2)0$ sequence, and with the present measurements. Since there is very little

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[13] R. G. Arns, R. E. Sund, and M. L. Wiedenbeck, U.M.R.I. Technical Report No. 2375-4-T, 1959 (unpublished); R. G. Arns and W. G. Monahan (unpublished).

[14] M. E. Rose, Phys. Rev. 91, 610 (1953).

[15] J. E. Albergini and R. M. Steffan, Phys. Letters 7, 85 (1963).

[16] M. Kregar and B. Elbek, Nucl. Phys. A93, 49 (1967).

interference from other cascades in the 2202–834-keV correlation, the previous measurements provide a check for the present correlation results. The agreement between the two correlation measurements for this cascade indicates that there is no serious attenuation of the present correlations. The weighted average for the two measurements would fit a $3(D, Q)2(E2)0$ sequence for the correlation, but it would require $0.35 \leq Q \leq 0.50$. This quadrupole fraction is too large to be consistent with the pair-conversion results of Belyaev *et al.*[17] which indicate that the 2202-keV transition is nearly pure $E1$. Although Bhattacherjee *et al.*[18] assumed a spin assignment of 3− for the 3036-keV level, Tirsell and Bloom[19] have pointed out that the β-γ circular-polarization measurements are also consistent with a 2− assignment. The latter authors also argue that the large quadrupole content required by a 3− assignment is rather improbable. The present measurements are then consistent with a $2(D, Q)2(E2)0$ sequence with $Q \leq 0.01$ for the 2202-keV transition.

When a single γ ray is involved in more than one directional-correlation measurement, the observed spin and multipole mixture of this transition must be the same in the various measurements. In the present experiment, there were several cases in which this consistency requirement was used to limit the possible spin assignments to a given level. However, in addition, it was necessary to assume the 3− assignment for the 2515-keV level, which was obtained from proton inelastic-scattering experiments,[5,6] in order to limit the assignments based on the remaining correlation measurements.

An example is the 894–834-keV correlation. This direct cascade correlation yielded experimental coefficients of $A_2 = +0.046 \pm 0.016$ and $A_4 = -0.012 \pm 0.030$. These coefficients will fit a $2(D, Q)2$, a $3(D, Q)2$, or a $4(Q, O)2$ sequence for the 894-keV γ ray. The 786–834-keV (1-3) correlation from the 2515-keV level also involves the 894-keV γ ray but as an unobserved transition. Thus the spins and multipole mixtures assumed for the 894-keV transition must be consistent in these two correlations. This alone was not sufficient to make a definite spin assignment to the 1728-keV level. However, with the assumption that the 2515-keV level is a 3− state, the 786–834-keV correlation fits only a $3(D, Q)4(Q, O)2(E2)0$ sequence. The spin of 4 is thus established for the 1728-keV level and the 894–834-keV correlation results may then be used to determine the octupole content of the 894-keV transition. A pure $4(Q)2(E2)0$ sequence has theoretical angular correlation coefficients of $A_2 = +0.102$ and $A_4 = +0.0091$. The present experimental coefficients for the 894–834-keV cascade are shown with the theoretical curves in Fig. 2. They require the 894-keV γ ray to be a $4(Q, O)2$ transition having an octupole fraction given by $0.004 \leq Q \leq 0.013$. Although it is extremely unlikely, one should not rule out the possibility of interference in this directional-correlation measurement due to another γ transition of 894-keV energy in coincidence with the 834-keV transition. The closest known γ ray[9] is at 878 keV and was excluded from the present measurements.

The spin-4 assignment to the 1728-keV level also requires a spin of 3 for the 3325-keV level in the 1597–834-keV correlation measurement.

The 2508–834-keV correlation results are consistent with either a 2 or 3 spin assignment for the 3342-keV level. Tirsell and Bloom give an argument, based on their β-γ circular-polarization work,[19] against both the 3325- and 3342-keV levels having a spin of 3. In addition, the pair-conversion coefficient measurement[17] shows that the transitions from these levels to the 834-keV level should be almost pure $E1$. In the 2508–834-keV correlation, a spin 3 assignment to the 3342-keV level would require a 10% quadrupole admixture in the 2508-keV transition. For a spin-2 assignment, the quadrupole content for this transition lies in the range $0.0 \leq Q \leq 0.02$. The level at 3342 keV was therefore assigned a spin and parity of 2−. The 3325-keV level is then a 3− level and the 2491-keV transition has a quadrupole content between 1 and 4%.

There are two correlations involving the 2065-keV

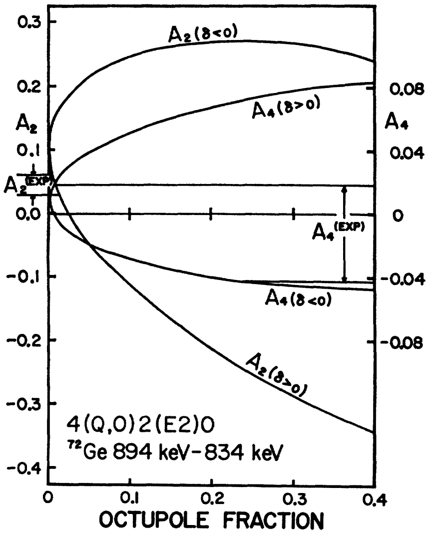

FIG. 2. The theoretical curves for A_2 and A_4 for a $4(Q, O)2(E2)0$ sequence plotted as a function of O, the octupole fraction in the first transition. The experimental values are for the 894–834-keV correlation. Note that both coefficients must fit the curves for the same sign of δ, the $M3/E2$ mixing ratio. The experimental uncertainty in $A_2^{(\mathrm{expt})}$ was used to limit the octupole fraction in the 894-keV transition between the 1728- and 834-keV levels to the values $0.004 \leq O \leq 0.013$.

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[17] B. N. Belyaev, S. S. Vasilenko, V. S. Gvozdev, and V. N. Grigor'ev, Yadern. Fiz. **3**, 13 (1966) [English transl.: Soviet J. Nucl. Phys. **3**, 9 (1966)].

[18] S. K. Bhattacherjee, S. K. Mitra, and H. C. Padhi, Nucl. Phys. **72**, 145 (1965).

[19] K. G. Tirsell and S. D. Bloom, Nucl. Phys. **A103**, 461 (1967).

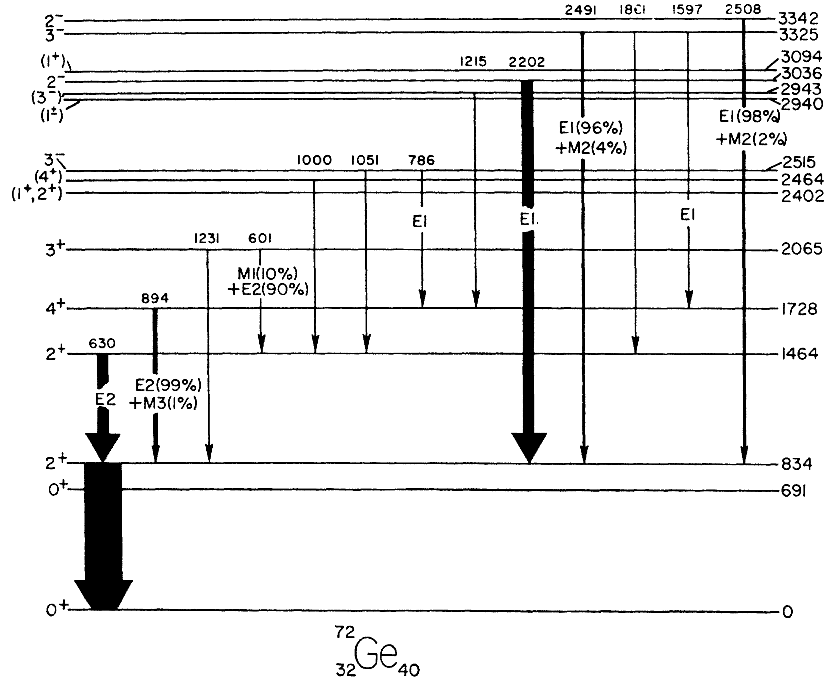

FIG. 3. A partial level scheme for ^{72}Ge showing the proposed spin assignments for the levels and multipole mixtures for the transitions. Only the transitions whose angular correlations were measured in this experiment are shown. See Ref. 9 for a detailed level scheme for ^{72}Ge.

level. The 1231–834-keV correlation is consistent with either a $1(D, Q)2(E2)0$ with $Q\leq 0.2$ or a $3(D, Q)2(E2)0$ with $0.14\leq Q\leq 0.96$. The possible sequences for the 601–834-keV (1-3 correlation with 630-keV γ ray unobserved) correlation are $1(D, Q)2(E2)2(E2)0$, with $0.0\leq Q\leq 0.85$; $2(D, Q)2(E2)2(E2)0$, with $Q\leq 0.10$; or $3(D, Q)2(E2)2(E2)0$, with $0.9\leq Q\leq 1.0$. A spin of either 1 or 3 is in agreement with each correlation measurement. The spin-1 value is rejected because there has been no observed ground-state transition.

The other correlation results listed in Table I do not give unique spin and mixing assignments. Since the 1728-keV level has a spin of 4, the 1215–834-keV correlation results are consistent only with a spin assignment of 3 or 4 for the 2943-keV level. The 1000–834-keV correlation, the only one involving the 2464-keV level, is consistent with a spin of 2, 3, or 4 for this level. The β^- log*ft* value of 9.5 indicates positive parity for this level.[9] There is no observed feeding from the ^{72}As side. It decays only to the 1464-keV, 2+ level and the 1728-keV, 4+ level and is fed from above by the 3325-keV, 3− level. Based on these observations, the spin-parity assignment of 4+ is strongly favored for the 2464-keV level. In the 1051–834-keV and the 1861–834-keV correlations, the first transition is known to be a $3(D, Q)2$. However, the quadrupole fractions are not limited by the present correlation measurements.

A partial level structure of ^{72}Ge is shown in Fig. 3. The levels shown are those which are known to be fed in the decay of ^{72}Ga. Only the transitions involved in the present directional-correlation measurements are indicated. A complete level structure for ^{72}Ge, as known from ^{72}Ga and ^{72}As decay, is given in Ref. 9. The spins in parentheses were determined from the β-decay log*ft* values and γ branching. Other spins and parities in Fig. 3 are based on the present assignments.

IV. DISCUSSION

In the Kisslinger-Sorensen (KS) calculations[20] the ground state of an even-even nucleus is the quasiparticle vacuum. The first intrinsic excited states for these nuclei will be the two quasiparticle states at an energy greater than the gap energy. If the quadrupole interaction is treated as a perturbation, there will be collective oscillations whose energies will fall in the gap. This description combines the effects of the shell model with those of the collective model.

In ^{72}Ge, there are four protons and 12 neutrons outside of the closed shell at 28. The shell-model levels between the magic numbers 28 and 50 are $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, and $1g_{9/2}$. The degeneracy of each level is $2j+1$, so the neutrons should fill the first two levels and the last two neutrons should occupy either the $p_{1/2}$ or $g_{9/2}$ level. The protons should occupy pairwise the $p_{3/2}$ and $f_{5/2}$ levels.

Since the first intrinsic excitations are two quasiparticle states, we will first look at the adjacent odd-A nuclei to obtain the single-particle spectra. If we think of the low-lying energy levels in ^{73}Ge and ^{73}As as being

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[20] L. S. Kisslinger and R. A. Sorensen, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **32**, No. 9 (1960); Rev. Mod. Phys. **35**, 853 (1963).

TABLE II. Comparison of reduced transition probabilities for transitions from the lowest 2+ states in ^{72}Ge with single-particle (SP) and KS estimates.

Transition	Energy (keV)	B (expt) (10^{-48} cm^4)	B(expt)/B(SP)	B(expt)/B(KS)
($E2$; $2+\rightarrow 0+$)	834	0.234	26	0.48
($E2$; $2+'\rightarrow 0+$)	1464	0.0015	0.17	0.35
($M1, E2$; $2+'\rightarrow 2+$)	630	0.711	38	···

single proton or neutron levels, then the first intrinsic states in ^{72}Ge should be obtained by breaking a pair of protons or neutrons and recoupling them with the single-particle energies. Since the single-particle energies are very small, i.e., on the order of 75 keV, we expect the first intrinsic states to be at the gap energy. The energy gaps for ^{73}Ge and ^{73}As given by KS are 2.6 MeV for neutrons and 3.0 MeV for protons. We therefore expect to find the collective states for ^{72}Ge below 3.0 MeV. The level structure should be similar to other even-even nuclei in the spherical region; i.e., it should exhibit a vibrational spectrum.

The 0+ first excited state of ^{72}Ge seems to be related to the single-particle structure in this region rather than showing the expected strong collective behavior. There are only four other nuclei which have 0+ first excited states—^{16}O, ^{40}Ca, ^{90}Zr, and ^{208}Pb. All of these are doubly magic except ^{90}Zr. An explanation for the 0+ first excited state in ^{90}Zr has been given by Bayman *et al.*[21] in terms of a pair-configuration mixture for the last two protons. ^{90}Zr has 40 protons and 50 neutrons, so the last two protons occupy the same levels as the last two neutrons in ^{72}Ge. The anomalous 0+ first excited state of ^{72}Ge might be due to a $(\frac{1}{2})^2{}_0$ and $(\frac{9}{2})^2{}_0$ neutron pair configuration. This could explain the fact that the β^+ and electron-capture transitions from ^{72}As feed the ground state 80 times more strongly than the first excited 0+ state. The only single-particle configuration which could give a 2− ground state for ^{72}As is an $f_{5/2}$ proton and a $g_{9/2}$ neutron. The relative transition probability from ^{72}As to the two 0+ states in ^{72}Ge is then a measure of the amount of $g_{9/2}$ mixture in their wave functions.

There are several excited states above the first excited state which do fit the vibrational pattern. The 2+ level at 834 keV and the 2+ and 4+ levels at 1464 and 1728 keV are expected to be the one- and two-quadrupole vibrational states, respectively. Since the lifetimes of the lowest two of these states have been measured,[22] we may compare the experimental values for the reduced transition probabilities for these states with the KS calculations and the single-particle estimates. This comparison is shown in Table II.

Since the 834-keV reduced transition probability is 26 times the single-particle estimate, the transition is clearly not of single-particle character. The B(KS) value for this transition is only a factor of 2 too large. The KS calculation does not assume an effective charge and uses the same parameters for the transition probability as were used in the calculations for the energy levels in this region. For these reasons the KS method seems to be an accurate description of the collective nature of this level. Kisslinger and Sorensen state[20] that their $B(E2)$ values tend to be larger than the experimental values as the vibrations get softer and one approaches the deformed region. The $2+'\rightarrow 0+$ crossover transition is forbidden in a first-order calculation, so the KS values in Table II are due to higher-order corrections to the basic theory.

Our results show that the $M1$ content of the $2+'\rightarrow 2+$ transition is less than 1.0%. The single-particle estimate for the $M1$-$E2$ ratio for this transition is 2.55×10^4. Also, from Camp's relative intensities, the crossover to the cascade branching ratio from the 1464-keV level is 0.15. The $2+'\rightarrow 2+$ transition is 38 times the single-particle estimate for an $E2$ transition. Therefore, the second 2+ state connot be considered to be a single-particle state. These experimental results support a vibrational picture and provide a sensitive test for a nuclear-structure calculation.

Another interesting feature of the collective states is the transition between the 1728- and 834-keV levels, which is an $E2$-$M3$ mixture with an octupole fraction given by $0.004<O<0.013$. The single-particle estimate for the $M3/E2$ ratio is 9.4×10^{-5}. This observed large relative enhancement of $M3$ over $E2$ for this transition is difficult to understand. Until the lifetime of the 1728-keV level has been measured, it is not possible to say whether the $E2$ is retarded or the $M3$ enhanced over a single-particle estimate.

The most energetic state in ^{72}Ge, which has been identified as a collective state, is the 3− level at 2515 keV This state has been labeled as the one-octupole-phonon state by the characteristic angular distribution of the inelastically scattered protons.[5,6] There is a similarity between this angular distribution and that obtained

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[21] B. F. Bayman, A. S. Reiner, and R. K. Sheline, Phys. Rev. **115**, 1627 (1959).

[22] Yu. P. Grangrskii and I. Kh. Lemberg, Izvest. Akad. Nauk SSSR (Ser. Fiz.) **26**, 1001 (1962).

from other 3− levels of nuclei in this region, e.g., the Ni isotopes.[23] In a strict vibrational description of the nucleus, this state should be at the same energy as the two-phonon collective states; however, the ratio of the energy of the 3− level in the Ni isotopes to the energy of the first excited 2+ level is nearly constant and has an average value of 3.08. The value of $E(3-)/E(2+)$ for ^{72}Ge is 3.02; however, the values of this ratio for ^{70}Ge and ^{74}Ge are 2.47 and 4.27, respectively. Even though this ratio changes rapidly in the Ge isotopes, the energy for the 3− levels remains almost constant. This indicates that the position of the 3− level is more independent of the neutron configuration than are the energies of the first excited 2+ levels. This is not expected. Since the energies for the 3− levels are close to the pairing energy, one would expect the particle configuration to contribute heavily to this state.

The lowest-energy two-quasiparticle configurations are expected to be the $(\frac{3}{2})(\frac{5}{2})$ and the $(\frac{3}{2})(\frac{1}{2})$. These configurations give rise to positive-parity states with angular momenta of 1, 2, 3, or 4 and energies at about the gap energy. Possible candidates for these states are the levels at 2065, 2402, 2464, and 2940 keV. If we assume that the level at 2402 keV has a spin of 2 and that the parity of the 2940-keV level is positive, then the spin-parity values for these levels would be 3+, 2+, 4+, and 1+, respectively. An interesting observation concerning these states is that there are no observed transitions between any of these levels.[9] They decay only to the collective states and to the 0+ ground and first excited states. One argument against an intrinsic interpretation for the 2065-keV level is the large $E2$ content of the 601-keV transition to the 1464-keV level. The 2065-keV level may then be interpreted as the 3+ member of the three-phonon quadrupole vibrational excitation. The relative intensities[9] for transitions from these levels do not show definite intrinsic or vibrational character. It is likely that these excitations are more complicated than either simplified point of view would indicate.

Above these states the level density becomes very large. The character of the higher excited states will have to be determined from the branching ratios for their γ decays. There are two known 2− and 3− levels above the collective octupole state. The 3− levels decay mainly to the one- and two-phonon levels. We would expect these transitions to be almost pure dipole radiations; in fact, the 786- and 2491-keV transitions were measured in this experiment to be electric-dipole transitions. If one looks at the trend for the relative intensities from the 3325-keV level, one sees that the intensity does increase with the energy. This is to be contrasted with the relative intensities from the 2515-keV octupole state, which decays mainly to the two-phonon states. The level at 2943 keV has transitions which are similar in intensity to those from the 3325-keV level, except there is no observed transition to the 1464-keV level. According to Camp's data[9] this transition would easily be observable if it had an intensity comparable to the intensity of the transitions to the 834- and 1728-keV levels. In any case, the 3− levels at 2943 and 3325 keV have more single-particle than collective character. It is interesting to note that both of these states decay more strongly to the 2515-keV (octupole) level than would be expected by a single-particle estimate.

The 2− states at 3036 and 3342 keV decay almost entirely to the one-phonon level at 834 keV. Both transitions are almost pure electric dipole. Compared to the branching from the 2− levels to the 834-keV level, the $E1$ transitions to the 2+′ two-phonon level are hindered. The 2− states are similar in character and are probably very simple particle configurations.

The discussion up until now has been based on the assumption of a spherically symmetric core plus valence nucleons. This gives rise to vibrational excitations and quasiparticle excitations. Another way of looking at the structure of ^{72}Ge would be to assume a permanently deformed core, which would give rise to a rotational spectrum. The difference between the ground state and the first excited state could be due to the difference between a prolate and an oblate deformation. This has been suggested by Kregar and Mihailovic.[24] If this is true, then we might expect two sets of excited states built on the two different core structures. The transitions from the excited states should show a difference in their intensities for decay to the ground state and the decay to the first excited state. Of the well-established levels there are no states which decay to the first excited state but not to the ground state. Of the remaining levels which have transitions to both the 0+ states, there is no significant enhancement for either transition. Thus, it would be very difficult to describe the excitation spectrum of ^{72}Ge on the basis of a deformed core, without allowing a strong vibration-rotation interaction.

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[23] H. W. Brock, Phys. Rev. **130**, 1914 (1963).

[24] M. Kregar and M. V. Mihailovic, Nucl. Phys. **A93**, 402 (1967).