Level Structure of Low-Lying Excited States of Ga^{66} Populated by the Decay of 2.2-h Ge^{66}†

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The decay of 2.2-h Ge^{66} to levels in Ga^{66} has been investigated by the use of both singles and coincidence γ-ray spectroscopic techniques that made exclusive use of high-resolution Ge(Li) detectors. The internal-conversion electron spectrum was also studied. A total of 23 transitions was observed in this decay; these were incorporated in a complete and unambiguous level scheme that differs markedly from those previously proposed. The excitation energies of the states in Ga^{66} found to be populated in this decay are 43.8, 108.9, 234.0, 290.9, 381.8, 514.6, 536.6, and 706.0 keV. The half-life of the Ge^{66} activity was redetermined to be be 2.23±0.10 h. The half-life of the first excited state was measured by delayed-coincidence techniques to be 21±2 nsec. The multipolarities of many of the transitions were determined. Spin and parity assignments of many of the excited states were inferred, and severe limitations could be imposed on the spin assignments of the remainder of the levels. The logft values of all β branches were established, and limits on the amount of isobaric-spin impurity present in the ground state of Ge^{66} were set. The level characteristics were found to be consistent with expectations derived from theoretical considerations.

I. INTRODUCTION

THE low-lying states of odd-odd ${}_{31}Ga_{35}{}^{66}$ have been the subject of only a few previously reported experimental investigations. Although the levels of this nuclide are accessible by means of some particular charged-particle reactions, no reports of studies of this type have appeared in the literature. All prior investigations[1–3] of these states have been based upon their population by the β decay of 2.2-h Ge^{66}. Since the ground state of Ga^{66} is itself unstable to β decay[4] ($t_{1/2}$=9.5 h) to Zn^{66}, the γ-ray complexities of the combined parent and daughter activities make the investigation of the Ge^{66} decay difficult. Therefore, it is not surprising that these complications have deterred many earlier investigations.

The Ga^{66} nuclide contains three protons outside the closed $f_{7/2}$ shell and presumably the configurations of the ground state and low-lying excited states would be dominated by the odd proton in the $2p_{3/2}$ orbital, although the $2p_{1/2}$ and $2f_{5/2}$ proton orbitals might also be expected to play non-negligible roles. The valence neutrons are also expected to occupy similar orbitals. Thus, the low-lying excited states of Ga^{66} may be expected to be characterized by positive parity. Since the ground-state spin-parity of Ga^{66} is known[5] to be 0^+, all transitions from higher levels to ground are of pure multipolarity. The spin of the parent Ge^{66} is also 0^+, and allowed β decay to excited states of Ga^{66} is expected to populate levels whose spin and parity are at most 1^+. These facets of the decay characteristics and of the expected shell-model configurations of the low-lying states combine to lead to the expectation of low-spin excited states and relatively simply defined multipole character for many of the γ-ray transitions.

In addition, β transitions to 0^+ states in Ga^{66} are forbidden by isobaric-spin selection rules, and such Fermi-type transitions would proceed by way of isobaric-spin impurities present in the wave function of the 0^+ parent level of Ge^{66}. Thus, identification of 0^+ levels in Ga^{66} together with experimental stipulation of the β branching (if any) to these states can provide illuminating estimates of the amount of isobaric-spin impurities present.

Previous studies[1,2] have shown the γ-ray spectrum to be very complex, with many closely spaced transitions. The earlier work[1,2] utilized NaI(Tl) detectors and, despite the numerous detailed γ-γ coincidence studies, the resulting level scheme for Ga^{66} appeared to contain several important inconsistencies and ambiguities which demanded clarification.

The present work describes an investigation of the levels in Ga^{66} populated in the β decay of Ge^{66}. High-resolution Ge(Li) detectors were used exclusively, both for γ-ray singles spectra and for coincidence spectra. The purpose of this investigation was to determine a clear, self-consistent, and unambiguous level scheme. In addition, since the expected shell-model configurations of the levels in this nuclide may lead to the occurrence of forbidden $M1$ transitions, this investigation included efforts to determine the lifetime of states that could signify the presence of such retarded transitions.

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[1] H. H. Hopkins, Jr., and B. B. Cunningham, Phys. Rev. **73**, 1406 (1948); H. H. Hopkins, Jr., *ibid.* **77**, 717 (1950).

[2] R. A. Ricci and R. Van Lieshout, Nuovo Cimento **4**, 1592 (1956); R. A. Ricci, R. K. Girgis, and R. Van Lieshout, Nucl. Phys. **21**, 177 (1960); Zing He-sung, N. S. Mal'tseva, V. N. Mekhedov, and V. N. Rybakov, Yadern. Fiz. **1**, 189 (1965) [English transl.: Soviet J. Nucl. Phys. **1**, 132 (1965)].

[3] H. H. Bolotin, Bull. Am. Phys. Soc. **8**, 524 (1963).

[4] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D.C.), NRC 60-4-23.

[5] J. L. Worcester, W. A. Nierenberg, R. Marrus, and J. C. Hubbs, Bull. Am. Phys. Soc. **2**, 383 (1957).

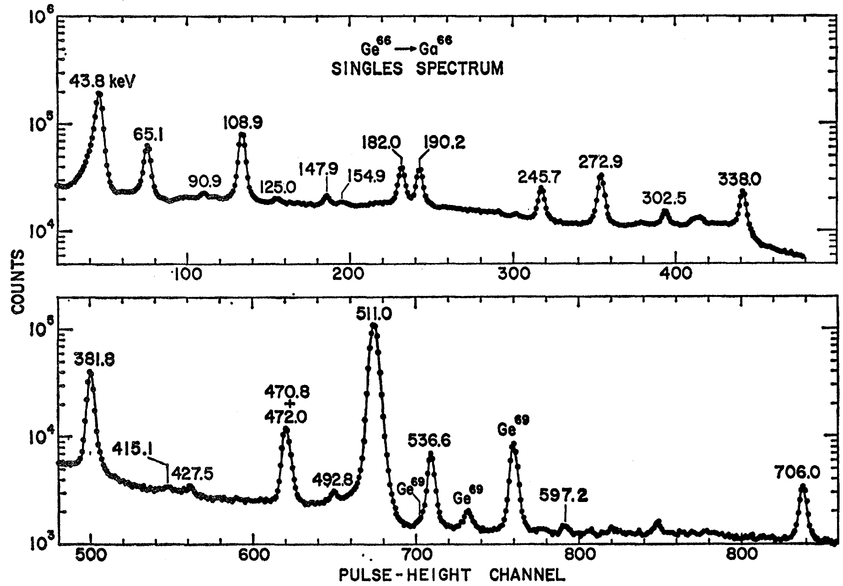

FIG. 1. Singles spectrum of γ rays following the decay of Ge^{66}. All energies are in keV. The γ rays from the Ge^{69} impurity are labeled.

II. SAMPLE PREPARATION AND HALF-LIFE OF PARENT ACTIVITY

The 2.2-h Ge^{66} activity was produced by means of the $Zn^{64}(\alpha, 2n)Ge^{66}$ reaction at the Argonne 60-in. cyclotron. A natural Zn target was employed. In order to maximize the ratio of the $(\alpha, 2n)$ reaction cross section to that of competing reactions, the target thickness was selected such that the α-particle energy decreased only from 36 to 28 MeV in traversing it. As a result of the use of the natural target and the necessarily incomplete discrimination against these other reactions, some vestiges of short-lived Ge^{65} (1.5 min) and Ge^{67} (19 min) were present. To permit these contaminating activities to decay to negligible proportions, 3 h were allowed to elapse from the termination of the α-particle bombardment to the initiation of the chemical separation. Traces of long-lived Ge^{69} (40 h) were also unavoidably produced, but the γ rays from this activity were readily identified.

The desired Ge^{66} activity was chemically separated from both the target material and the sizeable Ga daughter activities of the short-lived Ge parents produced in the bombardment. In this separation by benzene solvent extraction, the target was first dissolved in concentrated HCl and thoroughly mixed with the benzene solvent. The Zn and Ga fractions were selectively retained in the acid, and were removed by repeated scrubbings with concentrated HCl. The aqueous layer was finally removed by titration, centrifuging, and vigorously bubbling with air. The Ge activity was finally back-extracted with a few drops of 0.1 *N* HF. The desired fraction of the Ge^{66} yield was placed in small plastic vials for counting.

Because of the build-up of the 9.5-h Ga^{66} daughter activity, all samples of Ge^{66} activity were only used for $\sim$1.5 half-lives of the parent. Repeated bombardments and chemical separations were therefore required for those investigations lasting longer than $\sim$3.5 h, except as noted in the next paragraph.

The half-life of the Ge^{66} activity was determined with a single sample in a study of $\sim$12-h duration. The γ-ray spectrum was periodically recorded with a Ge(Li) detector, and the decay characteristics of several of the stronger transitions known to be associated with Ge^{66} were analyzed together to obtain the half-life. (The deadtime of the system varied considerably over the duration of this study because of the decay of the activity and the presence of the 9-h Ga^{66} daughter. This deadtime was carefully determined and corrections for it were applied.) The resulting half-life $T_{1/2}=2.23\pm0.10$ h disagrees with the value 2.4 ± 0.2 h reported previously.[2] Each individual γ ray assigned to Ge^{66} also displayed a half-life consistent with this value. A few of the observed transitions were due to the much longer-lived Ge activities and the Ga^{66} daughter, but were easily identified.

III. γ-RAY ENERGIES AND RELATIVE INTENSITIES

The singles γ-ray spectrum (Fig. 1) was obtained with the aid of a 30-cm^3 Ge(Li) detector characterized by a linewidth of 2.9 keV at a deposited energy of 1.33 MeV. The energies and relative intensities of the γ rays observed in the $Ge^{66} \rightarrow Ga^{66}$ decay are listed in Table I. All transitions appear to be fully resolved. Of special interest is the clear separation of the 182- and 190-keV γ rays previously accepted as a single 185-keV transition in earlier NaI(Tl) studies of this spectrum.

TABLE I. Transitions in Ga^{66}.

γ-ray energy (keV)	Relative γ-ray intensity[a]	Assignment Initial state (keV)	Final state (keV)
43.83±0.05	76.4	43.8→	0
65.10±0.05	21.8	108.9→	43.8
90.90±0.10	1.5	381.8→	290.9
108.93±0.05	45.1	108.9→	0
125.05±0.10	1.4	234.0→	108.9
147.87±0.08	3.3	381.8→	234.0
154.85±0.10	1.9	536.6→	381.8
181.96±0.05	25.7	290.9→	108.9
190.17±0.05	26.2	234.0→	43.8
245.75±0.05	21.0	536.6→	290.9
272.90±0.05	41.1	381.8→	108.9
290.99±0.10	1.1	290.9→	0
302.51±0.07	8.4	536.6→	234.0
338.01±0.05	34.0	381.8→	43.8
381.85±0.05	100	381.8→	0
415.13±0.10	1.8	706.0→	290.9
427.51±0.10	1.0	536.6→	108.9
470.76±0.07	31[b]	514.6→	43.8
472.0±0.25[c]	5[b]	706.0→	234.0
492.76±0.10	1.5	536.6→	43.8
536.58±0.05	20.8	536.6→	0
597.16±0.15	1.2	706.0→	108.9
706.04±0.07	13.4	706.0→	0

[a] The intensities of the γ rays are relative to that of the 381.85-keV γ ray taken as 100. The errors in the relative γ-ray intensities are 5–8% of the listed value for intensities >10, 10–20% for weaker transitions.

[b] After chance and underlying Compton coincidences were subtracted, a knowledge of the placement of all pertinent transitions in the level scheme allowed the relative intensities of the 147.9- and 302.5-keV γ rays in the singles spectrum to be compared with that obtained for these γ rays and that of the resolved 472.0-keV γ ray in coincidence with the 190.2-keV transition. From this one obtains the relative intensity of the 472.0-keV transition. This intensity was determined to be 5±1 relative to that of the 381.8-keV γ ray. Further, the combined γ-ray intensity of the two unresolved 470.8- and 472.0-keV transitions in the singles spectrum is 36 relative to the 381.85-keV transition (taken as 100). From a very careful peak fit of the "470-keV" γ-ray peak in the singles spectrum, ~15% of the unresolved doublet strength can be attributed to the 472.0-keV transition, in good agreement with the relative intensity presented in this table as obtained from the coincidence study.

[c] The listed γ-ray energy and its estimated error have been obtained from the observed shift in peak position relative to the much stronger 470.76-keV transition in the coincidence spectra. However, the mandatory placement of this transition dictated by the coincidence results imposes a smaller uncertainty on the listed energy of this γ ray when coupled with the listed errors in the energies of the 706.04-, 190.17-, and 43.83-keV transitions.

TABLE II. Comparison indicating the degree of consistency between the values obtained by independent computations of the excitation energy.

Excitation energy (keV)	Cascade energy sum (keV)	Crossover energy (keV)	Maximum energy spread (keV) of cascade sum	Average deviation (keV) of cascade sum[a]
43.8	43.83	43.83	0.02	0.01
	43.84			
	43.82			
108.9	108.93	108.93	0.02	0.04
	108.95		0.10[b]	
	108.97[b]			
	109.03[b]			
	108.95[b]			
234.0	234.06	234.00	0.06	
	233.98[b]		0.08[b]	0.03
	233.98[b]			
290.9	290.83	290.89	0.06	0.07
	290.95[b]		0.12[b]	
	290.99[c]		0.16[c]	
381.8	381.83	381.85	0.02	0.05
	381.83		0.12[c]	
	381.73[c]			
536.6	536.64	536.58	0.06	0.08
	536.64		0.13[b]	
	536.51[b]		0.20[c]	
	536.70[c]			
	536.44[c]			
	536.59[c]			

[a] The values listed in this column are obtained by taking the energy of the crossover transition as the standard.

[b] Includes weak transitions.

[c] Includes weakest transitions.

In addition, several previously unreported transitions were observed.

The γ-ray energies were determined by comparison with the positions of the γ-ray transitions at 121.970±0.030 keV in Co^{57} and at 1332.483±0.046 keV in Co^{60}, both of which are known[6,7] to high accuracy. The comparison was made with the aid of an extremely

[6] J. B. Marion (private communication).

[7] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **63**, 353 (1965).

linear ramp generator and a chopper, which in combination accurately defined the local differential nonlinearity of the electronic system over the entire energy range of interest. This information, coupled with the pulse-height positions of the calibration γ rays, yielded the energies of the transitions in the $Ge^{66}\rightarrow Ga^{66}$ spectrum to the accuracies quoted in Table I. Details of this method are presented elsewhere.[8]

The self-consistencies of the γ-ray energies determined is given in Table II. This table lists the various sums or differences of cascade and crossover transitions whose placements are defined in the final proposed level scheme presented in Sec. V. Many of these sums and differences involve rather weak transitions. Nevertheless, as is evident in Table II, those cascade and crossover energies that involve only the stronger transitions defining the energies of the various excited states in Ga^{66} show a maximum energy *spread* of ≤ 0.06 keV, while the maximum energy spread is ≤ 0.13 keV for those sums involving weak transitions, and is ≤ 0.2 keV for those involving even the very weakest γ-ray transitions.

The relative γ-ray intensities listed in Table II were obtained with the aid of well-calibrated γ-ray intensity standards run at the same source-to-detector distance. They served to define the peak detection efficiency of the detector as a function of γ-ray energy. The deadtime losses in the counting system were carefully determined in each intensity calibration and suitable corrections were made; otherwise, the determinations of the detection efficiencies at the peaks would have been spuriously low.

IV. γ-γ COINCIDENCE STUDIES AND MEASUREMENT OF EXCITED-STATE LIFETIMES

A. γ-γ Coincidence Studies

γ-γ coincidence spectra were obtained with a 1024×1024 channel two-parameter γ-ray spectrometer which utilized Ge(Li) detectors in each arm of the coincidence system. An $\sim$4-cm^3 planar drifted Ge(Li) detector and an $\sim$30-cm^3 modified coaxial Ge(Li) detector were used in the coincidence studies. Availability, not experimental criteria, dictated the choice of these detectors. [The coincidence counting time would have been materially reduced had both Ge(Li) detectors been of the larger volume.] The data were stored in address-event pairs on a magnetic tape unit. The tapes were later searched for the various gated coincidence pulse-height spectra. Both the zero and the gain of each analog-to-digital converter (ADC) of the coincidence system were stabilized by comparison against the peaks from two highly stable dual pulsers.[9] These peaks, whose repetition rate was 10 pulses/sec, were employed because of the low coincidence counting rate for all γ rays appearing in these spectra. The two pulsers were master-slave driven and each firing of the pulsers produced a tag pulse which was used to simulate a fast-coincidence signal. Thus, even in the coincidence mode of operation, each ADC received a sufficient number of stabilization pulses to assure proper zero and gain correction and yet the pulser repetition rate was small enough that it contributed only negligible deadtime to the system, so that the ADC's were virtually always free to process and record actual γ-ray coincidence events. The stabilization was necessitated by the lengthy coincidence running time required and by the replacement of new source material approximately every 3 h. These replacements produced large and abrupt counting-rate changes, which are conducive to shifts in gain and/or zero.

The tag pulse from the pulser was also utilized to gate the stabilizers, so that the stabilization concerned itself only with the peaks produced by the precision pulser and was thus unaffected by the presence of γ-ray pulses. Consequently, excellent stabilization is achieved even when the pulser peaks are inadvertently superimposed on γ-ray peaks. In addition, the pulser tag was employed to reject storage of the pulser peaks. The success of the stabilization was attested by the absence of any observable line shifts during coincidence runs lasting 14 h.

The fast-slow coincidence circuitry used leading-edge triggering and employed a fast resolving time (90 nsec) with 100% coincidence efficiency over the entire pulse-height range accepted by both detectors. The rather long fast-coincidence resolving time was dictated by the requirement to attain 100% coincidence efficiency even for the lowest-energy transitions (44 and 65 keV) present. The fast-coincidence circuit consisted of a time-to-pulse-height converter[10] and two stable single-channel analyzers (one set to accept the full prompt time distribution and the other set to cover an identical time interval over the chance-coincidence time distribution). Coincidences were recorded for all events satisfying the fast-slow requirements. Those events that involved the chance-coincidence timing were labeled with a tag bit on the magnetic tape and could later be sorted separately with the aid of this assignation tag. Even for the 90 nsec fast-coincidence resolving time employed, the contributions from chance coincidences were negligible.

Figure 2 displays some coincidence spectra typical of those obtained. These particular ones were selected to show some particularly interesting coincidence

[8] M. G. Strauss, F. R. Lenkszus, and J. J. Eichholz (unpublished).

[9] M. G. Strauss, L. L. Sifter, F. R. Lenkszus, and R. Brenner, IEEE Trans. Nucl. Sci. **15**, 518 (1968).

[10] R. Roddick and F. J. Lynch, IEEE Trans. Nucl. Sci. **11**, 399 (1964).

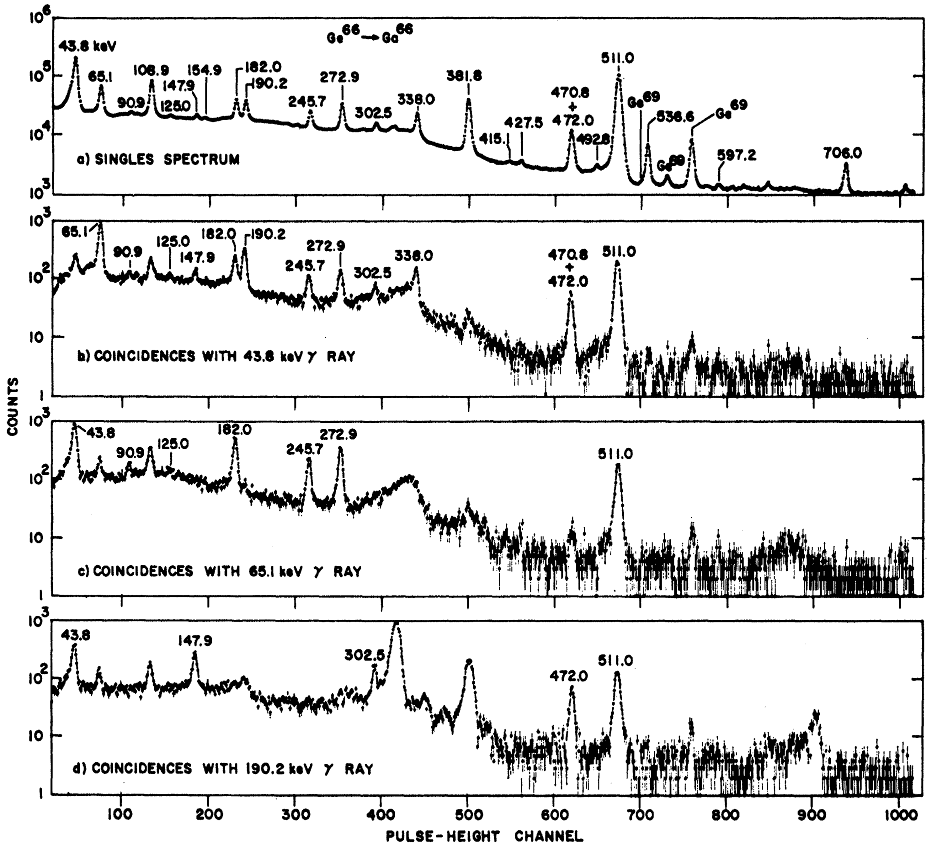

FIG. 2. Typical γ-ray spectra in coincidence with the 43.8-, 65.1-, and 190.2-keV γ rays are shown in (b)–(d), respectively. For comparison, a singles spectrum taken under identical conditions, is shown in (a). All energies stated are in keV. Coincidences with Compton distributions underlying γ-ray peaks used as gates have not been subtracted in this figure. Small chance-coincidence contributions have not been subtracted. True coincidence γ-ray peaks are labeled by energy in spectra (b), (c), and (d). Broad unlabeled "peaks," most evident in spectrum (d), are due to detector-to-detector scattering.

relationships which were new and/or crucial to the establishment of an unambiguous level scheme. These three coincidence spectra were obtained by gating on specific γ-ray transitions in the direct singles spectrum displayed in the upper portion of this figure. The spectra in coincidence with the 44-, 65-, and 190-keV γ rays not only show unambiguously that the "185-keV" line (previously thought to be a single transition) is a 181–190-keV doublet [Fig. 2(a)] but also demonstrate that the members of this doublet are not in coincidence with one another [Fig. 2(d)] and that each terminates at a different excited state [Figs. 2(b) and 2(c)]. The other point of special interest is that the "470-keV" γ ray, which appears to be a single transition even in the high-resolution Ge(Li) singles spectrum [Fig. 2(a)], is in coincidence with the 44- and 190-keV transitions but not with the 65-keV line [Fig. 2(c)]. However, inspection of Fig. 3 [an enlarged plot of the 470-keV region of Figs. 2(b) and 2(d)] shows a shift in the pulse height of this "470-keV" γ ray and therefore proves it to be a doublet. From the observed shift (1.2 keV) the energies of these transitions are found to be 470.8 and 472.0 keV, the former being in coincidence only with the 44-keV γ ray and the latter in coincidence with both the 44- and 190-keV transitions. From a careful unfolding of the singles peak into two transitions, the intensity of the 472-keV γ ray was determined to be $\leq 15\%$ of the intensity of the unresolved doublet seen in the singles spectrum. Slight tailing, present for all lines seen, restricts the determination of the relative intensities of these two components to a specification of this upper limit and does not permit a more accurate decomposition of these two lines.

Several relatively broad peaks seen in Figs. 2(b)–2(d) result from coincidences with Compton distributions underlying the γ-ray peaks used as gates. Although these peaks are evidently too wide to be γ rays, their identity was clearly established by setting equal (but slightly displaced) pulse-height gates on the underlying Compton distributions. However, one of the pulse-height gates is set on the γ-ray peak and the other on the adjacent Compton distribution, and the slight energy shift between these two gates displaces these peaks. Consequently, the peaks do not completely disappear when the spectra in coincidence with the underlying Compton distributions are subtracted from those obtained by gating on the associated adjacent γ-ray lines. The Compton peaks arise principally from scattering from each of the two unshielded Ge(Li) detectors to the other placed $\sim$135° from it. Although somewhat broader than real γ-ray peaks, these Compton

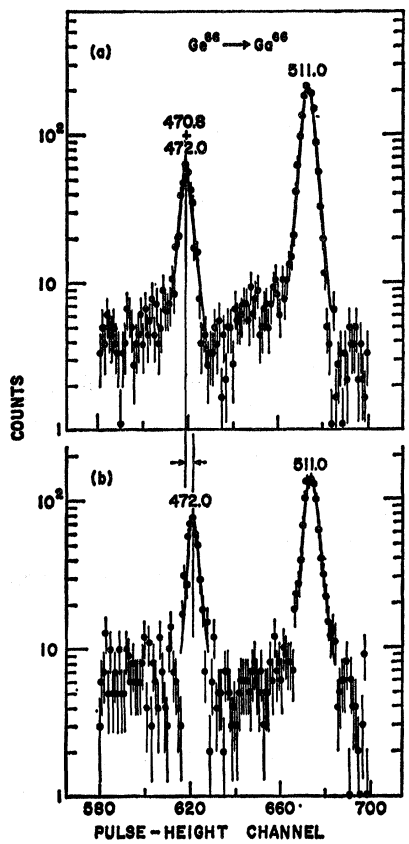

FIG. 3. Enlarged section of γ-ray spectrum in coincidence with (a) the 43.8-keV γ ray, and (b) the 190.2-keV γ ray. Note the displacement of the 472.0-keV peak in (b) from that of the conglomerate 470.8+472.0-keV peak in (a). The positions of the 511-keV annihilation radiation peaks are the same. All energies are in keV. Small chance or underlying Compton coincidences have not been subtracted in this figure.

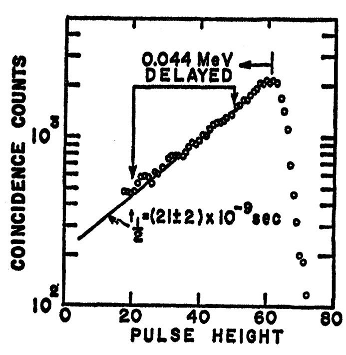

FIG. 4. Observed time-to-pulse-height delayed-coincidence spectrum between the 43.8-keV γ ray and the annihilation radiation. The slope on the left arises from delayed emission of the 43.8-keV γ ray and corresponds to a half-life of 21±2 nsec. The time calibration for this spectrum is 1.15 nsec/channel. The detectors used were NaI(Tl) scintillators.

peaks are still narrow enough that they are readily identified and do not mask true γ-ray peaks. If these peaks had caused trouble, they obviously could have been obviated by placing appropriate shielding between the detectors.

Table III summarizes the coincidence relationships thus established among the γ rays. All transitions listed in this table were seen in the coincidence spectra. As will be noted from a comparison with Table I, even some rather weak transitions were unambiguously observed to be present in some coincidence spectra.

TABLE III. Observed γ-γ coincidences.

γ-ray energy (keV)	Coincidence γ-ray energies[a] (keV)
43.8	65.1, 90.9, 125.0, 147.9, 182.0, 190.2, 245.7, 272.9, 302.5, 338.0, 470.8, 472.0
65.1	43.8, 90.9, 125.0, 182.0, 245.7, 272.9
108.9	90.9, 125.0, 182.0, 245.7, 272.9
182.0	43.8, 65.1, 90.9, 108.9, 245.7
190.2	43.8, 147.9, 302.5, 472.0
245.7	43.8, 65.1, 108.9, 182.0
272.9	43.8, 65.1, 108.9, 154.9(?)
302.5	43.8, 125.0, 190.2
338.0	43.8, 154.9(?)
381.8	154.9(?)
470.8 + 472.0	43.8, 190.2

[a] Those γ-ray energies followed by (?) appear only faintly in the coincidence spectra and unambiguous establishment of their presence in these spectra is not claimed. The coincidence relationships of these transitions are consistent with the proposed level scheme, but their placements in the scheme were established on the basis of energy and intensity fits.

B. Lifetime of 43.8-keV Excited State

As reported earlier,[8] the lifetime of the 43.8-keV first excited state was determined with the aid of two 2×1-in. NaI(Tl) scintillators. Figure 4 displays the time-to-pulse-height conversion spectrum obtained by gating one arm of the coincidence system on the 44-keV γ ray while the second arm viewed only the full-energy peak of the annihilation radiation. The two scintillators were placed at 90° to each other and were shielded from crystal-to-crystal scattering by an appropriately placed graded Pb wedge. The time calibration pertaining to this spectrum is 1.15 nsec/channel. The left-hand slope corresponds to the delayed emission of the 44-keV γ ray and yields a half-life of 21±2 nsec.

Since β^+ decay populates most of the high excited states, there could be doubt whether the delayed state was the one from which the 44-keV γ ray originates or a higher one that feeds this state. In order to resolve this ambiguity about the state with the 21-nsec half-life, a delayed-coincidence experiment was performed in which the first scintillator viewed the entire spectrum while the second arm of the system remained gated solely on the full-energy peak of the annihilation radiation. In this spectrum only those events occurring within the delay-time interval specified by the bracketing arrows in Fig. 4 were accepted. This delayed-coincidence spectrum is shown in Fig. 5. Shown for comparison in this figure is a portion of the singles spectrum viewed by the same scintillator. The presence of the 44-keV γ ray and the absence of all other transitions in this delayed spectrum at once certifies (a) that the delayed state is the one from which the 44-keV γ ray originates, (b) that the 44-keV transition is the sole transition issuing from this state, and (c) that the 44-keV γ ray populated no lower-lying excited state that decays within the 35-nsec time interval specified by the pulse-height gate set on the time distribution. Since all γ rays found to be in "prompt" coincidence with the 44-keV transition (Table III) are absent in the spectrum of Fig. 5, this study not only establishes that the measured half-life of 21 nsec is associated with the state from which the 44-keV γ ray issues, but ensures that the 44-keV γ ray originates from the first excited state of Ga^{66}.

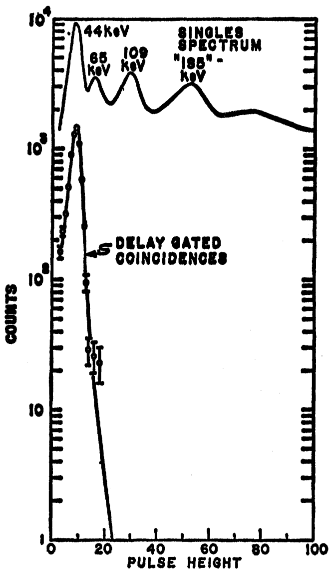

FIG. 5. Delayed-coincidence γ-ray spectrum (lower curve) obtained by viewing the entire γ-ray spectrum with one NaI(Tl) scintillator while gated by a second NaI(Tl) detector set on annihilation radiation. The delay time and the requisite time-duration "window" for pulses from the gating detector are specified by the bracketing arrows in Fig. 4. A small chance-coincidence contribution has been subtracted. Shown for comparison is a singles γ-ray spectrum (upper curve) viewed by the same detector.

V. DISCUSSION

The combined information gleaned from the spectrum in coincidence with the 44-keV γ ray [Fig. 2(b)] and from the delayed-coincidence study places the 44-keV transition between the first excited state and the ground state. The results of the γ-γ coincidence spectra that involve all but the weakest transitions (Table III) unambiguously define the ordering of these γ rays and establish the energies of the excited states between which each transition proceeds. The self-consistency and precision of the energies determined for the γ rays observed in this decay allow precise definition of the excitation energies of these states and permit those few very weak transitions observed in the singles spectrum to be positioned among these states with great confidence. Some very weak peaks in the coincidence spectra are consistent with these placements. Therefore, the proposed $Ge^{66} \rightarrow Ga^{66}$ decay scheme presented in Fig. 6 is felt to be unambiguously defined,[11] and is in strong disagreement with the one most recently proposed by Ricci *et al.*[2] [This disagreement obviously arises from the complexities of the γ-ray spectrum, which remained unresolved in the earlier NaI(Tl) investigation despite the extensive coincidence studies.]

The half-life of the 44-keV state (21×10^{-9} sec) can be compared with single-particle estimates[12] of the lifetime. When corrected for internal conversion by use of the theoretical total internal conversion coefficients[13] for pure $M1$ and $E2$ transitions (a mixture of both multipolarities is ruled out by the 0^+ ground-state assignment) and compared with single-particle estimates, the 44-keV transition displays a retardation factor of 129 if $M1$, and an enhancement factor of 769 if $E2$. The $E2$ enhancement, unrealistically large even for the most highly collective nuclei, is certainly ample reason to reject this multipolarity assignment in Ga^{66}. However, the $M1$ retardation factor associated with the 44-keV transition is consistent with those of retarded $M1$ transitions (presumably l forbidden) observed in this mass region.[14] Thus, an $M1$ assignment appears the most appropriate for this transition.

[11] A report of these results was presented at the 1968 Miami Beach, Florida, meeting of the American Physical Society [D. A. McClure and H. H. Bolotin, Bull. Am. Phys. Soc. **13**, 1426 (1968)]. After the manuscript of this study had been completed and at the time of its presentation at the American Physical Society meeting, a similar study was reported by H. Bakhru and I. M. Ladenbauer-Bellis, Bull. Am. Phys. Soc. **13**, 1427 (1968).

[12] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Co., Amsterdam, 1959).

[13] R. F. O'Connell and C. O. Carroll, Nucl. Data **A3**, 287 (1967).

[14] J. Kantele and O. Tannila, Nucl. Data **A4**, 359 (1968), and references therein.

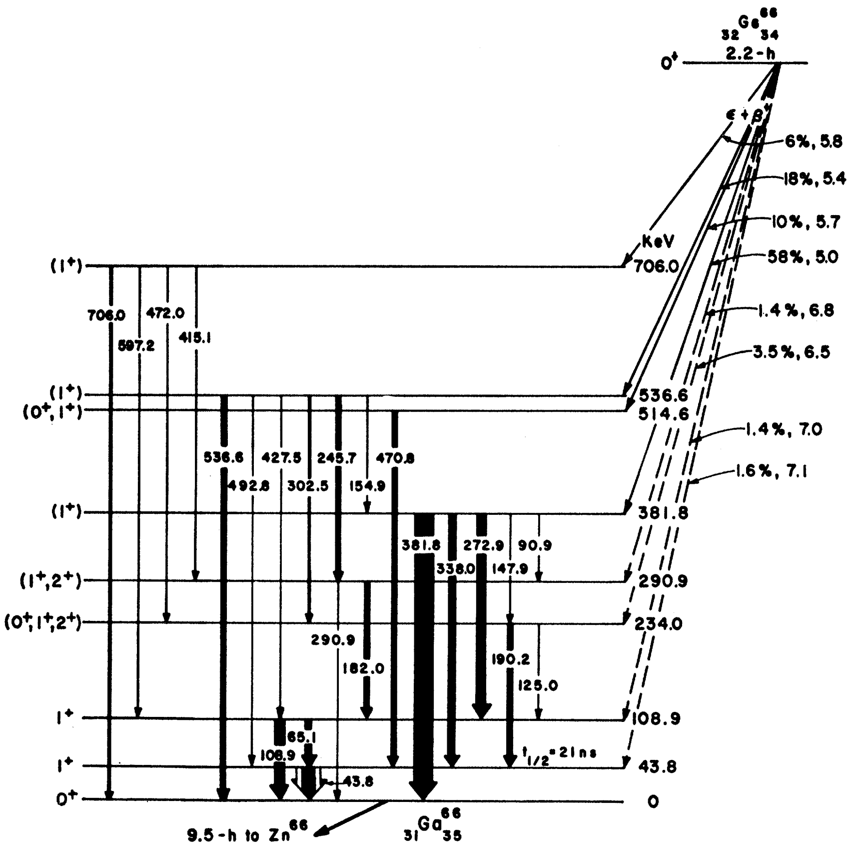

FIG. 6. Proposed β-decay and level scheme of 2.2-h Ge^{66}. All level excitation energies in Ga^{66} are in keV, as are the energies of the γ-ray transitions. The β branches indicated by dashed lines correspond to upper limits on the relative intensities of these groups (in %) and consequently to lower limits on stated values of $\log ft$. The spins and parities shown in parentheses are inferred from the results of the present experimental study. However, in no case should these be considered as experimentally measured parameters. The relative intensities of the γ-ray transitions are indicated by the breadths of the arrows. The open areas shown in the arrow representing the 43.8-keV transition indicate that fraction of the transition intensity proceeding by internal conversion.

Further evidence for an $M1$ assignment for the 44-keV transition comes from the combination of the intensity of the 44-keV γ ray relative to the intensities of those feeding the first excited states (Fig. 6 and Table I) and the β^+ spectrum end-point energies reported by Ricci *et al.*[2] These authors observed two major β^+ groupings associated with the decay of Ge^{66}; one is an $\sim$100% branch with a β^+ end-point energy of 1.3 ± 0.1 MeV and the other a $<10\%$ branch with a β^+ end-point energy of 2.0 ± 0.2 MeV. They attributed the lower-energy branch to the highest-energy inner β^+ group. The weak higher-energy branch, if it is correctly assigned to this decay, establishes that the β^+ feeding to levels near the ground state (including the level at 44-keV) is less than 9% of the total β^+ decay. If the 44-keV transition were $E2$, the large theoretical total conversion coefficient ($\alpha_T=12$) would demand that $\sim$75% of all the Ge^{66} decay populate the 44-keV state, in clear disagreement with the relative intensities of the β^+ groups reported earlier. On the other hand, an $M1$ assignment for this transition ($\alpha_T=0.62$) requires an upper limit of only $\sim$2% for the total Ge^{66} decay branch to this state and is in keeping with the β^+ findings of Ricci *et al.*[2] Thus, the above arguments strengthen the $M1$ assignment of the 44-keV transition.

On the basis of this multipolarity assignment and the relative intensities of the transitions present in the decay, the branching of the Ge^{66} decay to each level in Ga^{66} is as presented in Fig. 6. The four decay branches to the 381.8-, 514.6-, 536.6-, and 706.0-keV states in Ga^{66} account for more than 93% of all β decay. This branching, the 2.2-h half-life of the parent, and the reasonable assumption that the 1.3-MeV β^+ end-point energy is associated with the most energetic and intense branch to the 381.8-keV state in Ga^{66}, lead (after correction for orbital electron capture[15]) to $\log ft$ values of the β-decay branches to the four highest excited states shown in Fig. 6. These values are consistent with allowed decay. Similarly, the data presented here lead to $\log ft > 6.5$ for the decay to each of the four lowest excited states. (The $\log ft$ values of the decay branches to these lower states must be considered lower limits since they are based on the maximum β feeding of these states, the intensity of feeding being derived from the intensity balance of the γ-ray transitions to and from each of these states.) These $\log ft$

[15] M. L. Perlman and M. Wolfsberg, Brookhaven National Laboratory Report No. BNL 485 (T-110), 1958 (unpublished). See also C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1968), 6th ed., p. 575.

values are consistent with categorizing the β branches to the four lowest excited states as either l-forbidden ($\Delta l=2$) or first-forbidden transitions.

Even if a possible higher-energy β^+ branch to these low-lying states were treated as a single branch to the ground state, the 9% upper limit assigned to it by Ricci *et al.*[2] would demand $\log ft=6.3$. This $\log ft$ value must be considered a lower limit, since the β feeding to the first four excited states can, by itself, account for the full intensity of the higher-energy β group reported by Ricci *et al.*[2] In addition, within the errors associated with the relative intensities of the γ rays, the present data are equally well consistent with the absence of all direct β feeding to any of the four lower excited states. In short, no β feeding has been established to any state below 381.8 keV in Ga^{66}, including the ground state. Further, the value $\log ft=6.3$ for the possible $0^+\rightarrow0^+$ ground-state-to-ground-state β transition would be forbidden by isobaric-spin considerations. If this $\log ft$ is used to estimate the amount of isobaric-spin impurity required to permit this possible transition, a value of 5.5×10^{-2} is obtained. This amount of isobaric-spin admixture exceeds that established[16] for the $0^+\rightarrow0^+$ β decay of $Ga^{66}\rightarrow Zn^{66}$ by a factor of ~15. To bring the amount of isobaric-spin-impurity into accord with the upper limit of that found for other $0^+\rightarrow0^+$ β transitions in this mass region would require the intensity of the β branch to the 0^+ ground state to be $<1\%$. This upper limit on the intensity of this possible β branch is totally in accord with the above experimental findings which are consistent with no established, observed, or inferred direct β branch populating the ground state of Ga^{66}. On the basis of the association between the 1.3 ± 0.1 MeV end-point energy of the strongest β^+ group seen by Ricci *et al.*[2] and the 381.8-keV excited state in Ga^{66}, a total decay energy of 2.7 ± 0.1 MeV is inferred.

The 381.8-, 514.6-, 536.6-, and 706.0-keV levels are fed by allowed β decay from the 0^+ ground state of Ge^{66} and must therefore be assigned spins of 0^+ or 1^+. However, the 381.8-, 536.6-, and 706.0-MeV states decay to the 0^+ ground state of Ga^{66} by means of γ-ray transitions. This, as well as isobaric-spin forbiddeness for Fermi transitions, rules out the possible 0^+ assignments and restricts their spin and parity assignments to 1^+. Because of the natural breadth of the annihilation-radiation peak in the γ-ray spectrum, it was not possible to ascertain with certainty whether or not a 514-keV ground-state γ-ray transition was present in the decay of the state at this excitation energy. In addition, the coincidence studies were not performed under sufficiently favorable conditions to establish or reject this possibility unequivocally. Thus, with no direct experimental evidence for the decay of the 514.6-keV state to the 0^+ ground state, there are no adequate experimental grounds to reject the possible 0^+ assignment for this state. However, since a $0^+\rightarrow0^+$ β transition would be possible only if there were isobaric-spin impurities, the value $\log ft=5.7$ for the β branch to the 514.6-keV level would imply an isobaric-spin impurity of $\sim10\%$, a value much larger than those ascribed[16] to other such admixtures in this region (e.g., ~27 times that established in the $Ga^{66}\rightarrow Zn^{66}$ decay). Thus, the spin 1^+ for the 514.6-keV level is strongly favored on these grounds.

The pure $M1$ assignment of the 44-keV transition establishes the first excited state as 1^+.

The 108.9-keV state decays both to the 0^+ ground state and to the 1^+ first excited state. If the spin of the 108.9-keV level were as great as 3, a 108.9-keV octupole transition to the ground state could not be expected to complete successfully with the 65.1-keV transition to the 1^+ first excited state. The comparable transition probabilities of the 272.9- and 338.0-keV transitions from the 381.8-keV 1^+ state to the 108.9- and 43.8-keV levels rule out a spin >3 for the 108.9-keV state. Thus, the spin of the 108.9-keV level can be restricted to 1 or 2 (a spin-0 alternative is inadmissible because of the direct γ-ray transition from this state to the 0^+ ground state), and the 108.9-keV transition must be either pure dipole or pure quadrupole. The ratio of the theoretical K conversion coefficient[13] of the 108.9-keV transition to that of the pure-$M1$ 43.8-keV transition is 0.04 if the former transition is $M1$, and is 0.4 if it is $E2$. A six-gap "orange" spectrometer was used to study the internal-conversion spectrum. Although not of high statistical quality and therefore not presented here, the results are sufficiently reliable to reject the $E2$ possibility and is consistent with an $M1$ assignment. Therefore, the 108.9-keV state can be assigned spin 1. Although none of the above data can distinguish between an $E1$ or $M1$ assignment for this transition (the theoretical conversion coefficients are almost identical), shell-model considerations strongly suggest positive parity; it is difficult to concoct a reasonable shell-model configuration that would lead to a negative parity. Thus, all of the foregoing imply a spin and parity of 1^+ for the 108.9-keV state.

The theoretical K conversion coefficient of the 65.1-keV transition is 0.19 or 2.8 for $M1$ or $E2$, respectively. On the basis of the relative intensities of the γ-ray and K-conversion lines associated with the 65.1- and 43.8-keV transitions, the 65.1-keV transition can be assigned as $M1$ with admixture of $<15\%$ $E2$—again consistent with a 1^+ assignment for the 108.9-keV state.

A definitive spin assignment cannot be made for the 234.0-keV level. The absence of a ground-state γ ray from this state does not make it possible to reject a 0^+ assignment for this level, although such an argument was possible for some of the higher excited

[16] S. D. Bloom, Nuovo Cimento **32**, 1023 (1964).

states. The internal-conversion data were carefully scrutinized for the possible presence of a totally converted $E0$ 234.0-keV transition; but none was observed within spectral statistical limitations. However, theoretical considerations[17] strongly disfavor such a transition in competition with the 190.2-keV transition (if $M1$ or $E2$) to the first excited state. Thus, the lack of observation of the possible $E0$ transition does not rule out a 0^+ spin assignment. Three of the higher 1^+ states decay to the 234.0-keV level, each decay being in competition with higher-energy $M1$ transitions to lower levels. On the basis of single-particle transition probabilities[11] and what is known of the largest $M1$ retardations and $E2$ enhancements in this mass region, it is possible to restrict the spin of the 234.0-keV level to ≤ 2. These arguments restrict the spin of the 234.0-keV state to 0, 1, or 2. Again, shell-model considerations strongly suggest positive parity. Since only a lower limit can be set on the $\log ft$ value of the β decay to this level, it cannot be used to place further spin restrictions on this level.[18]

The presence of the ground-state transition from the 290.9-keV state rules out a possible spin-0 assignment for this level. From arguments similar to those used for the spin of the 234.0-keV state, the γ-ray branching from higher excited states of spin 1^+ allows the spin of the 290.9-keV level to be restricted to ≤ 2. Thus, this state has spin 1 or 2, with strong shell-model arguments for positive parity.

The above spin, parity, and $\log ft$ values are summarized in the level scheme (Fig. 6).

On the basis of probable shell-model configurations for the levels in odd-odd ${}_{31}Ga_{35}^{66}$, it becomes fairly evident that a sizeable degree of configuration mixing would be expected in any meaningful description of these states. Alternatively, if one adopts a more collective approach by assuming some moderate degree of oblate deformation, then the applicable Nilsson orbitals[19] available for the protons are $K_\pi = \frac{5}{2}^-, \frac{3}{2}^-$, and $\frac{1}{2}^-$ while those of the neutrons are $K_\nu = \frac{3}{2}^-$ and $\frac{5}{2}^-$. These can couple in a variety of ways to lead to $K=0$, 1, 2, 3, 4, and 5. Of most significance, these couplings lead to two $K=0$ bands and five $K=1$ bands, as well as several bands with $K \geq 2$. From these considerations, a large number of $J^\pi = 1^+$ low-lying excited states and two $J^\pi = 0$ states can be anticipated, in agreement with the spin assignments and possible spin limitations for the low-lying states of this nuclide. Similarly, a moderate degree of prolate deformation results in like conclusions. The retarded $M1$ 44-keV transition can be understood on the basis of K forbiddenness by assigning the ground state and first excited state to $(K^\pi, J^\pi) = (0^+, 0^+)$ and $(1^+, 1^+)$, respectively.

Further inferences would require rather extensive theoretical calculations, and it is doubtful that the results would justify the effort without additional experimental determinations of, say, the lifetimes of higher excited states and unequivocal spin assignments for the few levels for which only spin limitations could be prescribed. However, the experimentally determined characteristics of the low-lying levels of Ga^{66} appear to be consistent with general theoretical considerations and expectations.

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[17] E. L. Church and J. Weneser, Phys. Rev. **103**, 1035 (1956).

[18] If the spin of the 234.0-keV level were 0^+, it would be expected that the β branch to this state would be considerably weaker than the upper limit of 3.5% obtained from the γ-ray intensity balance into and out of this level. This expectation arises from consideration of the amount of isobaric-spin impurity required to permit this Fermi-type transition to proceed and yet be consistent with isobaric-spin impurity established in this mass region. For example, an isobaric-spin admixture equal to that found in the $0^+ \rightarrow 0^+$ $Ga^{66} \rightarrow Zn^{66}$ β decay would imply $\log ft \approx 8.6$, so that the intensity of the β branch to the 234.0-keV state would be $\sim 0.07\%$.

[19] S. V. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **29**, No. 16 (1955).