pendence, and the slope-parameter T therefore becomes meaningless.

It is clear that the three types of calculations or analyses used here to extract information about the nature of the reaction mechanisms are at their best when applied to heavy nuclei.

ACKNOWLEDGMENTS

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Studies on the Decay of Ge^{67}†

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The excited levels of Ga^{67} have been investigated from the decay of Ge^{67} with Ge(Li), Si(Li), and standard scintillation counters. γ rays of the following energies were observed: 166.5, 360, 558, 576, 661, 710, 720, 728, 828, 900, 915, 981, 1082, 1116, 1283, 1450, 1677, 1509, 1644, 1810, 1837, 2004, 2100, 2170, 2210, 2510, 2559, 2726, 2958, 2991, 3065, and 3157 keV. The half-life of Ge^{67} was measured to be 19 ± 0.3 min. With the help of γ-γ coincidence studies, a consistent level scheme of Ga^{67} at 166.5, 333, 828, 1082, 1450, 1810, 2170, 2726, 3157, and 3398 keV has been obtained. Three major positron groups with end-point energies of 3.18 MeV (65%), 2.5 MeV ($\sim$25%), and 1.54 MeV ($<$10%) have been assigned to the decay of Ge^{67}. Each group probably consists of more than one component. The results including spin and parity assignments of some of the excited levels of Ga^{67} are discussed. The half-life of the 166-keV level is measured by delayed coincidence to be less than $(0.22\pm0.05)\times10^{-9}$ sec.

1. INTRODUCTION

THE decay of the 19-min isotope of Ge^{67} has been previously studied by two groups of investigators.[1,2] Aten[1] in 1956 first reported a 2.9-MeV positron branch attached to this isotope. These authors also reported only one strong γ ray with an energy of 170 ± 10 keV. The level scheme as shown in *Nuclear Data Sheets*[3] was presented by Ricci and Van Lieshont.[2] These authors reported a γ ray of 170 ± 10 keV in coincidence with another 170-keV γ line. Upon examining the information in Ref. 3, however, it is evident that many of the γ rays have not been fitted into a decay scheme. Even the energy of the second excited state in Ga^{67} is not precisely known.

With the availability of high-resolution solid-state counters, the present work proposes to reexamine the decay of Ge^{67} to establish a level scheme of Ga^{67} with good energy determination.

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[1] A. H. W. Aten, Jr., Physica **22**, 288 (1956).
[2] R. A. Ricci and R. Van Lieshout, Nucl. Phys. **10**, 360 (1959).
[3] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D.C. 20025), NRC 2-341-1959.

2. SOURCE PREPARATION

Ge^{67} was produced from Zn^{64} by an (α, n) reaction, using $\sim$19-MeV α particles from the heavy-ion accelerator. The targets used were thin foils of natural Zn. The energy of the α particles and the time of the bombardment were kept low, to avoid any $(\alpha, 2n)$ products. The bombardment time chosen was about 15 min. After cooling the Zn target for 2 min, the following chemical separation was performed. The irradiated Zn target was dissolved in a few drops of $6N$ HNO_3. Two mg of Ga hold-back carrier (1 mg/ml) and 3 mg of Sb (3 mg/ml) were added. The solution was evaporated to near dryness, cooled, and the residue was transferred with $6N$ HCl solution to a centrifuge tube. H_2S was passed through to precipitate Sb sulfide and coprecipitate the Ge as a sulfide. Sb was chosen as a carrier because of the quick formation of an easily centrifugable sulfide. The Sb-Ge sulfide precipitate was centrifuged, digested with $6N$ H_2S-saturated sulfuric acid, filtered, washed with water and alcohol, and dried. These sources were used for our γ-ray measurements. Immediately after the chemical separation no Ga activities were observed, indicating that this Ge-Sb

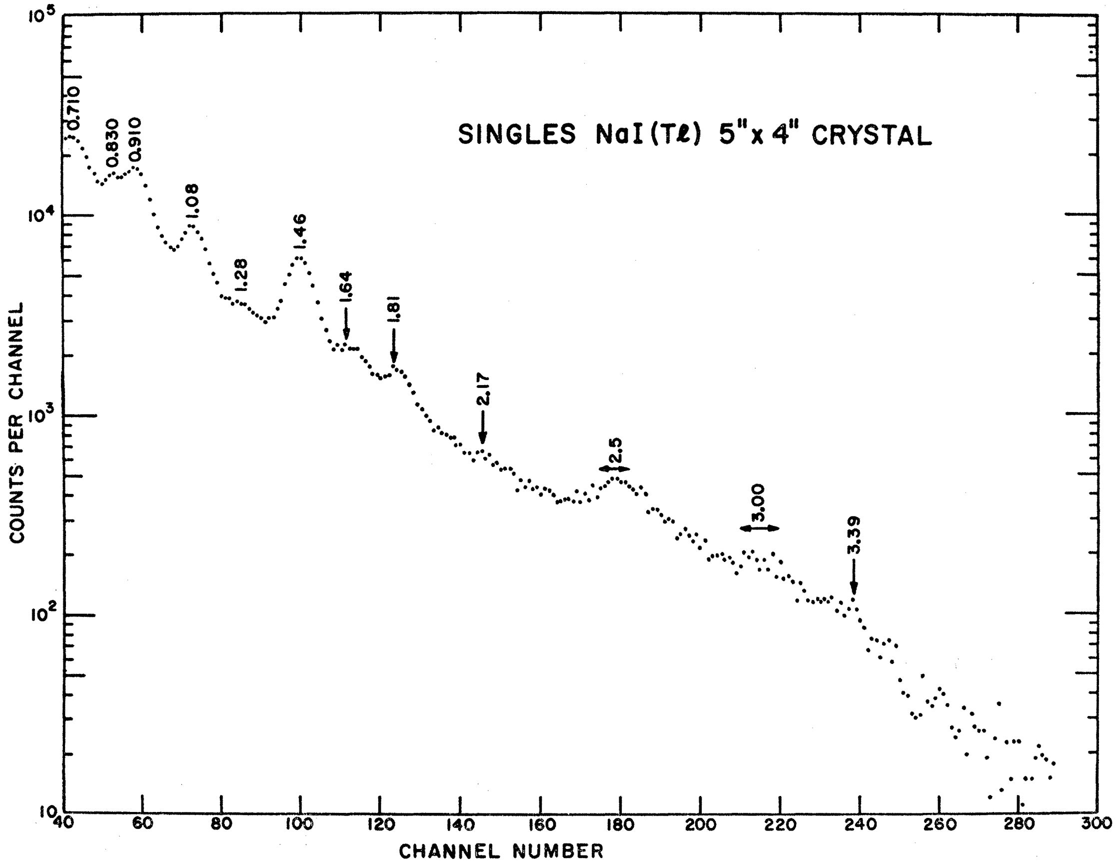

FIG. 1. Singles γ-ray spectrum taken with a 5×5-in. NaI(Tl) crystal.

coprecipitation method is an extremely clean and fast procedure for obtaining Ge sources.

3. EXPERIMENTAL RESULTS

A. γ-Ray Singles Spectra

γ-ray studies were carried out using several 3×3-in. NaI(Tl) scintillation counters and Ge(Li) and Si(Li) detectors. In addition, a 4×5-in. cylindrical NaI(Tl) crystal was used for the high-energy γ rays.

Figure 1 shows the γ-ray spectrum taken with a 5×4-in. NaI(Tl) crystal. As one can see in this figure, the photopeaks at 511, 910, 1080, 1460, and 1800 keV are broader than the resolution of the crystal at those energies. Figures 2 and 3 show the low-energy and the high-energy sides of the γ-ray spectrum taken with a 25-cc Ge(Li) detector. This detector system had a resolution of 3.8 keV at the 1.33-MeV Co^{60} line and a photopeak-to-Compton ratio of 11/1. Because of the window thickness, the detector dead layer, etc., the detection efficiency for low-energy γ rays was poor, and depended on the source-detector geometry. Therefore the intensity of the 166.5-keV line was checked with a NaI(Tl) as well as with a Si(Li) detector. The data shown in Figs. 2 and 3 were therefore used only for γ rays above 166.5 keV. The energy calibration was performed in each run using standard sources of Bi^{207}, Ba^{133}, Co^{60}, Cs^{137}, and Na^{22}. Since the half-life of the Ge^{67} is 19 min, as many as 8 to 10 samples were used for each experiment (to accumulate the data). To avoid the contamination of Ga^{67} each source was employed only for 15 min, and then rejected.

The energy of the previously reported[2] γ ray of 170±10 keV in coincidence with another 170-keV line was accurately determined to be 166.5±0.25 keV. For this the following experiments were conducted. Using an ORTEC-biased amplifier, the singles spectrum was amplified and analyzed. Figure 4 shows the biased amplifier spectrum taken with a 16-cc Ge(Li) planer detector. The 166.5-keV line was found to be symmetric. In the second experiment, a cooled Si(Li) detector TMC W-80-2AA was used to measure the low-energy conversion electron spectrum. This detector, cooled to dry-ice-and-acetone temperature, had a resolution of better than 3.5 keV under the actual operating conditions of the present experiment. Figure 5 shows the low-energy side of the conversion electron spectrum. From these figures an upper limit of 166.5±0.25 keV

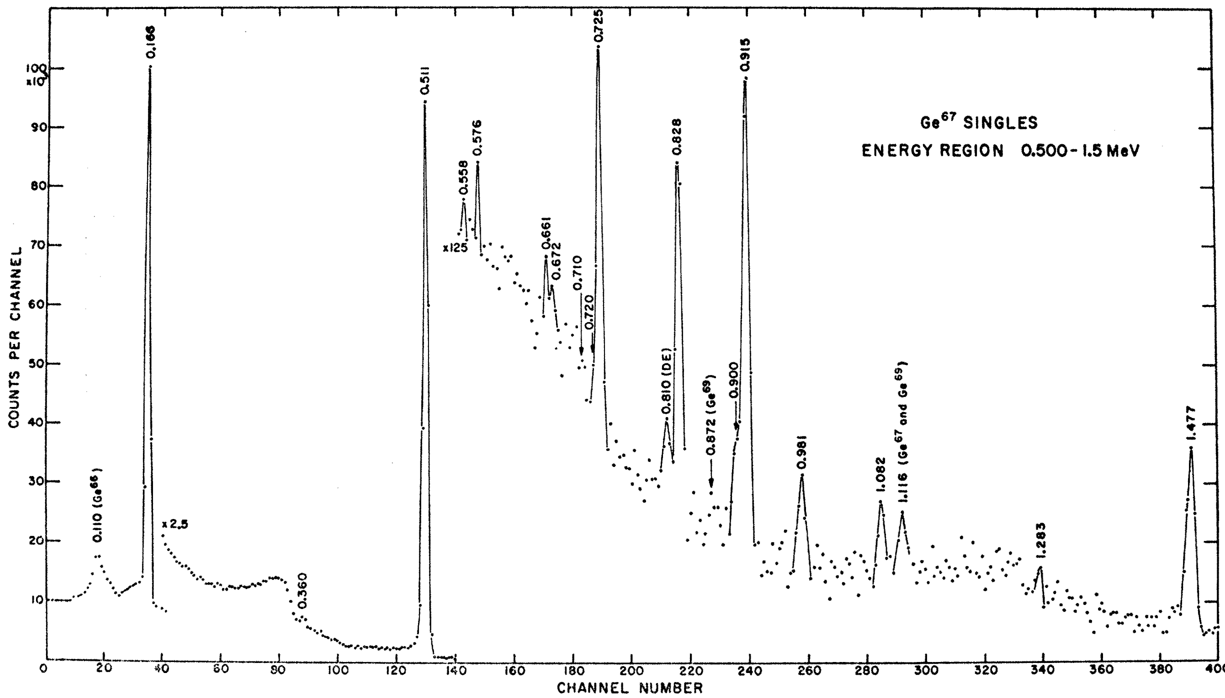

FIG. 2. Low-energy γ-ray spectrum from Ge^{67} taken with a 25-cc Ge(Li) detector.

was assigned to the second γ ray in coincidence with the 166.5-keV line.

Table I lists all the γ rays which have been identified with the decay of Ge^{67}. The criteria for the identification were the following: (a) accurate half-life of 19 min, (b) calculation of double escape peaks for the high-energy γ rays, and (c) accurate half-life of 19 min for the escape peaks. The γ rays shown in Fig. 3 and listed in Table I were confirmed with NaI(Tl) experiments.

The 110-keV line is identified as small contamination from Ge^{66} (2.4 h). The 872- and 1100-keV lines belong to Ge^{69} (40 h). The 2.376- and 2.210-MeV lines are the double escape peaks of the 3.398- and 3.232-MeV peaks. Similarly, the 2.135-, 2.043-, 1.969-, and 1.704-

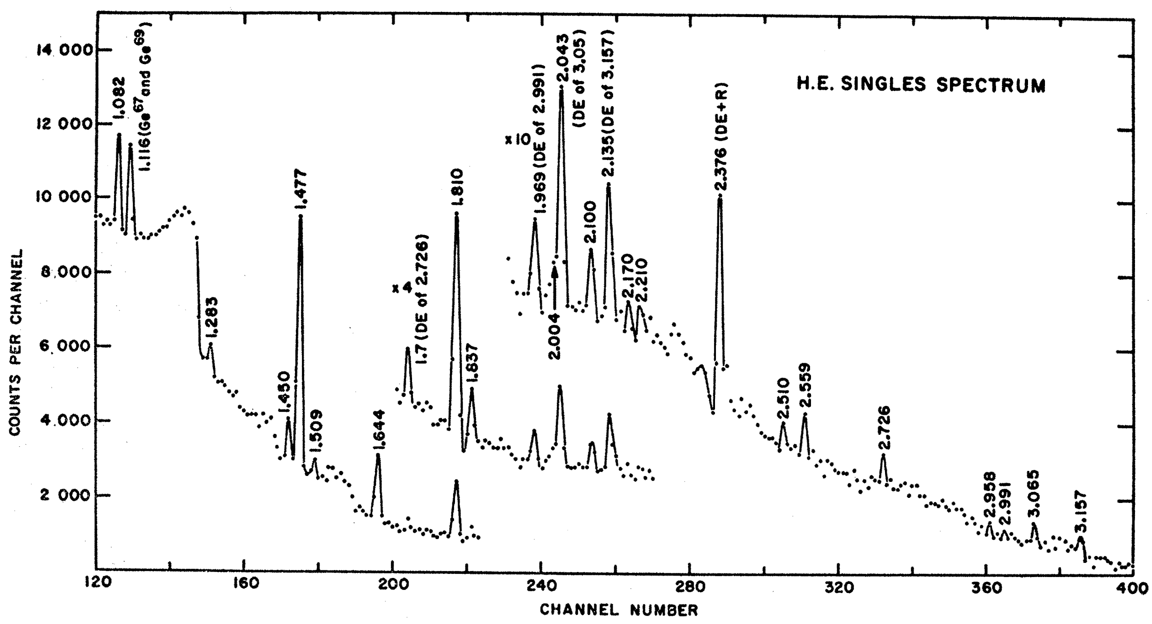

FIG. 3. High-energy side of the γ-ray spectrum from Ge^{67} taken with a 25-cc Ge(Li) detector.

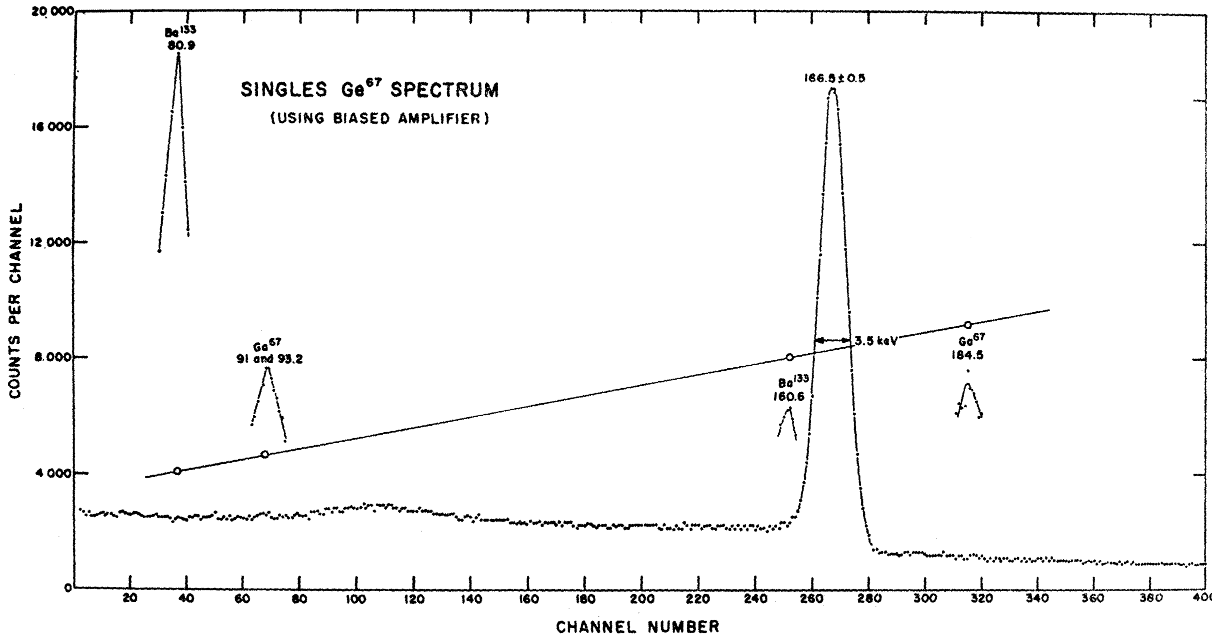

FIG. 4. γ-ray spectrum taken with a biased amplifier and a 16-cc Ge(Li) detector.

MeV lines are the double escape peaks of 3.157-, 3.065-, 2.991-, and 2.726-MeV lines, respectively. The relative intensities of the observed γ rays are given in Table I. These relative intensities are the mean values taken from a number of different measurements recorded at different times, different system gains, and with two Ge(Li) detectors. The associated errors in these intensities include uncertainties in the background and the errors in the relative photopeak efficiency curves for the Ge(Li) detectors, which were obtained in two ways: First, a set of standard γ-ray sources whose relative intensities have been measured with NaI(Tl) detectors was used; second, a set of points was obtained from the sources emitting several γ rays whose relative intensities were known from well-established decay schemes. The efficiency curves resulting from the separate methods were in very good agreement. The error for the intensities greater than

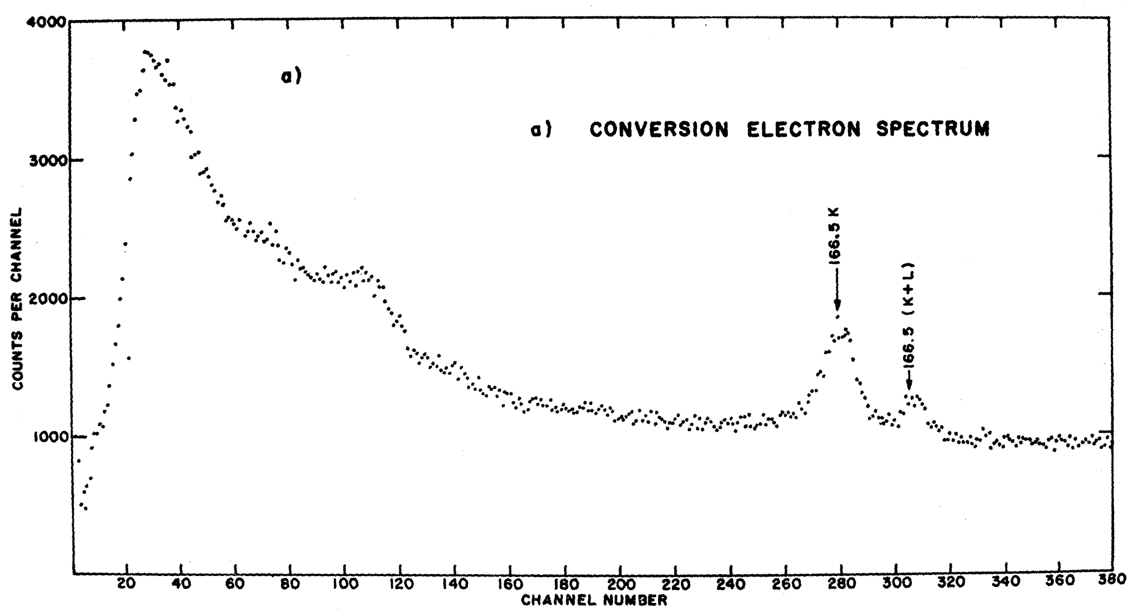

FIG. 5. Low-energy side of conversion-electron spectrum using a cooled Si(Li) detector.

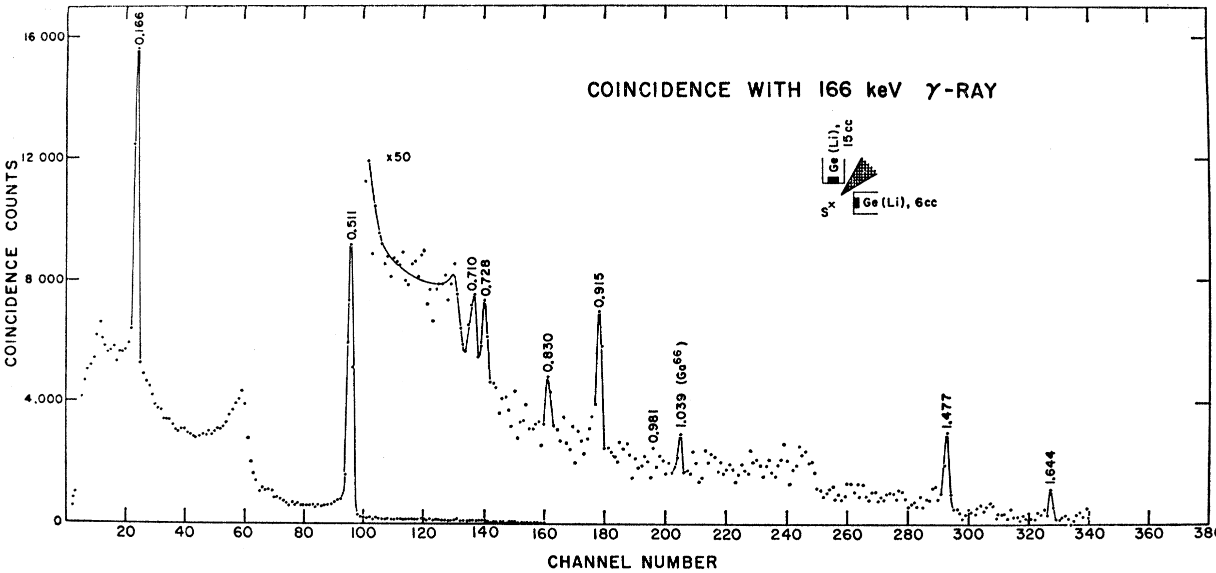

FIG. 6. Ge(Li) spectrum in coincidence with 166-keV γ ray.

1% is of the order of 10%. In Table I, the intensity of the 166.5-keV γ ray is arbitrarily taken to be 127 (compared to the intensity of 511 as 2×100). The accuracy of the energy values is better than 1 keV for transitions below 1 MeV and better than 2 keV for transitions above 1 MeV. Table I can be compared with a similar one in Ref. 2. Some of the differences between the two are easily understood in terms of the differences in the detectors. The 750-, 840-, 920-, and 1100-keV γ rays reported by Ricci and Van Lieshout[2] probably correspond to our (710-, 720-, 728-), 828-, (900-, 915-), and (1082-, 1116-) keV lines. The 1.48-MeV γ ray previously reported has been resolved into a 1450- and a 1477-keV line. Similarly, the 1830-keV γ ray earlier reported has been resolved into 1810- and 1837-keV lines.

TABLE I. γ-ray energies and their relative intensities.

γ-ray energy (keV)	Relative intensity	γ-ray energy (keV)	Relative intensity
166.5	127	1477	9.7
360	6	1509	0.7
511	2×100	1644	2.4
558	0.1	1810	2
576	0.2	1837	0.5
661	0.3	2004	0.9
710	0.08	2100	0.9
720	0.16	2170	0.1
728	4.5	2210	0.1
828	5.7	2510	0.1
900	2.4	2559	0.15
915	11.1	2726	~0.15
981	2.8	2958	~0.05
1082	2.6	2991	~0.1
1116	2	3065	~0.1
1283	0.4	3157	~0.1
1450	1		

B. Coincidence Measurements

The γ-γ coincidence spectra were measured in the geometry shown in Fig. 6. From Figs. 2 and 3 it is evident that, except for the 166.5-, 511-, 728-, 828-, and 915-keV γ rays, γ rays from Ge^{67} would be almost undetectable if nothing more than NaI(Tl) counters were used. On the other hand, in using Ge(Li) detectors, limitations were imposed by the rapid drop in counter efficiency with the increasing γ-ray energies. In the present coincidence studies, a compromise solution was adopted in using two Ge(Li) detectors or one NaI(Tl) counter and one Ge(Li) detector. The resolving time of the coincidence circuit used was $2\tau=40$ nsec. Figure 6 shows the spectrum taken with a 16-cc Ge(Li) detector in coincidence with the 166-keV line. A 6-cc planer Ge(Li) detector was used for the 166-keV gate. Each source after chemical separation was counted for a period of 30 min and then rejected. This eliminated high contamination of Ga^{66} growing from the decay of Ge^{66}, and Ga^{67} from the decay of Ge^{67}. The presence of the high-intensity 511-keV line shows that the 166.5-keV line is strongly fed by positrons. Figure 7 shows the coincidence spectra taken with a 25-cc Ge(Li) detector in coincidence with the (a) 915-, (b) 1477-, (c) 1810-, and (d) 1644-keV lines. The above gates were selected in a 16-cc Ge(Li) detector. In some of these spectra no coincidences were observed of weak γ rays (>1 MeV), because of the poor statistics or because

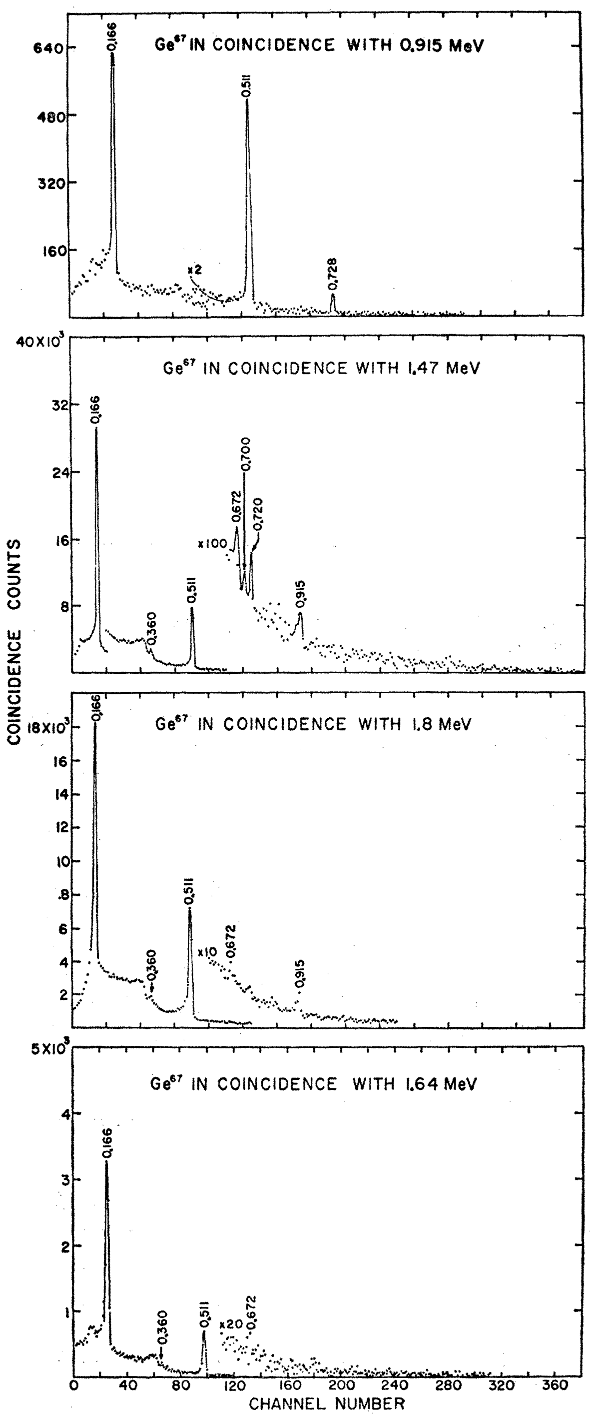

FIG. 7. Coincidence spectra taken with a 25-cc Ge(Li) detector in coincidence with the (a) 915-, (b) 1477-, (c) 1800-, and (d) 1644-keV lines.

TABLE II. Results of γ-γ coincidences (Ge^{67} decay).

γ ray in gate (keV)	Coincident γ rays recorded with Ge(Li) detector (keV)
166.5 (Ge)	166.5, 360, 511, 710, 728, 915, 981, 1283,[a] 1477, 1644
166.5 (NaI)	166.5, 360, 511, 661, 728, 915, 981, 1283, 1477, 1644, 1837, 2004, (2380, 2559),[a] (2991, 3065, 3157, 3232)[a]
511 (Ge)	166.5, 661, 728, 828, 915, 1450, 1477
511 (NaI)	166.5, 661, 728, 828, 915, (1082, 1116),[a] 1283,[a] 1450, 1477, 1644, 1810[a]
915 (Ge)	166.5, 511, 672,[a] 728
915 (NaI)	166.5, 360, 511, 672,[a] 728, 1644[a]
728 (Ge)	166.5, 360, 511, 915, 1082,[a] 1450, 672[b]
1470 (Ge)	166.5, 360, 511, 672, 915
1450–1477 (Ge)	166.5, 360, 511, 672, 915
1640 (Ge)	166.5, 360,[a] 511, 672,[a] 915[a]
1640 (NaI)	166.5, 360,[a] 511, 672,[a] 915, 1082[a]
1800 (NaI)	166.5, 360, 511, 672, 915

[a] Weak.
[b] Very weak.

of the interference of the Ga^{67} positrons. The 166.5-keV line is in coincidence with another 166.5-keV line. This point is confirmed by the fact that various lines have been observed with an energy difference of 166.5 and 333 keV. Compared to the intensity of the first 166.5-keV line as 100, the relative intensity of the 166.5-keV line originating from the 333-keV level is obtained as (27±2) from the coincidence results. Table II gives results of the γ-γ coincidences.

In order to get a better estimate of these intensity values the various coincidence spectra were normalized by correcting the coincidence rates for the detection efficiencies. By comparing the 728–166.5-keV cascade intensity with the 915-166.5-keV cascade it was possible to obtain a value of ~2 for the intensity of the 915- to the 728-keV γ ray. This result was combined with the results in Table I and used for the final decay scheme.

C. Triple Coincidence Results

In order to confirm that the 166.5-keV γ ray is in coincidence with another 166-keV γ ray, the following experiment was performed. A 25-cc Ge(Li) detector was used in conjunction with two 3×3-in. NaI(Tl) detectors at 90° to each other. Enough lead was placed between the detectors to avoid Compton scattering. The ORTEC fast triple coincidence (2τ=40 nsec) unit was used for the triple coincidence. The triple coincidence was tested by selecting 511- and 1270-keV gates in the two NaI(Tl) crystals and using a strong Na^{22} source. No 511-keV counts were observed even after

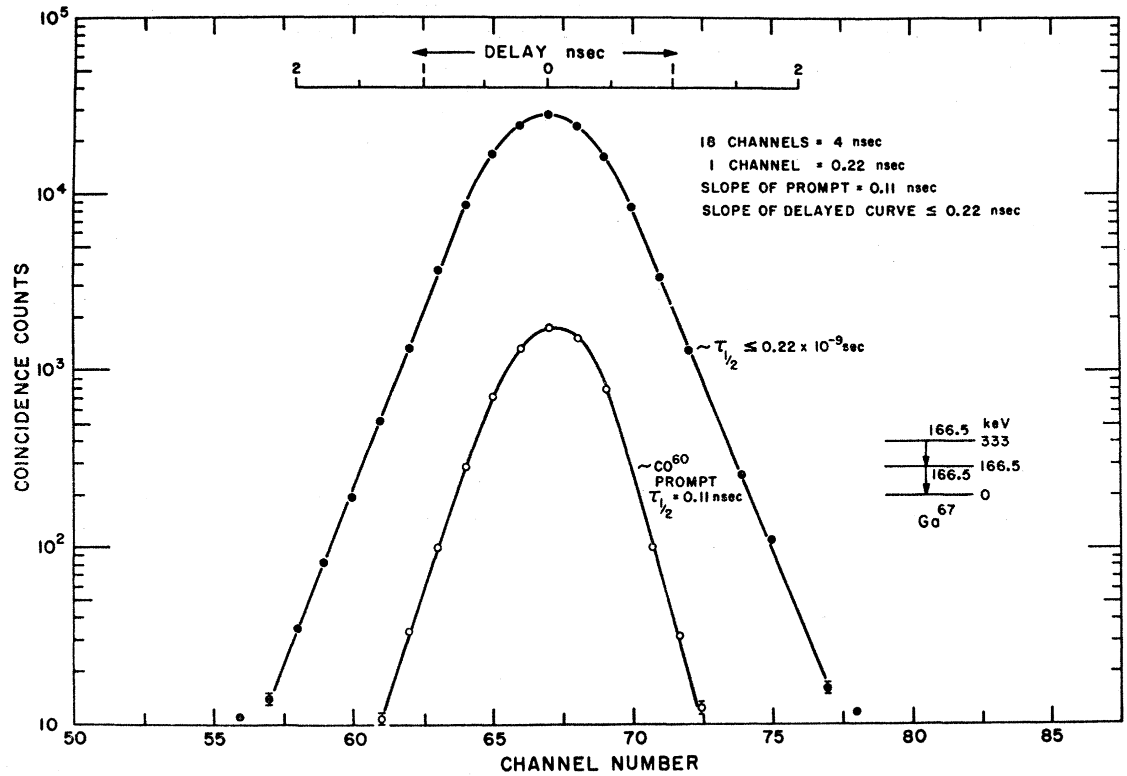

FIG. 8. Prompt and the delayed time spectra. The prompt curve taken with Co^{60} at the same energy settings is represented by open circles. The slope of the prompt curve is 0.11 nsec.

10 h of accumulation. The chance coincidence rate was checked by selecting 511 and 511 keV in both gates. The NaI(Tl) detectors were used to select the 511- and 166.5-keV photopeaks as the gates and the Ge(Li) detector recorded the spectrum in coincidence with the 511- and the 166.5-keV photopeaks. Use of several Ge^{67} sources was made. These sources were capsuled in a 1×1-in. Plexiglas to stop the high-energy positrons. This experiment gave the confirmation of the 166–166.5-keV cascade.

D. Lifetime of the 166.5-keV Level

A possible approach to the question of multipolarities is the investigation of the lifetime of the levels. In the present experiment, we have measured the half-life of the 166.5-keV level.

Two Naton plastic scintillators of $\frac{1}{2}\times\frac{1}{2}$ in. were used with Amperex XP 1020 photomultipliers. Care was taken to ensure that all the positrons from the source were stopped outside the scintillators. Fast signals were derived from two ORTEC time-pickoff units and fed into an ORTEC time-to-pulse-height converter. Energy selection channels were set so as to accept the entire Compton spectrum of the 166.5-keV γ ray which is above the noise. Coincidence ($2\tau=40$ nsec) between these two channels was mainly selected out by the coincidence between the 166.5- and the 166.5-keV γ rays. The coincidence output was used to gate a multichannel analyzer, whose input was the spectrum from the time-to-pulse-height converter. The resultant time spectrum recorded in the analyzer is shown in Fig. 8. The half-life measured for the 166.5-keV state is smaller than $(0.22\pm0.05)\times10^{-9}$ sec.

The measured lifetime of the 166.5-keV γ ray can be compared with the value of about 1×10^{-11} sec for an $M1$ transition and about 5×10^{-6} sec for an $E2$ transition, calculated from the Weisskopf formula. From these considerations, the 166.5-keV transition is predominantly $M1$. From the measurement of the

TABLE III. Analysis of the positron spectrum of Ge^{67}.

Energy (MeV)	Relative intensity (%)	ϵ/β^{+} [a]	log *ft*
3.18	40	0.8	5.8
3.01	25	0.5	6.5
2.5 } [b] 2.27 }	25	1.2	5.75
1.54[b]	<10	1.5	5.4

[a] Ratio of electron capture to β^{+} decay rate.
[b] These β^{+} energies were obtained from the level scheme of Ga^{67}.

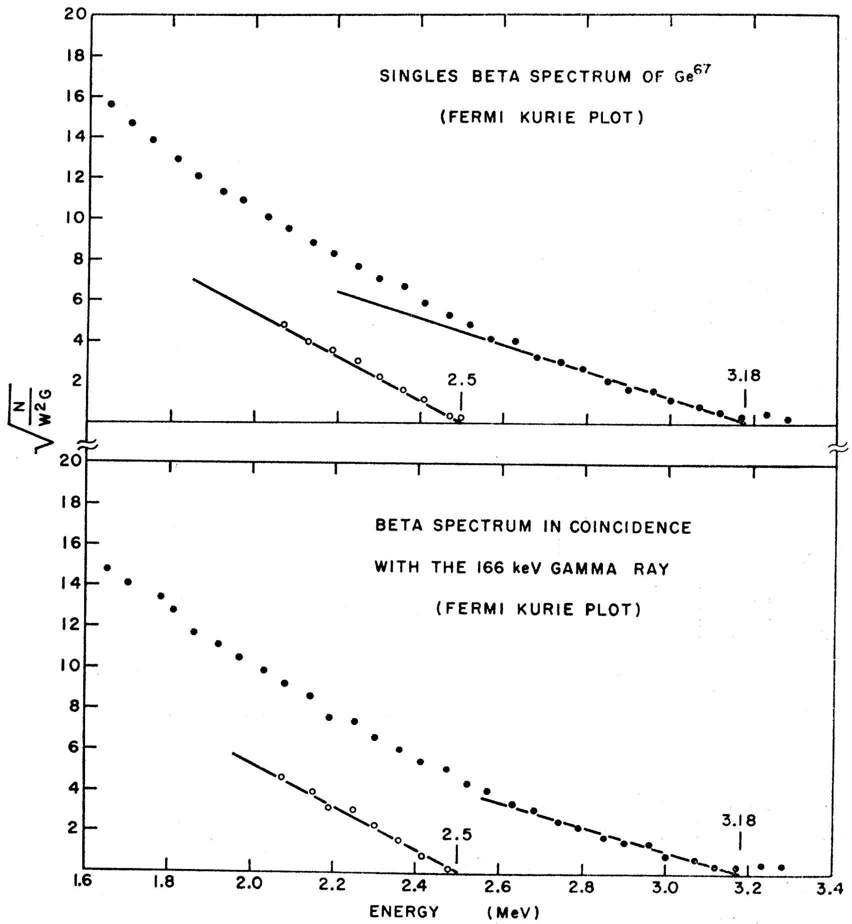

FIG. 9. Fermi-Kurie plots of the β-ray spectra (a) in singles and (b) in coincidence with the 166-keV γ ray.

k/L ratio of the 166.5-keV transition, it is not possible to distinguish between $E1$ and $M1$ multipolarities. Hence this experiment was not tried.

E. β-Spectrum Studies

The β spectrum was taken using a 1×2-in.-diam anthracene crystal covered with a 200-μg/cm^2 aluminum reflector. The spectrometer was calibrated with the known conversion lines of Bi^{207} and Cs^{137}, and the known end-point energies of Sr^{90}. The Fermi-Kurie plot of the spectrum, corrected for resolution, gave end-point energies of 3.18 MeV (40%), 3.01 MeV (25%), 2.5 MeV (~25%), and 1.54 MeV (<10%) (see Fig. 9). Each group might have more than one component. Table III gives the analysis of the γ spectrum. The β spectrum in coincidence with the 166-keV line also gave an end-point energy of 3.18 MeV (Fig. 9). Comparing the intensities of the β groups, it is seen that there is no β branch (greater than 2%) feeding the ground state of Ga^{67}.

4. DISCUSSION

The decay scheme of Ge^{67} established on the basis of energy, intensity considerations, and coincidence relationship is shown in Fig. 10. The errors in the γ-ray energies are smaller than 2 keV in these experiments.

The levels of Ga^{67} have been previously studied by the (p, n) reaction. Rester *et al.*[4] reported levels at 166, 356, 820, 910, 1250, and 1550 keV in Ga^{67}. Their results were based on singles and on conversion-electron spectrum studies. No coincidence studies were reported by these authors. Some of the γ rays reported by Rester *et al.* are the same as reported in this paper. More recently the γ rays belonging to the decay of Ge^{67} have been reported by Vrzal.[5] The values of their energies and intensities agree with our results; however, no coincidence studies were performed by these authors. It was confirmed that the 166.5-keV γ ray is composed of two γ-ray transitions, since the total intensity of the observed peak in the γ-ray spectrum is too high to be explained by the sum of the intensities of all other γ rays in cascade plus that of the 3.18-MeV β branch. The triple coincidence measurement as given earlier also gives a line at 166.5 keV.

[4] D. H. Rester, F. E. Durham, and C. M. Class, Nucl. Phys. **80**, 1 (1966).

[5] Ya. Vrzal (private communication); Abstract in the Bulletin of the Conference on Nuclear Physics, 1968 (in Russian) (unpublished).

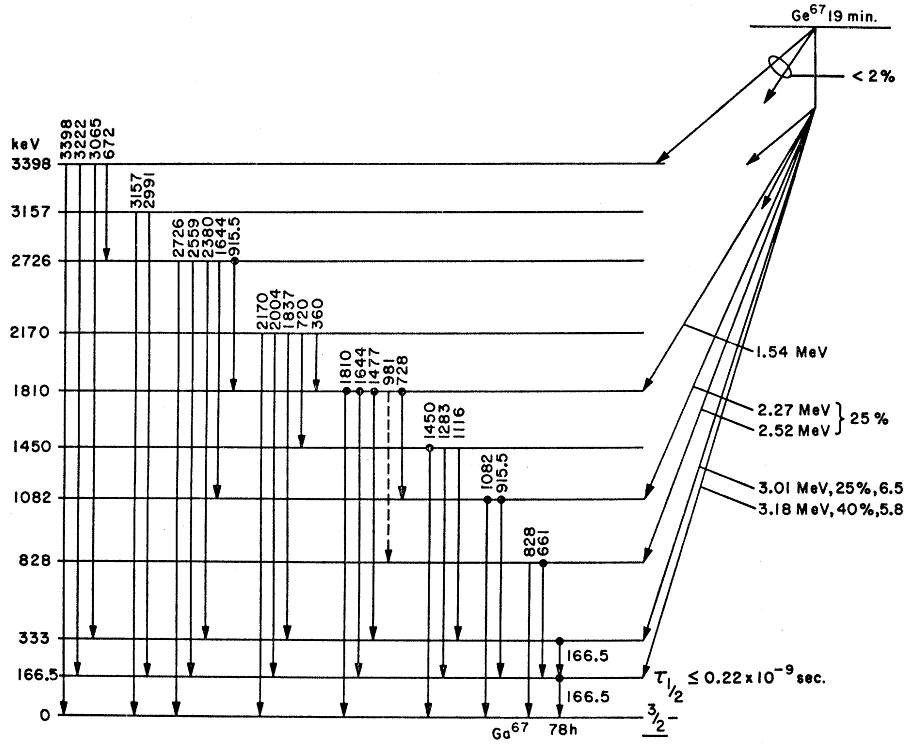

FIG. 10. Proposed decay scheme of Ge^{67}.

Furthermore, the observed γ rays showed energy differences of 166.5 and 333 keV. These arguments strongly suggest that there are two γ rays of equal energy in coincidence. The levels at 828, 1082, and 1450 keV are based on the coincidence of the 166.5-keV line with the 661-, 915.5-, and 1283-keV lines, respectively. The crossover transitions from these levels to the ground state of Ga^{67} have been observed. Similarly, the coincidence of the 720- with the 1450-keV line gives a level at 2170 keV. This is also supported by the fact that the crossover from this level to the ground state, to the 166.5- and 333-keV levels, has been observed. The levels at 1870, 2726, 3157, and 3398 keV are based on the similar argument.

The ground-state spin of Ga^{67} has been experimentally measured to be $\frac{3}{2}$ and negative parity has been assigned to it on the basis of allowed $\log ft$ values to various levels of Zn^{67}. The measured half-life of the 166.5-keV level in Ga^{67} shows that this transition is mostly $M1$ or $E1$, and the assignment of $\frac{1}{2}^-$ or $\frac{5}{2}^-$ are the most probable values for this transition. From $Zn^{66}(d, n)$ stripping reactions,[6] and also from $Zn^{66}(He^3, d)$ reactions,[7] the lp values of 1, 1, and 3 have been assigned for the ground, ~165-, and ~340-keV states, respectively. (These values have been recently received by us from the Nuclear Data group.) Expectations from shell model likewise favor negative parity for the lowest-lying states. From the systematics of odd-mass Ge isotopes, assignment of $\frac{3}{2}$ or $\frac{5}{2}$ could be made for the ground state of Ge^{67}. Since the decay from the ground state of Ge^{67} to the ground state of Ga^{67} has not been observed (an upper limit of 2% has been placed for this β group), the $\frac{3}{2}$ assignment is not possible, and only a $\frac{5}{2}$ is the remaining value. Since there is a strong positron feeding to the 166.5-keV level in Ga^{67}, and the $\log ft$ value is 5.8, it suggests that this state has a spin and parity of $\frac{5}{2}^-$. Similarly, the level at 333 keV could have a value of $\frac{7}{2}^-$.

[6] V. V. Okorokov, in Proceedings of the Eighteenth Annual Conference on Nuclear Spectroscopy and Structure of Atomic Nuclei, 1968 (in Russian), p. 116 (unpublished).

[7] B. Zeidman, R. H. Siemssen, and L. L. Lee, Bull. Am. Phys. Soc. **10**, 1126 (1965).

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