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A Ge(Li)-Ge(Li) STUDY OF THE DECAY OF 2.4 h ^{66}Ge †

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Abstract: The level structure of ^{66}Ga was investigated from decay of the 2.4 h ^{66}Ge. From singles γ-ray energy and intensity measurements employing a high resolution Ge(Li) detector, from coincidence relationships determined in γ–γ coincidence measurements employing two Ge(Li) detectors, and from β^+–γ coincidence measurements, it was established that levels at 43.5, 108.9, 233.9, 290.8, 381.7, 422.8, 514.3, 536.5, 706.3 and 866.1 keV are populated in the decay of 2.4 h ^{66}Ge. A possible level at 639.9 is also considered. From present log *ft* values and relative γ-ray intensities many J^{π} values were assigned.

E | RADIOACTIVITY ^{66}Ge; measured E_γ, I_γ, E_{β^+}, $\gamma\gamma$-, $\beta^+\gamma$- coin; deduced Q, log *ft*. ^{66}Ga deduced levels, J, π. Ge(Li), anthracene detectors.

1. Introduction

The nucleide ^{66}Ge was first identified by Hopkins and Cunningham [1]), who reported decay by positon emission with a half period of 2.5 h. The first systematic study of the decay properties of ^{66}Ge was attempted by Ricci, Girgis and Van Lieshout [2,3]) by means of scintillation detectors and coincidence techniques. These authors reported levels at 46, 114, 360, 380, 515, 565, 660, and 760 keV. More recently, Bolotin [4]) reported preliminary results on the lifetime of the 46 keV state and on conversion electron studies. During the preparation of this manuscript McClure and Bolotin [5]) reported preliminary results on the decay of ^{66}Ge by use of Ge(Li) detectors and Ge(Li) × Ge(Li) coincidence measurements. At the same time Bakhru and Ladenbauer-Bellis [6]) reported preliminary results of the decay of ^{66}Ge. The latter mentioned authors report γ-rays at 44.3, 65, 109.3, 126, 148, 182, 191, 235, 246, 274, 302, 338, 383, 414, 428, 471, 493, 537, 596, 706, 756, 821 and 865 keV, emitted in the decay of ^{66}Ge. The present investigation was undertaken in order to establish a more accurate decay scheme which is essential for the evaluation of excitation function data [7]) of ^{4}He-ion induced reactions on ^{64}Zn that the first author of this work has previously analysed [8]) and of more recent excitation function data from ^{64}Zn(α, 2n) and ^{56}Fe(^{12}C, 2n) reactions [9]). The level structure and the γ-rays emitted from low-lying excited states is also useful in that it facilitates the interpretation of on-beam studies of the γ-rays from nuclear reactions in this region that we are planning to study.

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2. Experimental procedures

2.1. PRODUCTION OF THE ^{66}Ge SAMPLES

The ^{66}Ge samples were prepared by the ^{64}Zn(^{3}He, n) reaction at the Washington University cyclotron on natural Zn foils. The energy of the ^{3}He ion beam was kept below 15 MeV to minimize competing reactions. This method of source preparation was preferred over the ^{64}Zn(α, 2n) reaction because it yielded a higher ratio of activity of ^{66}Ge relative to ^{67}Ge and ^{69}Ge. In all the experiments radiochemical purification of the Ge activity from the daughter Ga activity was employed. For this purpose

TABLE 1

Energies and relative intensities of γ-rays following 2.4 h ^{66}Ge decay

γ-ray energy (keV) [a]	Relative γ-ray intensity [a]
21.2±1.0	4.1±1.0
39.5±0.3	18.8±3.0
43.5±0.3	87.3±8.0
54.4±0.2	0.9±0.2
65.5±0.3	24.8±2.0
91.0±0.2	1.2±0.2
96.4±0.2	0.6±0.1
108.9±0.1	42.7±0.5
125.0±0.2	1.7±0.3
147.8±0.2	3.1±0.1
154.7±0.1	1.2±0.2
182.0±0.1	25.2±2.0
190.6±0.5	25.6±3.0
245.6±0.5 [b]	18.3±2.0 [c]
245.6±0.5 [b]	2.0 ±0.3 [c]
272.8±0.3	38.8±2.0
290.8±0.3	2.1±0.5
302.4±0.3	8.1±1.5
315.6±0.6	2.8±0.8
337.8±0.3	27.2±2.0
381.7±0.3	100
415.4±0.4	1.8±0.2
427.6±0.4	2.3±0.2
470.8±0.4 [b]	28.7±2.0 [c]
472.0±0.4 [b]	8.8±2.0 [c]
492.9±0.6	1.9±0.2
536.8±0.5	22.3±2.0
597.5±0.6	1.2±0.1
640.0±0.5	0.7±0.2
706.2±0.5	13.5±0.2
757.2±0.6	2.6±0.2
866.2±0.6	0.3±0.2

[a]) Energies and intensities from 5 independent measurements of singles.
[b]) Energies estimated from energy sums.
[c]) Intensities obtained from the coincidence spectra.

the Zn foils were dissolved in 6 M HCl containing Ge^{IV} and Ga^{III} carriers. The Ga activities were removed quantitatively by adsorption on a Dowex-1 anion exchange column. The Ge activity that elutes first is separated by adjusting the pH to ≈ 0.3 and precipitating GeS_2 which is centrifuged and mounted for counting.

2.2 DETECTION EQUIPMENT AND METHODS OF COUNTING

The Ge(Li) detectors that were used had active volumes of 20 and 30 cm^3 with full widths at half maximum 2.4 and 3.5 keV for the γ-rays from a ^{137}Cs source, respectively. These detectors were also used for the γ–γ coincidence measurements.

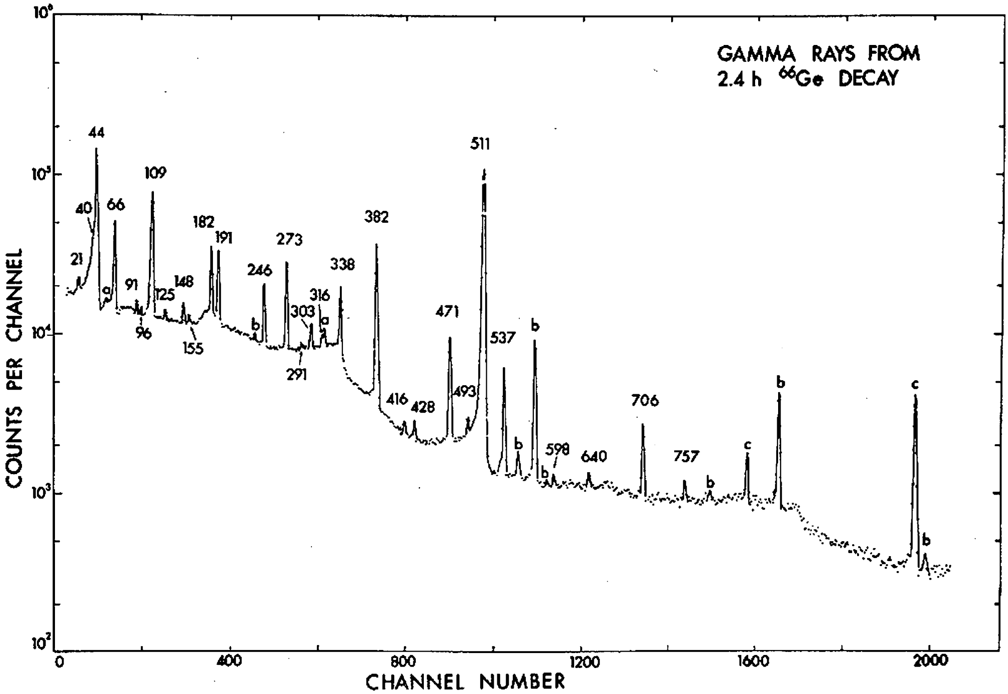

Fig. 1. Singles γ-ray spectrum from 2.4 h ^{66}Ge decay. The peaks labeled with energies in keV belong to ^{66}Ge. The peaks labeled a were too weak to identify with any nucleide. The peaks labeled b were identified with ^{69}Ge decay, and those labeled c with the ^{66}Ga decay.

The properties of the detectors and the two-parameter pulse-height analysis system used have been described elsewhere [10]). For positon end point energies β^+–γ coincidence spectra were recorded using one 3.8×3.8 cm anthracene detector coupled with a photomultiplier tube.

3. Results and construction of the decay scheme

Singles γ-ray spectra with minimum amounts of ^{66}Ga activity were recorded immediately after purification from the Ga activities. Spectra were recorded as a

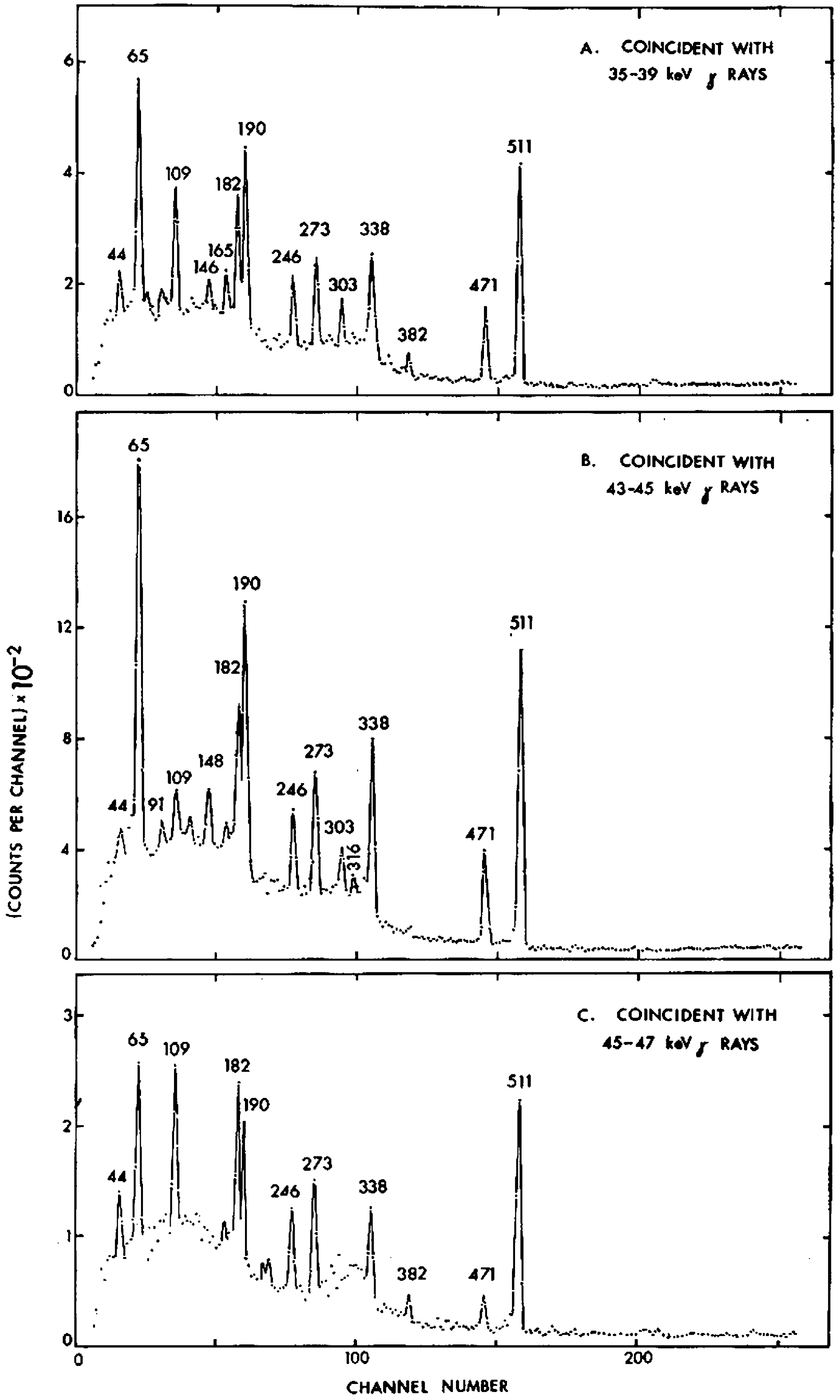

Fig. 2. Spectra obtained with the 30 cc Ge(Li) detector in coincidence with the indicated regions in the 20 cc Ge(Li) detector.

function of time and this allowed clear identification of the γ-rays listed in table 1 with the 2.4-h ^{66}Ge decay. A typical singles spectrum recorded for 80 min following separation is shown in fig. 1. The energies and relative intensities of the γ-rays listed in table 1 were determined from the peak centroids and areas as described previously [11]).

The γ–γ coincidence relationships were established by recording the coincidence spectra in a 256×1024 channel two-parameter configuration employing the two

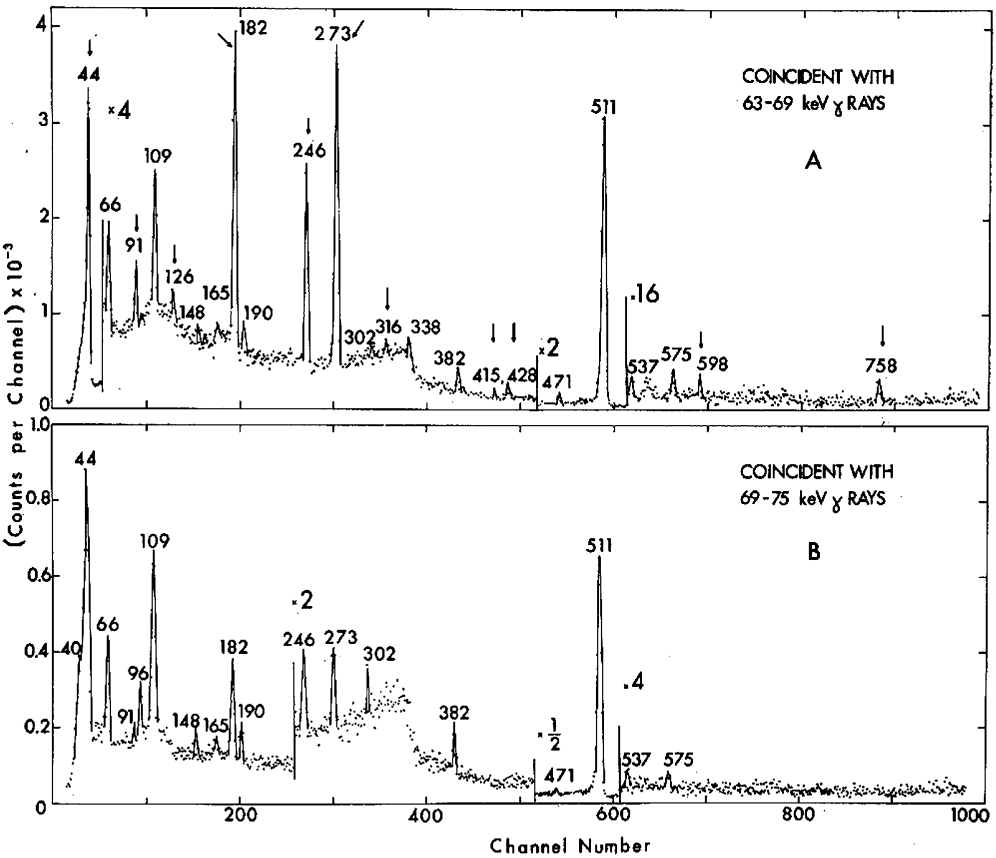

Fig. 3. Spectra of the γ-rays from ^{66}Ge decay observed with the 20 cc Ge(Li) detector in coincidence with the indicated energy regions in the 30 cc Ge(Li) detector. The selected gate in the upper part A contains the 66 keV γ-ray, while part B displays the contribution from Compton scattered higher energy γ-rays.

Ge(Li) detectors. The coincidence relationships are summarized in table 2 and the important coincidence spectra are displayed in figs. 2–9. On the basis of this evidence, the level scheme shown in fig. 10 is proposed. It should be pointed out that the proposed decay scheme is only in partial agreement with the scheme proposed by Ricci and coworkers [3]). When the intensity of the 44 keV γ-ray is corrected for internal conversion (assumed to be M1) it becomes the most intense transition and its intensity exceeds the sum of the intensities of the γ-rays coincident with it. This establishes the first excited state at 43.5 keV.

A level at 108.9 keV is firmly established from the observed coincidence of the 44 keV γ-ray with the 66 keV γ-ray (fig. 3 A,B) and the observed strong cross-over 108.9 keV transition to the ground state.

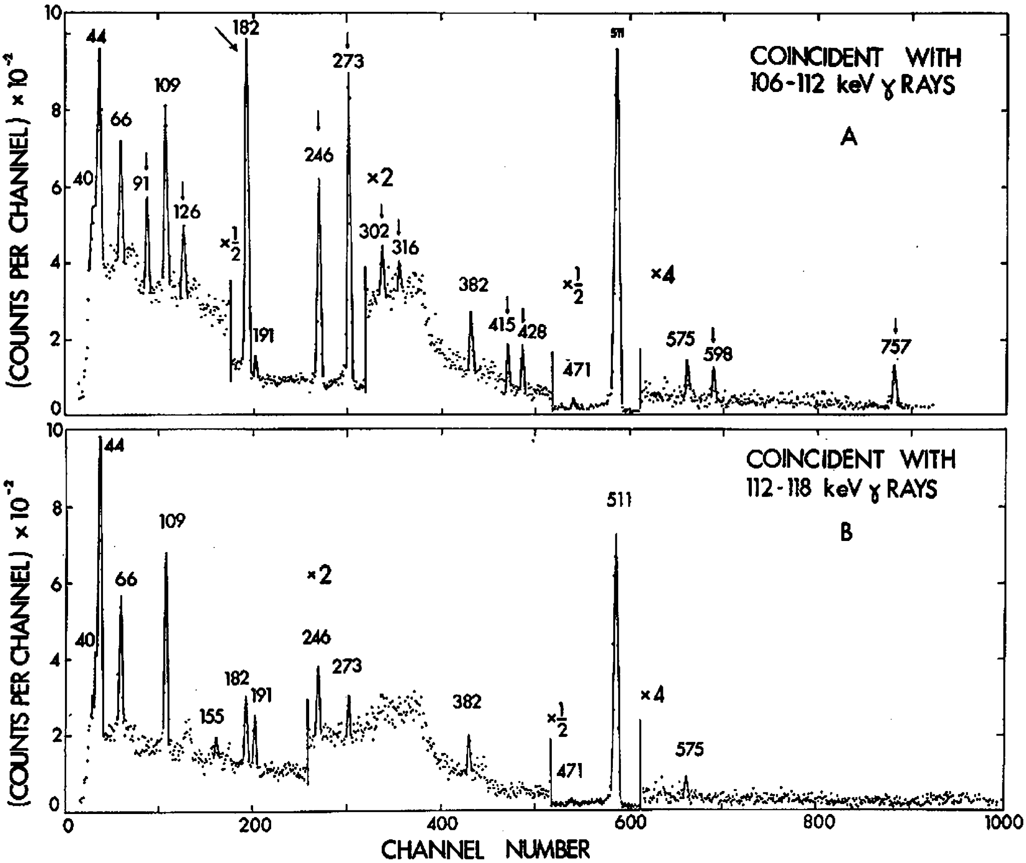

Fig. 4. Spectra of the γ-rays from ^{66}Ge decay observed with the 20 cc Ge(Li) detector in coincidence with the indicated energy regions in the 30 cc Ge(Li) detector. Part A displays the spectrum coincident with the 109 keV γ-ray and B displays the Compton background.

Levels at 290.8, 381.7, 536.5 and 706.3 keV are firmly established from at least two observed coincidences with γ-rays de-exciting lower-lying levels, as summarized in table 2 and shown in figs. 3, 4, 5, 6, and 8. However, when the spectrum of the γ-rays coincident with the 185–192 keV region is examined closely, the peak at 472 keV is shifted toward higher energy by ≈ 1 keV (fig. 5B). This shows that the 471 keV peak is an unresolved doublet and from energy sums the energies of the two members of the doublet are determined to be 470.8 and 472.4 keV. The 190 keV γ-ray is in coincidence with the 44 but not with the 109 keV γ-ray. The 471 keV γ-ray is in coincidence with the 44 keV γ-ray suggesting a level at 514 keV, which is confirmed by the 21.4 keV γ-ray assigned between the 512.3 and 536.5 keV levels. Since only

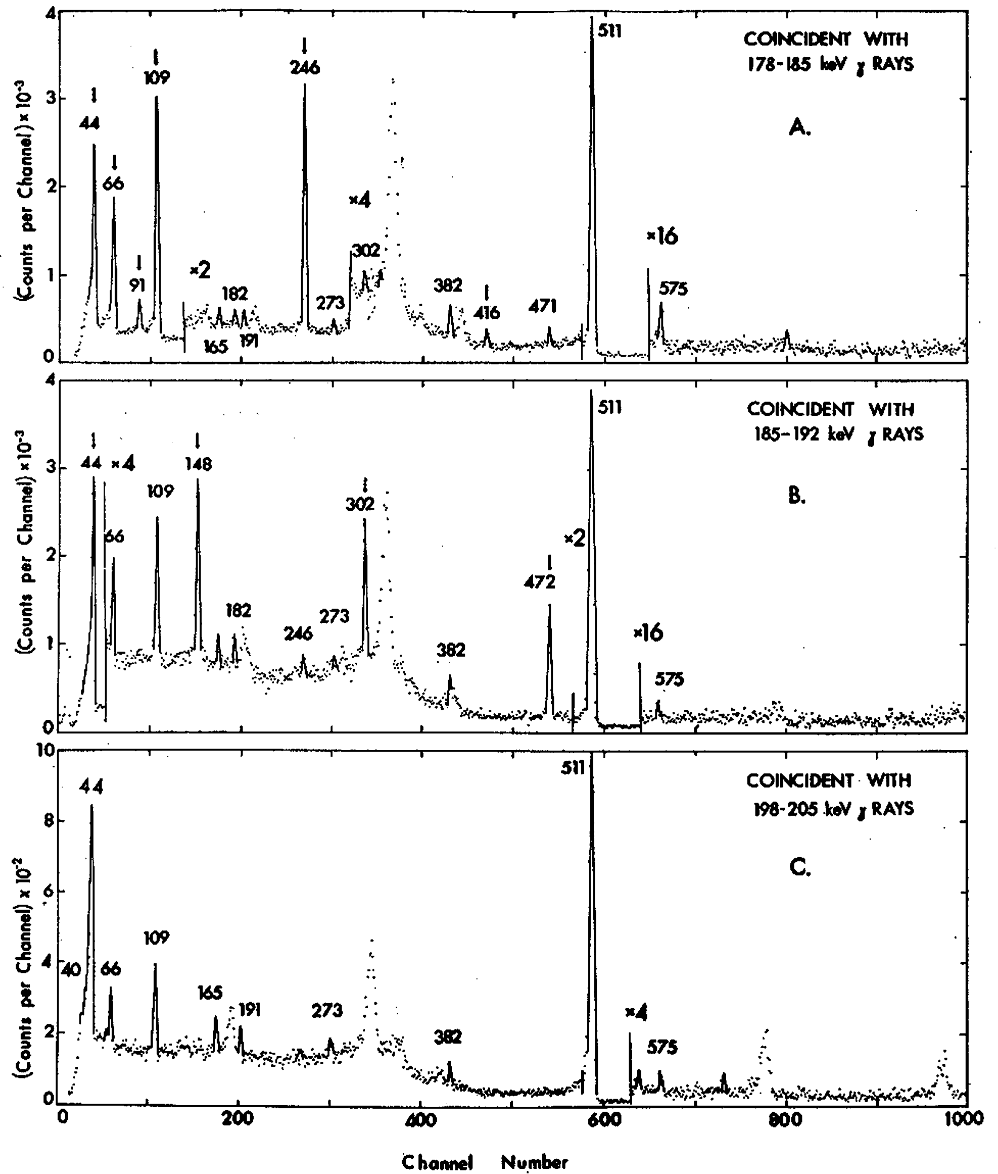

Fig. 5. Spectra of the γ-rays from ^{66}Ge decay observed with the 20 cc Ge(Li) detector in coincidence with the indicated energy regions in the 30 cc Ge(Li) detector. Parts A, B and C display the spectra coincident with the 182, 190 keV γ-rays, and the Compton background, respectively.

the 472 and not the 471 keV γ-ray appears to be in coincidence with the 190 keV γ-ray, its intensity can be determined from the intensity of the 472 keV peak relative to that of 148 or 302 keV peaks, in the spectrum coincident with the 185–192 keV region (fig. 5B), when compared to the singles intensity of these γ-rays. This gives an intensity of 8.8 and 28.7 for the 472 and 471 keV γ-rays, respectively. This result

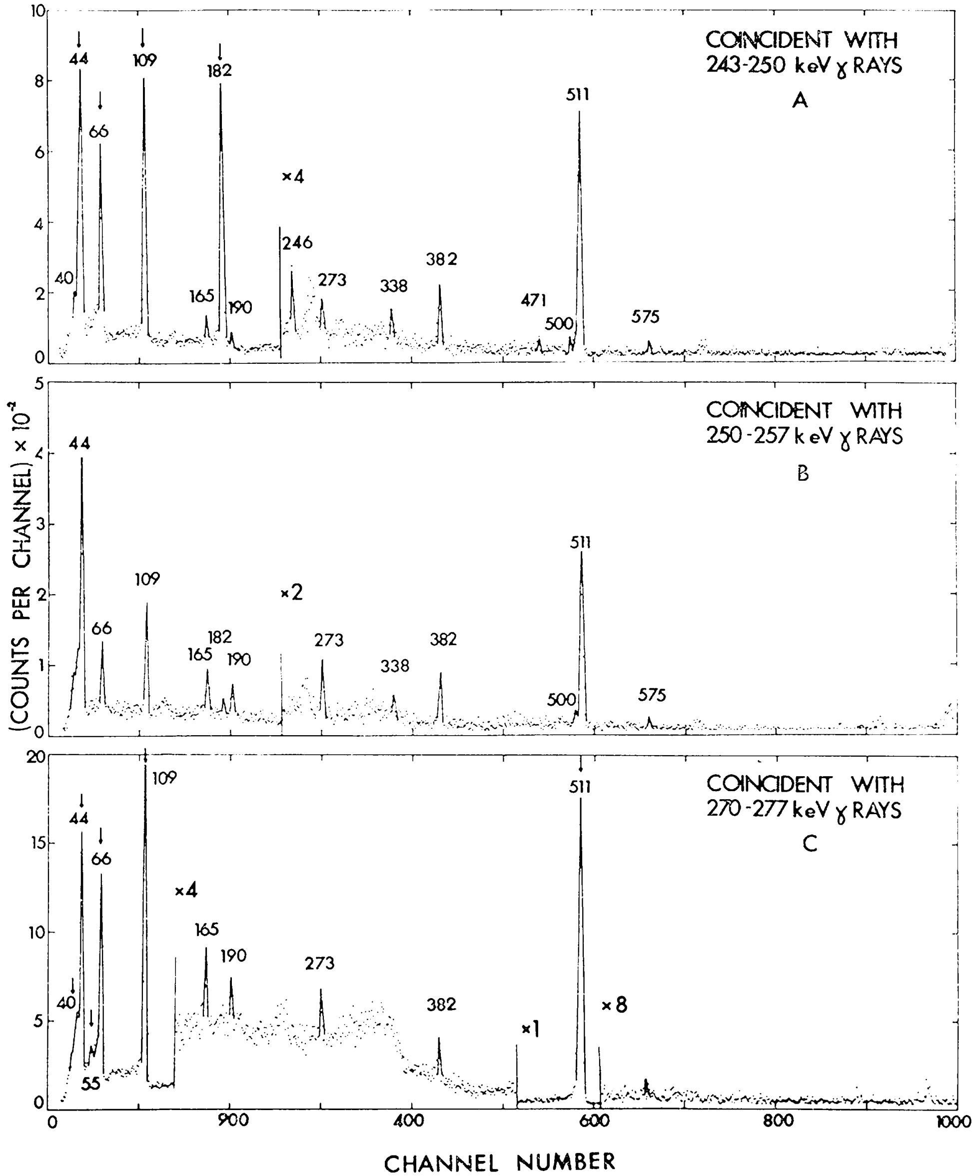

Fig. 6. Spectrum of the γ-rays from ^{66}Ge decay, observed with the 20 cc Ge(Li) detector in coincidence with the indicated energy regions in the 30 cc Ge(Li) detector. Parts A and C display the spectra coincident with the 246 and 273 keV γ-rays, and part B the corresponding Compton background.

suggests a level at 233.9 keV which is consistent with the presently available coincidence information.

Interestingly, the 302 keV γ-ray was observed in strong coincidence with the 190 and 125 keV γ-rays, but not with the 471 or 472 keV γ-rays (figs. 5B, 7A, and 9A). This information excludes the possibility of the 302 keV γ-ray populating the 514 or the 706 keV level. This 302 keV γ-ray cannot de-excite the 514 keV level because this will require a level at 212 keV and no γ-rays that could de-excite such a level were observed. Furthermore, the 148 keV γ-ray was seen in coincidence with the 125 and

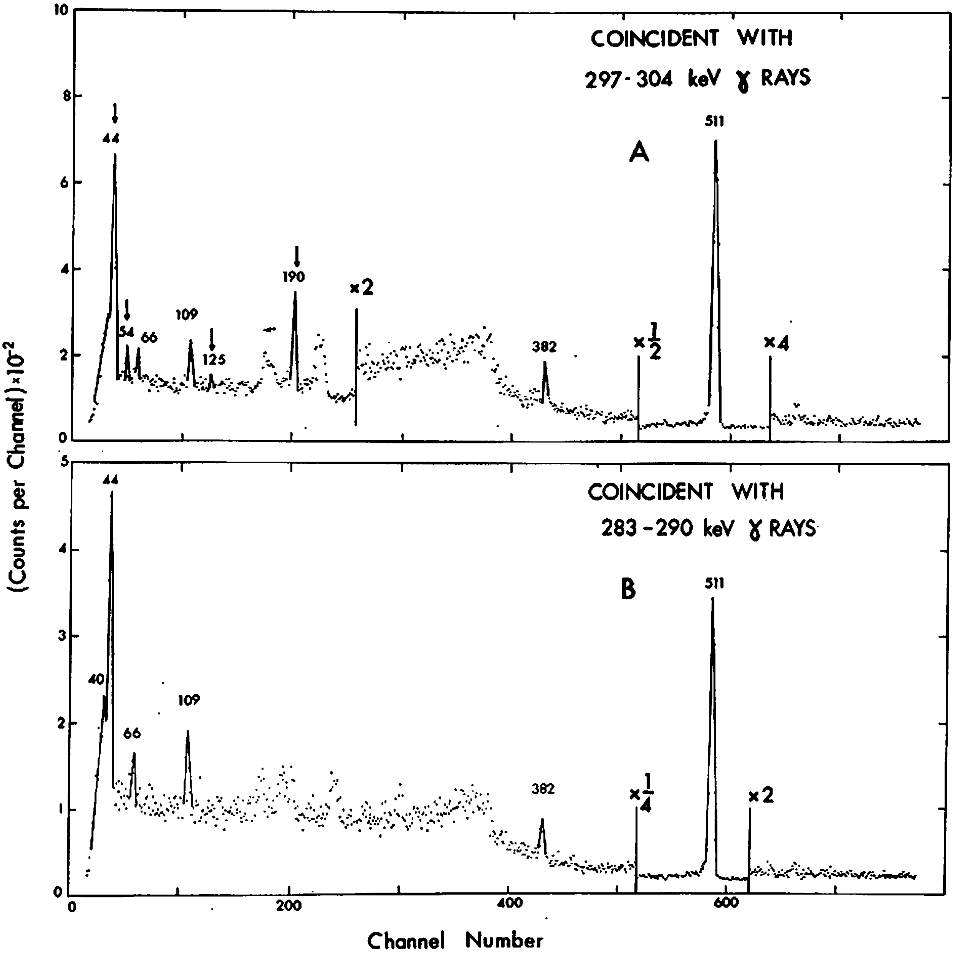

Fig. 7. Spectra of the γ-rays from ^{66}Ge decay observed with the 20 cc Ge(Li) detector in coincidence with the indicated energy regions in the 30 cc Ge(Li) detector. Part A displays the spectrum coincident with the 302 keV γ-ray and B the corresponding Compton background.

the 190 keV γ-rays (fig. 5B). This information further supports the presence of a level at 233.9 keV populated by the 148, 302 and 472 keV γ-rays and de-excited by the 125 and 190 keV γ-rays.

The 246 keV line appears also to be an unresolved doublet in view of the fact that it was seen in weak coincidence with the 243–250 keV region. From the spectrum coincident with the 243–250 keV region (fig. 6A) the fraction of the 245 keV γ-ray that de-excites the 291 keV level was estimated from the relative intensity of the 246 and 182 keV peaks.

The 316 keV γ-ray was observed in coincidence only with the 44, 66 and 109 keV γ-rays, thus suggesting a level at 422.8 keV. This is further supported by the observed coincidences between the 40 keV γ-ray and the 273, 338, and 382 keV γ-rays (figs. 2, 6C and 8A).

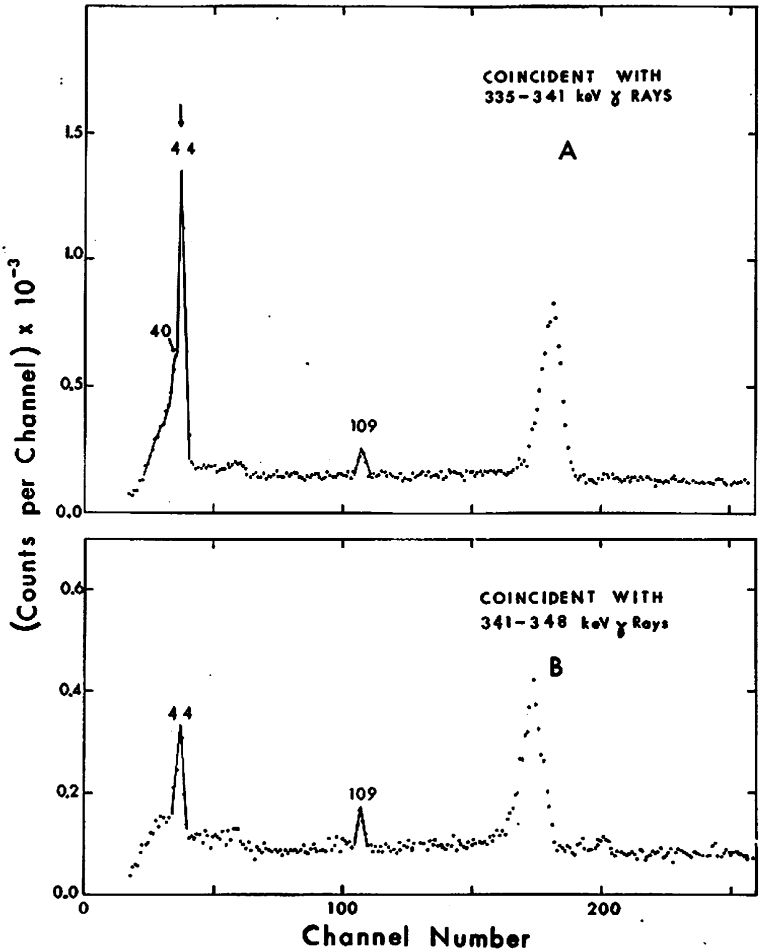

Fig. 8. Spectrum of the γ-rays from ^{66}Ge decay observed with the 20 cc Ge(Li) detector in coincidence with the indicated energy regions in the 30 cc Ge(Li) detector. Part A displays the spectrum coincident with the 338 keV γ-ray and B the corresponding Compton background.

Finally, the 640 keV γ-ray was not seen in coincidence with any γ-ray and is therefore tentatively assigned to populate the ground state.

In comparing the proposed decay scheme with the work of Ricci and coworkers [3]) there is no need to invoke levels at 360, 565, 660 and 760 keV in order to explain the present singles and coincidence data. In fact the proposed scheme accommodates the observed transitions with the exception of the 55 and 97 keV transitions.

The Q_{EC} value for the decay of ^{66}Ge was determined by a $\beta^+ - \gamma$ two parameter coincidence experiment.

Fig. 11 shows the Fermi-Kurie plot analysis of the positon spectrum coincident with the 44 keV γ-ray. Contributions from underlying Compton-scattered γ-rays have

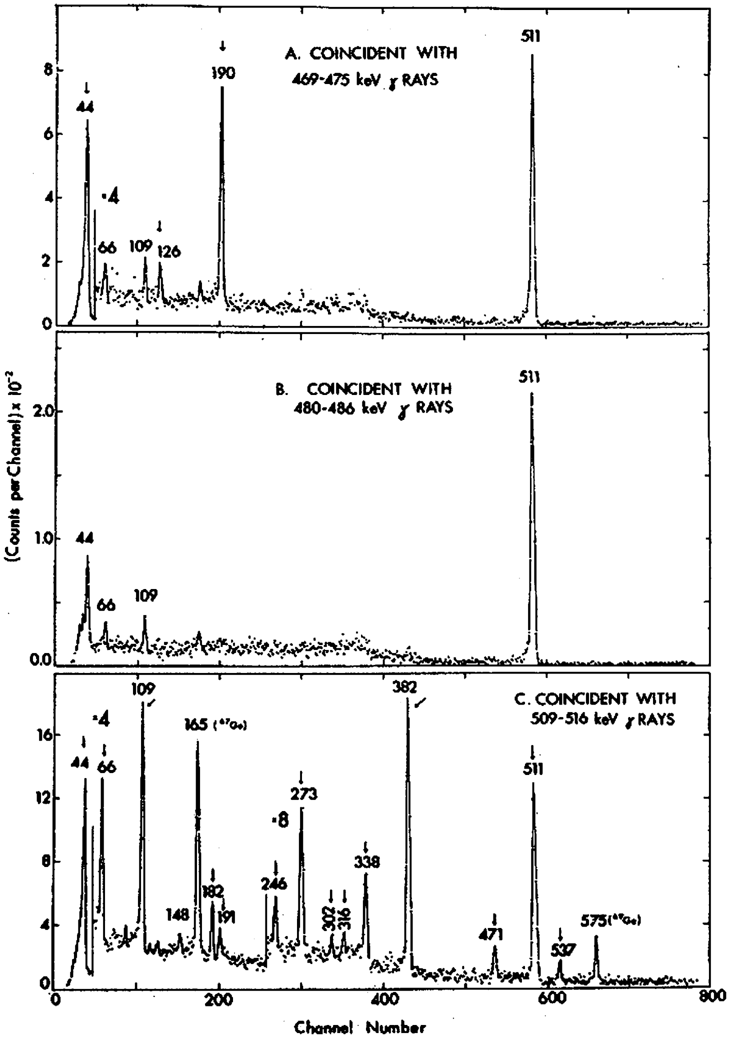

Fig. 9. Spectrum of the γ-rays from ^{66}Ge decay observed with the 20 cc Ge(Li) detector in coincidence with the indicated energy regions in the 30 cc Ge(Li) detector. Parts A and C display the spectra coincident with the 471 and 511 keV γ-rays, and B the Compton background.

been properly subtracted and no contributions from ^{66}Ga are expected to be present. The hard component has an end point energy of 1370 ± 30 keV and populates the 44 keV level. The 234 and 291 keV levels are only weakly populated by positon decay and a low intensity group representing these two unresolved components was observed with an approximate end point of 1160±40 keV. A strong component with an end point of 1040±30 keV is assigned to populate the 382 and perhaps the 423 keV level. Finally, a component with an end-point energy of 850±50 keV was observed and assumed to correspond to the 514 and 537 keV levels. Analysis of the positon spectrum coincident with the 382 keV γ-ray gave an end-point energy of 1050±50 keV. Since the positon spectra were not corrected for distortion due to scattering effects in the plastic scintillator intensities of the β^+ groups were not calculated and only the end-point energies for the most energetic groups were used in

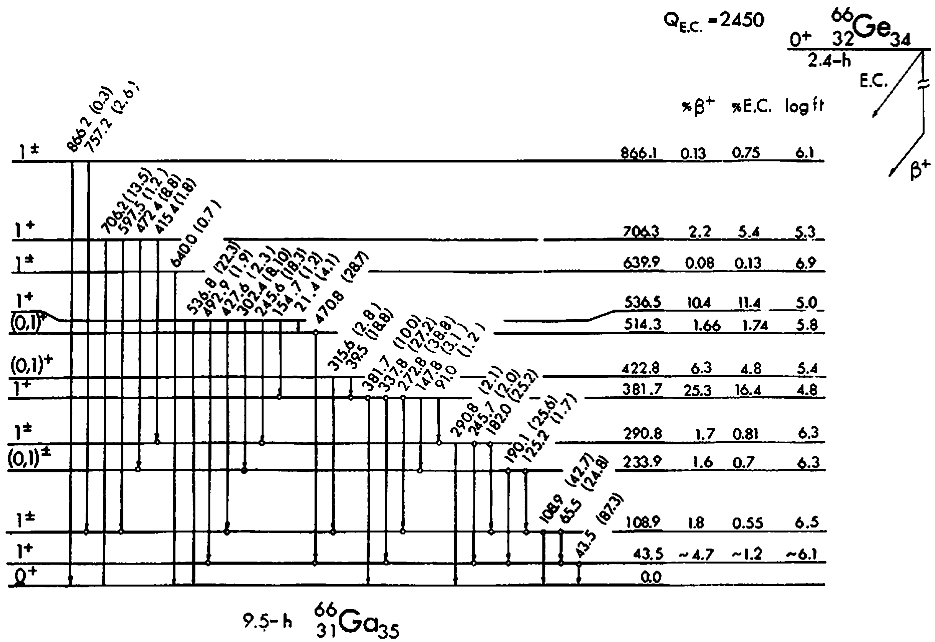

Fig. 10. Proposed decay scheme for 2.4 h ^{66}Ge. The energies are given in keV and the γ-ray intensities are relative to the intensity of the 382 keV γ-ray taken as 100.

obtaining a Q_{EC} value of 2450±50 keV for the transition to the ground state of ^{66}Ga. This value is substantially lower than the value of 3.0 MeV of Ricci *et al.* [3]) from singles measurements. The log *ft* values calculated in this work are based on the present value for Q_{EC}, and are lower only by about 0.2 from the values corresponding to a Q_{EC} of 3.0 MeV.

4. Assignment of J^π values and discussion

The total angular momentum and parity J^π for the even nucleus ^{66}Ge are certainly 0^+. The *J*-value for the ^{66}Ga nucleus has been determined [12]) to be 0, and its parity is almost certainly positive [3]). The ^{66}Ge(0^+) → ^{66}Ga(0^+) transition, of pure Fermi

TABLE 2

Summary of γ–γ coincidences from narrow gates placed on the indicated γ-rays as displayed in the corresponding figures [a])

Fig. no.	Gate on γ-ray (keV)	Coincident γ-ray (keV)																						
		40	44	55	66	91	109	125	148	155	182	190	246	273	302	316	338	382	415	428	471	472	598	757
2A	40		S		S		S							S			S	S						
2B	44	S			S	S			S		S	S	S	S	S	S	S	S			S	S	S	S
3A	66	S	S			S		S			S		S	S		S			S	S			S	S
4A	109	S	S			S		S			S		S	S	W	S			S	S			S	S
	148							S				S												
5A	182		S		S	S	S						S						S					
5B	190		S						S						S							S		
6A	246		S		S		S				S		W											
6C	273	S	S	S	S		S																	
7A	302		S	S				W				S												
8A	338	S	S																					
	382	S								S														
9A	471		S					W				S												
9C	511	S	S		S		S			S														
	493		S																					

[a]) Observed strong coincidences are indicated by S and weak coincidences by W.

type, is isospin forbidden and in analogy with the well known case $^{66}Ga(0^+) \rightarrow$ $^{66}Zn(0^+)$ with a log*ft* value of 7.8, it is expected to be substantially retarded. On this basis and the lack of observation of a hard β^+ component of significant intensity, the β-decay to the ^{66}Ga ground state has been neglected. The correction of the transition intensities for internal conversion is significant particularly for the 21,

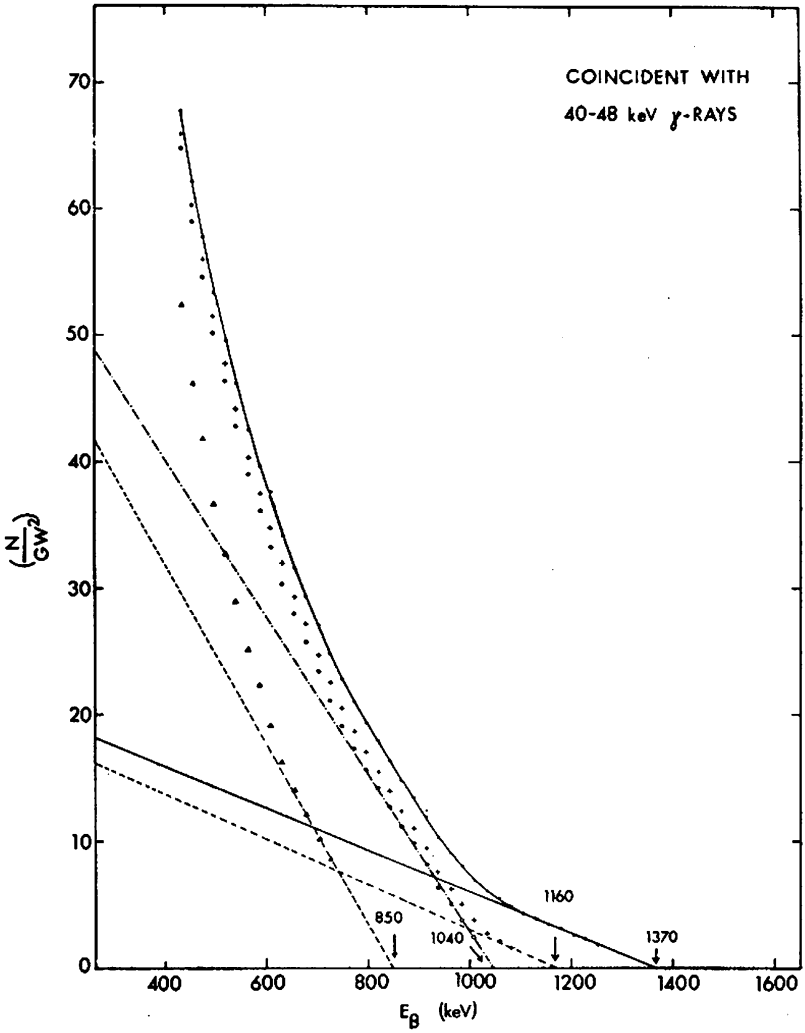

Fig. 11. Fermi-Kurie plot of the positon spectrum obtained in coincidence with the 44 keV γ-ray. The end-point energies are given in keV.

40, 44, 66, and 109 keV transitions. Of these the 44 and 109 keV transitions must be pure multipoles because they populate the 0^+ ground state. This and the resulting log*ft* value for the 44 keV level establish the J^π value as 1^+ and the multipolarity as M1 [3]). The 66 keV transition cannot be E2 because of intensity balance for the 44 keV level. The β-decay to the 109 keV level on the basis of the estimated limits for the logft value must be either allowed or first forbidden. This evidence limits the J^{π} value for the 109 keV level to $1^{\pm}$.

The levels at 382, 537, and 706 keV are strongly populated in β-decay and the calculated logft values suggest allowed transitions. This limits the J^{π} value to $(0, 1)^{+}$. These levels de-excite to populate the 0^{+} ground state by observed γ-transitions and this limits the J^{π} value to 1^{+} for these levels.

The 291, 640, and 866 keV levels are most probably populated by allowed or first-forbidden transitions and since these levels de-excite to feed the 0^{+} ground state by observed γ-decay their J^{π} value can be limited to $1^{\pm}$.

The levels at 423 and 514 keV are populated by allowed β-decay and since they do not populate the ground state directly their J^{π} value can be limited to $(0, 1)^{+}$.

Finally, the 234 keV level is probably populated by allowed or first-forbidden β-decay and it does not populate the ground state directly. This information limits the J^{π} value to $(0, 1)^{\pm}$ for this level.

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