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DECAY OF ^{56}Co AND ^{66}Ga: ENERGY AND INTENSITY STANDARDIZATION

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Abstract: The energy and intensity of the γ-ray transitions from the decay of 77.3 d ^{56}Co and of 9.3 h ^{66}Ga have been carefully measured using a high-resolution Ge(Li) detector in conjunction with a split annular NaI(Tl) detector operated as a Compton suppression spectrometer or as a pair-three-crystal coincidence spectrometer. The following new γ-transitions were observed in the decay of ^{56}Co and were assigned to the well-known level scheme of ^{56}Fe: 263.48±0.11, 486.6±0.4, 1160.06±0.13 and 1640.3±0.2 keV. More accurate values for the energy and intensity of the weaker transitions in the ^{56}Co decay are offered. Twenty-one new γ-transitions have been identified with the decay of ^{66}Ga. From singles anti-Compton and γ-γ coincidence measurements it was established that levels at 1039.24, 1872.70, 2372.24, 2780.2, 2938.4, 3105.07, 3229.05, 3332.2, 3381.32, 3433.08, 3688.90, 3791.29, 4046.5, 4086.19, 4295.52, 4461.5 and 4806.4 keV are populated in the decay of ^{66}Ga. A possible level at 3807.5 keV is also discussed. More accurate values for the energy and intensity of the γ-rays from ^{66}Ga are offered for convenient high-energy and intensity standardization of Ge(Li) spectrometers. From the log *ft* values determined and from γ-ray intensity information J^{π} values to many levels in ^{66}Zn are deduced.

E | RADIOACTIVITY: ^{56}Co [from ^{56}Fe(p, n)]; measured E_{γ}, I_{γ}, 511-γ-511 three-crystal coin; deduced log *ft*. ^{56}Fe deduced levels, J, π. ^{66}Ga [from ^{63}Cu(^{4}He, n)]; measured E_{γ}, I_{γ}, γ-γ, 511-γ-511 three-crystal coin; deduced log *ft*. ^{66}Zn deduced levels J, π. Natural Fe and Cu targets; Co and Ga chemical purification; Ge(Li) and NaI(Tl) detectors, Ge(Li)-NaI(Tl) Compton suppression, three-crystal coincidence spectrometer.

1. Introduction

In recent years the level structure of ^{56}Fe has been the subject of many nuclear reaction spectroscopic studies [1–9]) and of any studies via ^{56}Co and ^{56}Mn radioactivity [10–17]). The importance of the radioactivity studies has been twofold. Firstly, precise measurements of the energy and intensity of the γ-rays from ^{56}Co or ^{56}Mn have helped in limiting the J^{π} assignment to a number of well-known levels in ^{56}Fe. Secondly, many γ-rays from ^{56}Co decay with substantial intensity lie in the energy range 840–3300 keV and are convenient as energy and relative intensity standards.

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Although many high-resolution studies of the ^{56}Co γ-rays have been made recently, the most precise measurements of the energies of the prominent γ-rays from ^{56}Co are those of Gunnink *et al.* [18]) and of Aubin *et al.* [19]), while the most thorough study of the weaker γ-rays is that of Scott and Van Patter [20]). The latter authors have utilized a coincidence-anticoincidence Ge(Li)-NaI(Tl) system and reported five very weak new transitions.

The purpose of this work was to measure the energy and intensity of the γ-rays from 9.3 h ^{66}Ga, which range from 800–4800 keV, and thus provide a standard source for reliably extending the energy and intensity calibration of our Ge(Li) spectrometers to higher energies that are needed in studies of γ-rays emitted in nuclear reactions [21]). For this purpose we have used a high-resolution 25 cm^3 Ge(Li) detector in conjunction with a NaI(Tl) annular detector 19 cm in diameter and 13 cm in length. This system can be operated in an anticoincidence mode to suppress the Compton distributions and as a pair-escape three-crystal coincidence spectrometer. In this work ^{56}Co sources were utilized as internal standards and a close examination of the ^{56}Co spectra revealed four new γ-ray transitions that can be assigned to the already known decay scheme. Furthermore, additional measurements of the energy and intensity of the γ-rays from ^{56}Co have been made and are reported briefly here.

The level structure of ^{66}Zn has also been the subject of several recent studies by means of reaction spectroscopy [22–27]) and ^{66}Ga radioactivity [28–35]). The most thorough studies of the decay of ^{66}Ga that have employed Ge(Li) detectors are the singles measurements of Freedman *et al.* [32]), of Wien [33]), of Vrzal *et al.* [34]), and the Compton suppression and three-crystal coincidence work of Camp [35]).

The present study of the decay of ^{66}Ga has revealed twenty-one new γ-rays which can be incorporated in an improved decay scheme. A semiempirical method for reliably extending the relative efficiency calibration of a three-crystal coincidence spectrometer up to $\approx$ 6.0 MeV is offered. Finally, improved decay schemes for the decays of ^{56}Co and ^{66}Ga are presented.

2. Experimental procedures

2.1. PREPARATION OF ^{56}Co AND ^{66}Ga SAMPLES

The samples of ^{56}Co were prepared by the $^{56}Fe(p, n)$ reaction using a 10 MeV proton beam from the Washington University cyclotron. The targets employed were high purity natural iron foils (20 mg/cm^2). In all the experiments the ^{56}Co activity was purified radiochemically. In some test spectra taken from targets that were not purified, some unidentified weak long-lived peaks, other than those from 267 d ^{57}Co and 71 d ^{58}Co, were observed. The following purification procedure was employed. After bombardment the iron foils were dissolved in 3-5 ml of aqua regia. The HNO_3 was destroyed by boiling to near dryness and the solution was made 6 M in HCl. The Fe^{III} was removed by two extractions with 20 ml of ethyl ether, previously equilibrated with 6 M HCl. The Co activity was adsorbed from the aqueous phase on a Dowex 1 anion exchange column. The column was washed with 10 ml of conc. HCl and then the Co activity was eluted with 4 M HCl. To this solution 1 mg of Co carrier was added, and $K_3Co(NO_2)_6$ was precipitated by addition of 5 ml of 3 M acetic acid saturated with KNO_2. The precipitate was allowed to digest near boiling for 10 min and then centrifuged, filtered, washed with distilled H_2O and mounted for counting.

The ^{66}Ga samples were prepared through the ^{63}Cu(^{4}He, n) reaction by bombardment of 20 mg/cm^2 natural copper foils with 12.5 MeV ^{4}He ions from the Washington University cyclotron. In all the experiments the ^{66}Ga activity was purified radiochemically according to the following procedure. The bombarded copper foils were dissolved in 1 ml of conc. HNO_3 and to the solution 3 ml of conc. HCl and 5 mg of Ga^{III} carrier were added. This solution was evaporated to dryness and the residue was dissolved in 20 ml of 7 M HCl. From this solution Ga^{III} was extracted into 25 ml of isopropyl ether, the organic phase was washed twice with 15 ml of 7 M HCl solution, and the Ga^{III} was back-extracted with 10 ml of water twice. To this solution $\approx$ 5 mg of Fe^{III} carrier were added and sufficient 10 M NaOH was added to bring the pH to $\approx$ 13. The $Fe(OH)_3$ precipitate was coagulated by boiling, centrifuged and discarded. The solution was neutralized with conc. HCl, to this 0.5 ml of a saturated solution of ammonium acetate was added and the pH adjusted to $\approx$ 6 by dropwise addition of conc. NH_4OH solution. The $Ga(OH)_3$ formed was allowed to digest by boiling for 10 min, then filtered and mounted for counting.

2.2. DETECTION SYSTEM

The γ-ray spectra were recorded with a Ge(Li)-NaI(Tl) coincidence-anticoincidence spectrometer, similar in principle to that described by Rauch *et al.* [36]). The spectrometer consists of a 25 or 29 cm^3 Ge(Li) coaxial detector which is axially placed at the center of the NaI(Tl) annulus, see fig. 1. The energy resolution of these detectors is 2.4 and 2.8 keV FWHM for the 1.33 MeV ^{60}Co radiation. The annulus (length 12.7 cm, outer diameter 19.1 cm and inner diameter 6.5 cm) is split axially into four optically isolated quadrants with each quadrant coupled to an RCA 8054 photomultiplier. This permits the annulus to be used simultaneously as a Compton suppression shield in anticoincidence with the Ge(Li) detector and as a three-crystal pair-escape coincidence spectrometer. The NaI(Tl) annulus is completely shielded from the source by a 15 cm or 20 cm lead collimator which is lined with 1.00 mm Cd and then with 0.5 mm Cu metal sheets to reduce the production of Pb X-rays.

A Cosmic Radiation Laboratories multiple coincidence unit is used to provide the logic signals and tag each Ge(Li) pulse as (i) rejected by Compton scattering, (ii) three-crystal coincidence or (iii) residual pulse which constitutes the Compton suppressed spectrum. By proper routing it is possible to store the data simultaneously in a Nuclear Data 4096-channel analyzer as three 1024-channel spectra. Use of the same analogue-to-digital converter permits a convenient relative calibration of the Compton suppressed spectra and the three-crystal coincidence spectra. In this present system it is further possible to store each of the above spectra in a 4096-channel resolution by using the buffer tape system of the two-parameter pulse-height analyzer in conjunction with a digital tagging of each related address pulse.

The present NaI(Tl) annulus reduces the Compton distribution by a factor of 3.6 and the double escape peaks by a factor of 7. With this spectrometer and our 25 cm^3 Ge(Li) detector a resolution of 2.1 keV FWHM at 662 keV and a ratio of peak-to-Compton minimum of 126 : 1 are obtained.

As shown in fig. 1 the sources were mounted in an anti-annihilation arrangement[37]).

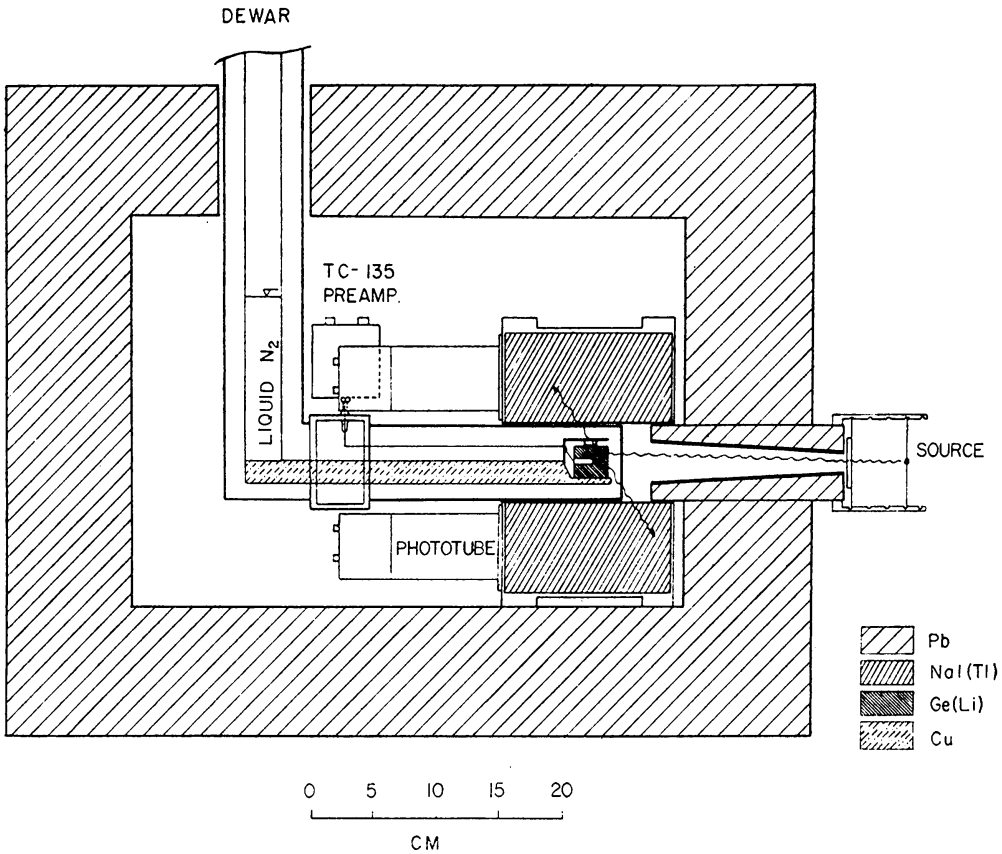

Fig. 1. Schematic drawing of the Compton suppressing Ge(Li)-NaI(Tl) spectrometer. The four photomultiplier tubes are mounted axially on the NaI annulus.

2.3. ENERGY DETERMINATION

Energies up to 1.9 MeV were determined by recording the ^{56}Co or ^{66}Ga spectra simultaneously with a number of standard sources: ^{131}I, ^{139}Ce, ^{133}Ba, ^{137}Cs, ^{207}Bi, ^{54}Mn, ^{88}Y and ^{60}Co. The calibrations were extended up to 3.3 MeV utilizing the well-established [18-20]) values of the higher energy peaks from ^{56}Co in conjunction with the double-escape pair-peak calibrations. In the case of ^{66}Ga mixed calibration spectra with ^{56}Co were taken and the calibrations were extended to 4806 keV through the pair-peak calibrations. The peak positions were determined by a fit to a Gaussian shape by the least-squares technique using the computer program described by Gunnink *et al.* [18]). The energy of the most intense peak in each "unknown" spectrum was determined as a weighted average from several independent measurements and these were used as internal standards for obtaining the energy of the weaker γ-rays again as a weighted average from several separate spectra. To correct for a small non-linearity of the pulse-height analysis system at high channels a cubic dependence of the energy versus channel number was assumed and the calibration equation of each spectrum was determined by a least-squares fit to a cubic equation.

2.4. EFFICIENCY CALIBRATION

The relative efficiency calibration of this spectrometer for full energy peaks in singles spectra was obtained from peak areas utilizing sources with γ-rays of known relative intensity: ^{133}Ba [values from ref. [38])], ^{180m}Hf, ^{57}Co, ^{207}Bi, ^{60}Co, ^{24}Na [values from ref. [39])], and by means of absolute intensity standard sources of ^{137}Cs, ^{54}Mn, ^{57}Co and ^{60}Co. The most intense peaks from ^{56}Co [values from ref. [20])] and from ^{66}Ga [values from ref. [35])] were also used and were found consistent with a straight line extrapolation to higher energy of a log-log plot of the relative efficiency versus energy.

The relative efficiency calibration of this spectrometer for the full energy peaks in Compton suppressed spectra was found identical to that of the non-suppressed singles. A possible source of error for spectra of sources such as ^{56}Co or ^{66}Ga is the loss of counts due to anticoincidence between some high-energy γ-rays detected in the efficient NaI(Tl) annulus that penetrate the lead shield. In the case of ^{56}Co or ^{66}Ga this effect was determined to be $\approx 0.1\,\%$ for the 846.78 or 1039.24 keV transitions, respectively. This is well within the experimental error and therefore no detailed corrections were necessary.

The relative efficiency curve for the three-crystal pair peaks was determined from the peak areas of the most intense γ-rays from ^{56}Co and ^{66}Ga and the results are shown in fig. 2. We have measured the ratio of the area of the three-crystal pair peaks to the area of the double escape peaks in the singles spectrum and found it to be 0.20 ± 0.01 and independent of energy. We have also measured the ratio of the area of the three-crystal pairs peaks to the area of the double escape peaks in the Compton suppressed spectrum and found it to be 1.50 ± 0.05 and independent of energy. For a cylindrical five-sided Ge(Li) detector one can fit the relative efficiency data for the three-crystal pair peaks with the following approximate expression

$$\varepsilon_\pi = \frac{1}{4\pi l^2}\left\{\pi(r_1+R)^2\int_0^{h_1-R}\mu_\pi \exp(-\mu x)\mathrm{d}x + [\pi(r_2-R)^2-\pi(r_1+R)^2]\int_0^{h_2-R}\mu_\pi \exp(-\mu x)\mathrm{d}x\right\}, \qquad (1)$$

where r_1, r_2, h_1 and h_2 are defined in fig. 3; μ_π and μ are the linear attenuation coeffi-

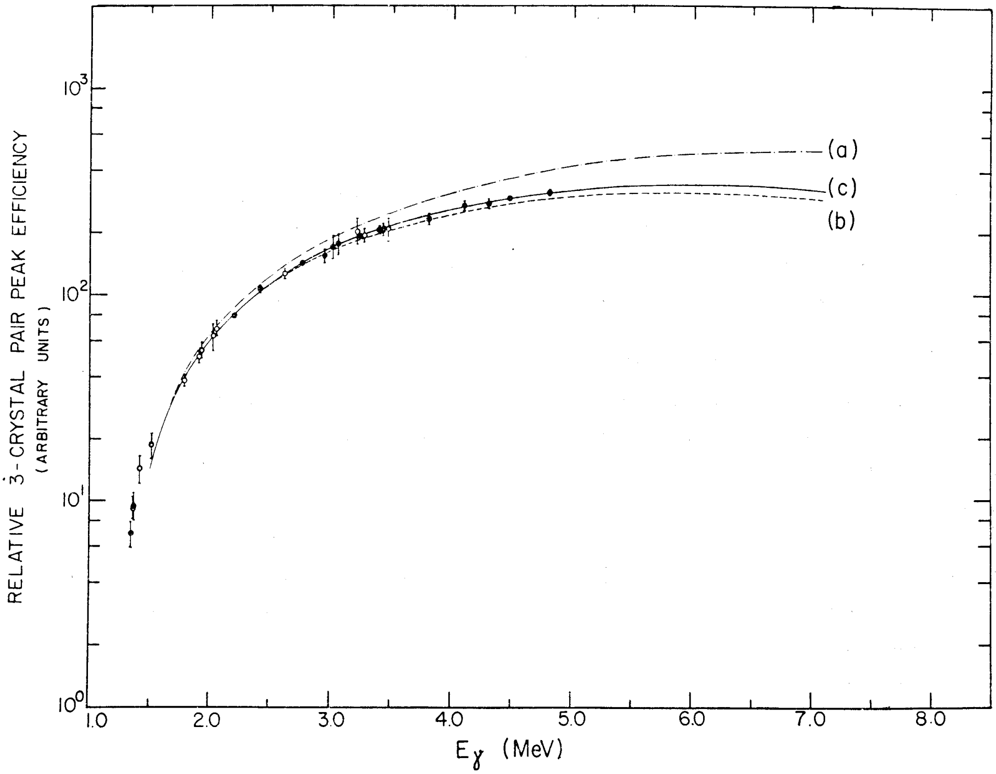

Fig. 2. Relative peak efficiency of the three-crystal pair spectrometer as a function of γ-ray energy. (a) The efficiency calculated by neglecting the radial shrinking; (b) The efficiency calculated including radial shrinking with $R = R_0$; (c) The efficiency calculated with radial shrinking and $R = 0.9\ R_0$.

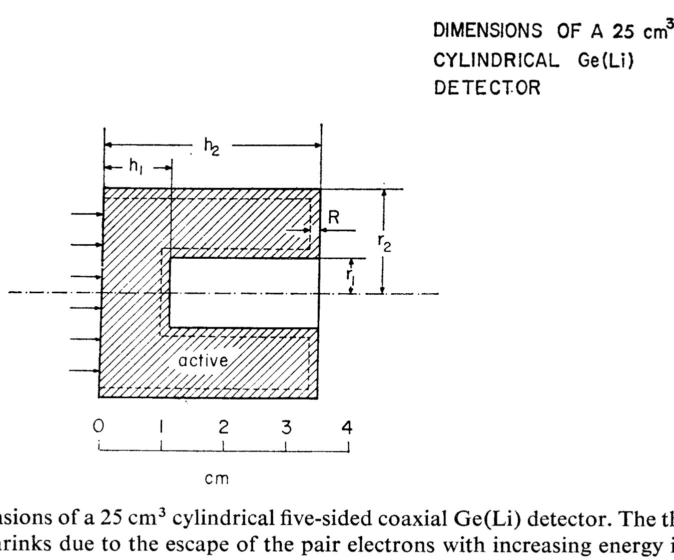

Fig. 3. Dimensions of a 25 cm^3 cylindrical five-sided coaxial Ge(Li) detector. The thickness by which the detector shrinks due to the escape of the pair electrons with increasing energy is indicated by R.

cients for pair production and total absorption in Ge; R is a surface thickness from which one of the electrons escapes the active volume of the detector; and l is the distance of the source from the detector, assumed large compared to r_2 so that the parallel beam approximation can be made. Upon integration eq. (1) yields a relative pair detection efficiency

$$\varepsilon_\pi(\text{rel}) = \frac{\mu_\pi}{\mu}\left(1+\frac{R}{r_1}\right)^2\left\{1-e^{-\mu(h_1-R)}+\left[\left(\frac{r_2-R}{r_1+R}\right)^2-1\right]\left[1-e^{-\mu(h_2-R)}\right]\right\}. \quad (2)$$

The thickness R by which the detector shrinks with increasing energy is approximated by the range of the electrons in Ge. The range of 1-8 MeV electrons is approximately given by [40]) $R_0(\text{mm}) = 0.97E(\text{MeV})-0.2$, and the energy of the electrons is approximated by $\frac{1}{2}[E_\gamma(\text{MeV})-1.022]$. In fig. 2 curve (a) gives the relative pair efficiency calculated by neglecting the radial shrinking [$R = 0$ in eq. (2) except for the exponential terms]. Curve (b) in fig. 3 includes radial shrinking with $R = R_0$ and curve (c) includes radial shrinking with $R = 0.9R_0$. Curve (c) of fig. 2 fits the experimental data quite satisfactorily for γ-ray energies higher than $\approx$ 1.8 MeV and can be used to reliably extrapolate the efficiency curve to $\approx$ 6.0 MeV.

2.5. γ-γ COINCIDENCE MEASUREMENTS

In the case of the ^{66}Ga decay the γ-γ coincidence relationships were established in a two-parameter γ-γ coincidence experiment employing a 25 cm^3 Ge(Li) detector and a 7.6×7.6 cm NaI(Tl) detector in a 2048×128 channel configuration covering the ranges 40-4000 and 40-4300 keV in the Ge(Li) and NaI(Tl) detectors, respectively. The detectors were positioned at $\approx 90°$ with $\approx$ 1.5 cm Pb absorber between them to minimize the crystal-to-crystal Compton scattering events. The standard electronics and pulse-height analysis system employed have been described elsewhere [41]). The coincidence resolving time employed was $\approx$ 100 nsec and the total coincidence rate varied between 100-200 counts / sec. Data were accumulated for 24 h. Under these experimental conditions the random coincidence events were determined to be $\lesssim 5\,\%$ of the total coincidence events and they were not subtracted from the illustrations.

3. Results and discussion

3.1. DECAY OF ^{56}Co

A typical Compton suppressed spectrum of the γ-rays from the decay of ^{56}Co is shown in the upper part (a) of figs. 4 and 5. In the same figures the lower part (b) displays a typical three-crystal coincidence pair-escape (511-γ-511) spectrum of ^{56}Co taken with the same gain for a period of 36 h. Only three foreign peaks from ^{57}Co and ^{58}Co are seen in the Compton suppressed spectrum. The four new γ-rays at 263.9, 486.6, 1159.8 and 1640.3 keV have been observed in at least three independent spectra with the same relative intensity over a period of several months from the same source and have been assigned to follow ^{56}Co decay. The energies and intensities measured in this work are summarized in table 1. The energies and intensities given in columns 2 and 5 of table 1 are weighted averages from a number of independent measurements given in parentheses. The energy values given in column 3 represent the transition

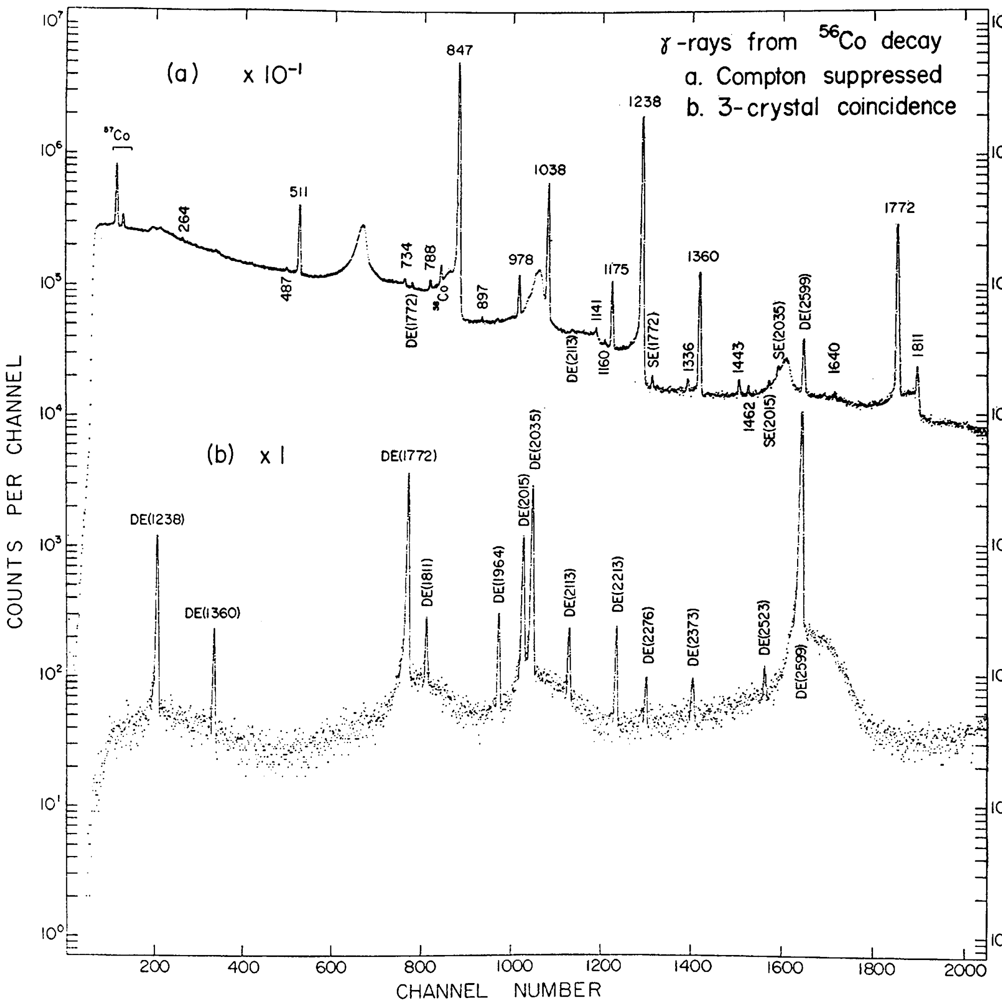

Fig. 4. Typical spectra of the lower energy γ-rays from ^{56}Co decay. The upper spectrum (a) displays a Compton suppressed singles spectrum and the lower spectrum (b) shows a three-crystal coincidence pair escape spectrum obtained under the same gain.

energies between levels populated in the decay of ^{56}Co, whose energies are established as weighted averages of sums. The values in parentheses indicate the number of energy sums leading to the level that de-excites by emission of the γ-ray in question. The intensities from this work are in good agreement with the results of Aubin *et al.*[19]). and the results of Scott and Van Patter [20]) which are summarized in column 4.

The decay scheme of ^{56}Co is rather well established [10-17,20]) and fig. 6 summarizes the decay properties of ^{56}Co together with the new information from this work. Thus, the new γ-rays at 263.48, 486.6, 1160.06 and 1640.3 keV are assigned to

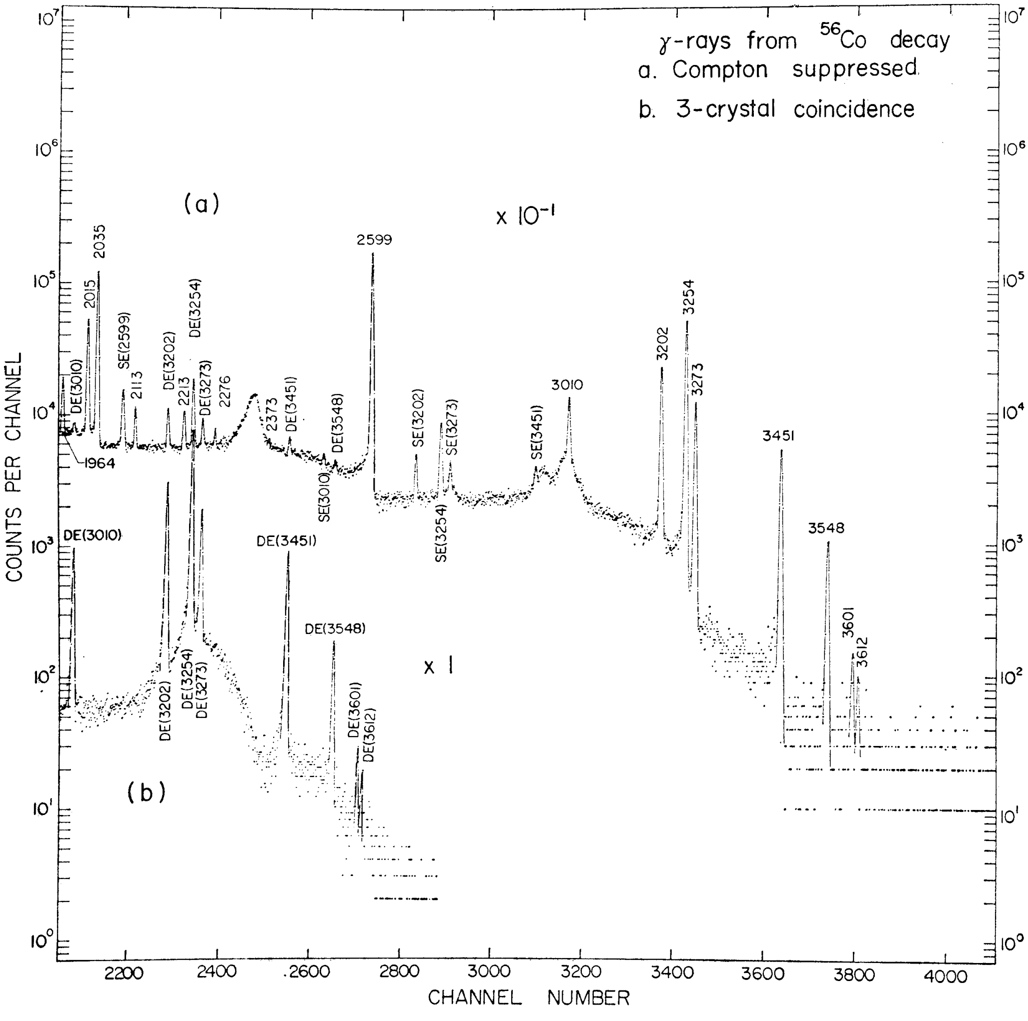

Fig. 5. Typical spectra of the higher energy γ-rays from ^{56}Co decay. The upper spectrum (a) displays a Compton suppressed singles spectrum and the lower spectrum (b) shows a (511-γ-511) escape spectrum obtained under the same gain.

de-excite already established levels at 4120.01, 3856.53, 4120.01 and 4298.16 keV, respectively, on the basis of good energy agreement (see table 1). Furthermore, the γ-ray at 1335.5 keV is assigned on the basis of a much better energy agreement to de-excite the level at 4458.5 keV rather than the level at 4298.16 keV as reported by Scott and Van Patter [20]). In this work no evidence was found for broadening of the

TABLE 1

Energy and intensity of the γ-rays from ^{56}Co decay

Transition	E_γ (keV) measured [a])	E_γ (keV) from scheme [b])	I_γ from ref. [20])	I_γ this work [a])
11 → 8	263.9 9(3)	263.48 11(5)		0.03 1(3)
8 → 6	486.6 4(5)	486.6 3(5)		0.066 6(4)
8 → 5	733.4 2(5)	733.61 13(5)	0.11 4	0.21 4(5)
7 → 3	787.7 2(5)	787.6 2(3)	0.36 3	0.31 6(5)
1 → 0	846.83 6(5)	846.78 6(1)	100	100
8 → 4	896.3 2(5)	896.58 14(5)	0.14 4	0.06 1(5)
10 → 5	977.4 1(5)	977.5 1(5)	1.55 8	1.35 5(5)
5 → 2	1037.77 8(5)	1037.84 8(2)	12.8 3	14.0 7(5)
10 → 4	1140.1 2(5)	1140.47 13(5)	0.17 3	0.24 4(5)
11 → 4	1159.8 4(5)	1160.06 13(5)		0.11 2(5)
12 → 5	1175.06 8(5)	1175.24 11(4)	2.04 13	2.25 5(6)
2 → 1	1238.26 6(6)	1238.30 4(1)	69.5 13	68.5 12(7)
15 → 5	1335.5 3(4)	1335.6 3(3)	0.12 2	0.15 2(5)
7 → 2	1360.26 9(6)	1360.29 9(3)	4.30 13	4.37 13(5)
10 → 3	1442.9 5(5)	1442.2 3(5)	0.23 3	0.20 2(5)
11 → 3	1462.7 2(6)	1462.2 2(5)	0.12 3	0.08 2(6)
12 → 3	1640.3 2(5)	1640.3 2(4)		0.05 2(5)
8 → 2	1771.58 10(7)	1771.45 10(5)	15.5 5	16.0 5(7)
3 → 1	1811.0 2(6)	1810.8 2(1)	0.62 6	0.62 6(7)
9 → 2	1964.04 14(6)	1963.92 11(2)	0.64 3	0.74 3(7)
10 → 2	2015.42 10(6)	2015.34 9(5)	2.93 14	3.13 10(7)
11 → 2	2035.00 13(6)	2034.93 13(5)	7.42 26	8.1 2(7)
4 → 1	2113.35 10(6)	2113.17 13(1)	0.35 4	0.39 3(7)
12 → 2	2213.12 10(6)	2213.08 9(4)	0.44 4	0.40 3(7)
5 → 1	2276.0 2(6)	2276.14 11(2)	0.13 2	0.15 2(7)
15 → 2	2373.4 6(3)	2373.4 3(3)	0.12 2	0.12 2(3)
6 → 1	2523.2 8(3)	2523.2 8(1)	0.09 3	0.054 15(3)
7 → 1	2598.64 6(7)	2598.59 6(3)	17.0 4	17.2 4(7)
8 → 1	3009.85 11(7)	3009.75 11(5)	0.89 11	0.93 6(7)
9 → 1	3202.18 7(7)	3202.22 7(2)	3.22 12	3.10 11(7)
10 → 1	3253.72 7(7)	3253.64 9(5)	7.71 27	7.5 2(7)
11 → 1	3273.21 8(7)	3273.23 8(5)	1.56 10	1.72 5(7)
12 → 1	3451.49 8(7)	3451.38 8(4)	0.90 9	0.89 3(7)
13 → 1	3548.28 10(7)	3548.28 10(1)	0.17 1	0.18 1(7)
14 → 1	3601.3 4(5)	3601.3 4(1)	0.019 5	0.014 4(5)
15 → 1	3611.9 6(3)	3611.7 3(3)	0.007 3	0.011 3(3)

The intensities are given per 100 decays.

[a]) Numbers in parentheses indicate the number of measurements used to obtain the reported value as a weighted average.

[b]) This is the transition energy deduced from the ^{56}Fe level energies assigned in fig. 6. The level energies are weighted averages of energy sums the number of which is given in parentheses. If the number of sums is one then the adopted value of ref. [19]) is used.

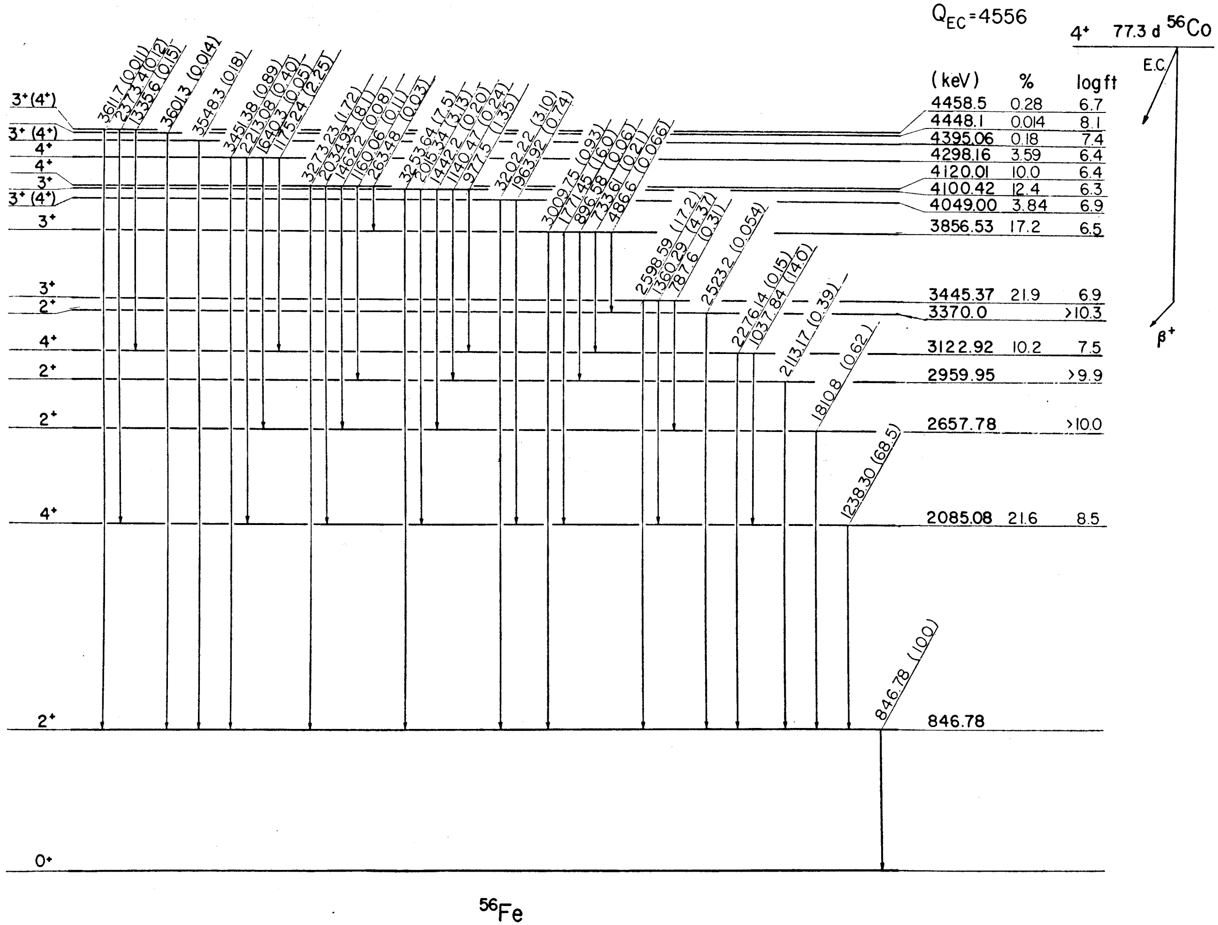

Fig. 6. Proposed decay scheme for 77.3 d ^{56}Co. The energies are given in keV and the γ-ray intensities in parentheses are given per hundred decays.

733.4 keV line which in the present spectra is well resolved from the background and because of the good energy agreement it is assigned to de-excite the level at 3856.53 keV. An upper limit of 0.03 for a 730.4 keV γ-ray can be placed on the basis of the present data and therefore no such transition is assigned to de-excite the 4100.42 keV level [see fig. 5 in ref. [20])].

TABLE 2

Levels in ^{56}Fe populated in the decay of ^{56}Co

Level no.	Level energy (keV)	Population by (β^++EC) per 100 decays	log *ft*	J^π
1	846.78 6	−1.3 13		2^+
2	2085.08 7	21.6 12	8.5	4^+
3	2657.78 21	−0.02 7	>10.0	2^+
4	2959.95 12	−0.02 6	> 9.9	2^+
5	3122.92 9	10.2 7	7.5	4^+
6	3370.0 8	−0.01 2	>10.3	2^+
7	3445.37 6	21.9 4	6.9	3^+
8	3856.53 9	17.2 5	6.5	3^+
9	4049.00 9	3.84 11	6.9	$3^+(4^+)$
10	4100.42 6	12.4 3	6.3	3^+
11	4120.01 6	10.0 2	6.4	4^+
12	4298.16 6	3.59 7	6.4	4^+
13	4395.06 12	0.18 1	7.4	$3^+(4^+)$
14	4448.1 4	0.014 4	8.1	
15	4458.5 3	0.28 3	6.7	$3^+(4^+)$

Table 2 lists the energy levels in ^{56}Fe populated in the decay of ^{56}Co together with the percent (β^++EC) population as deduced from the proposed level scheme and the measured γ-ray intensities. The log *ft* values given in table 2 are based on a value of 4556 keV for Q_{EC} [ref. [20])] and on calculated β^+/EC ratios given on p. 575 of ref.[39]). The J^π values given in table 2 are those given in ref. [20]) and are consistent with the present data.

3.2. DECAY OF ^{66}Ga

A typical Compton suppressed spectrum of the γ-rays emitted in the decay of ^{66}Ga is shown in the upper part (a) of figs. 7 and 8. In the same figures the lower part (b) displays a typical three-crystal coincidence pair-escape spectrum from ^{66}Ga taken with the same gain for a period of 24 h utilizing four freshly prepared and purified sources. Twenty-one new γ-ray transitions have been observed in this decay with a half-life between 8-10 h and were consequently assigned to the ^{66}Ga decay. The energy and intensity of the γ-rays measured in this work are given in the second and fourth columns of table 3. These values are weighted averages of independent measurements, the number of which is given in parentheses. The energy values given in the third column are the transition energies between levels populated in the decay of ^{66}Ga with energies determined as weighted averages of sums, the number of which is also given in parentheses.

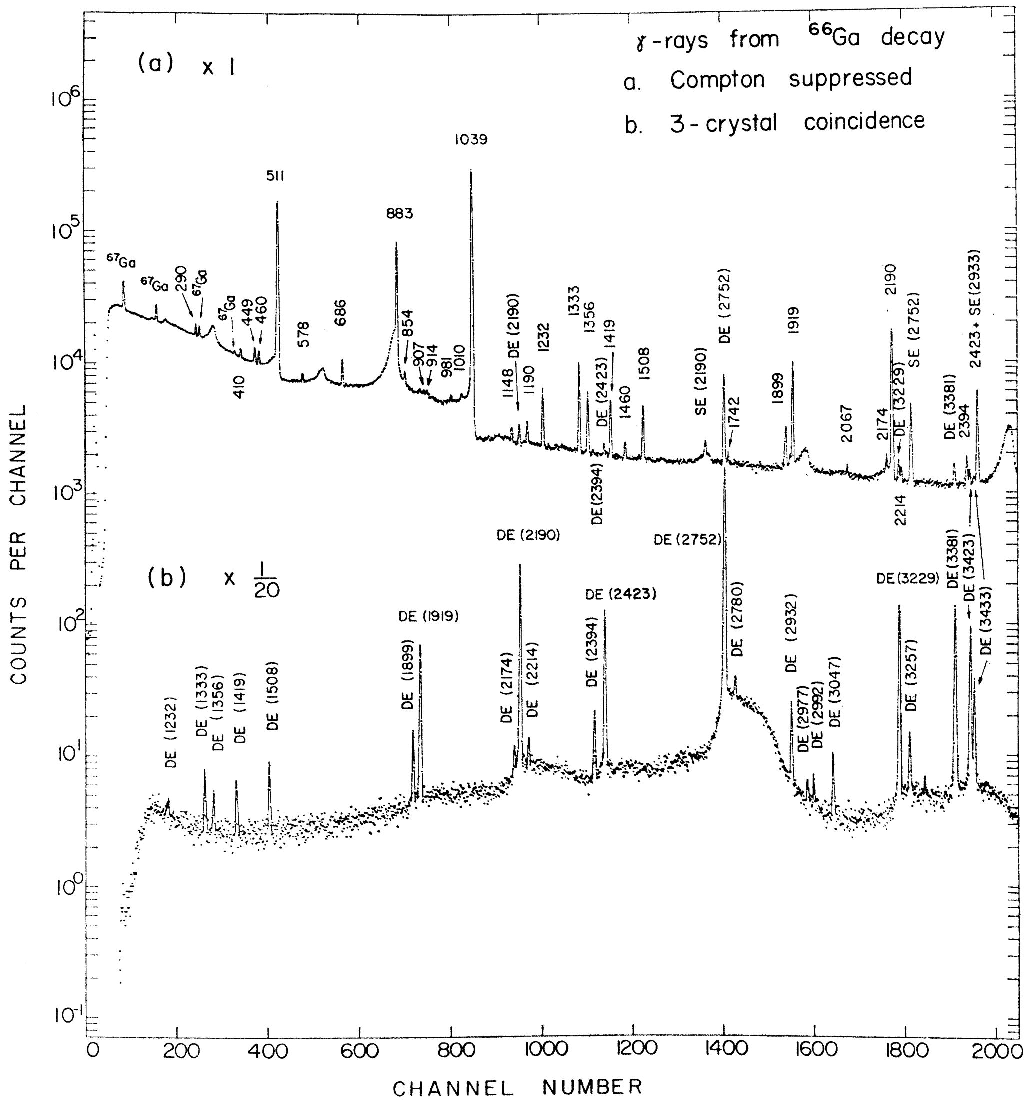

Fig. 7. Typical spectra of the lower-energy γ-rays from ^{66}Ga decay. The upper part (a) displays a typical Compton suppressed singles spectrum, and the lower part (b) shows a (511-γ-511) escape spectrum of the singles γ-rays from ^{66}Ga obtained with the same gain.

The following two additional γ-rays at 171.9±0.2 (0.28±0.01) and 854.3±0.3 (5.7±0.6) keV, with the intensities given in parentheses, have been identified with the decay of ^{66}Ga, but they were not assigned in the decay scheme.

The coincidence relationships of the γ-rays from ^{66}Ga were established in a two parameter NaI × Ge(Li) experiment and the results are summarized in table 4.

The coincidence spectra shown in figs. 9-12 present the most important evidence on which the proposed decay scheme is based.

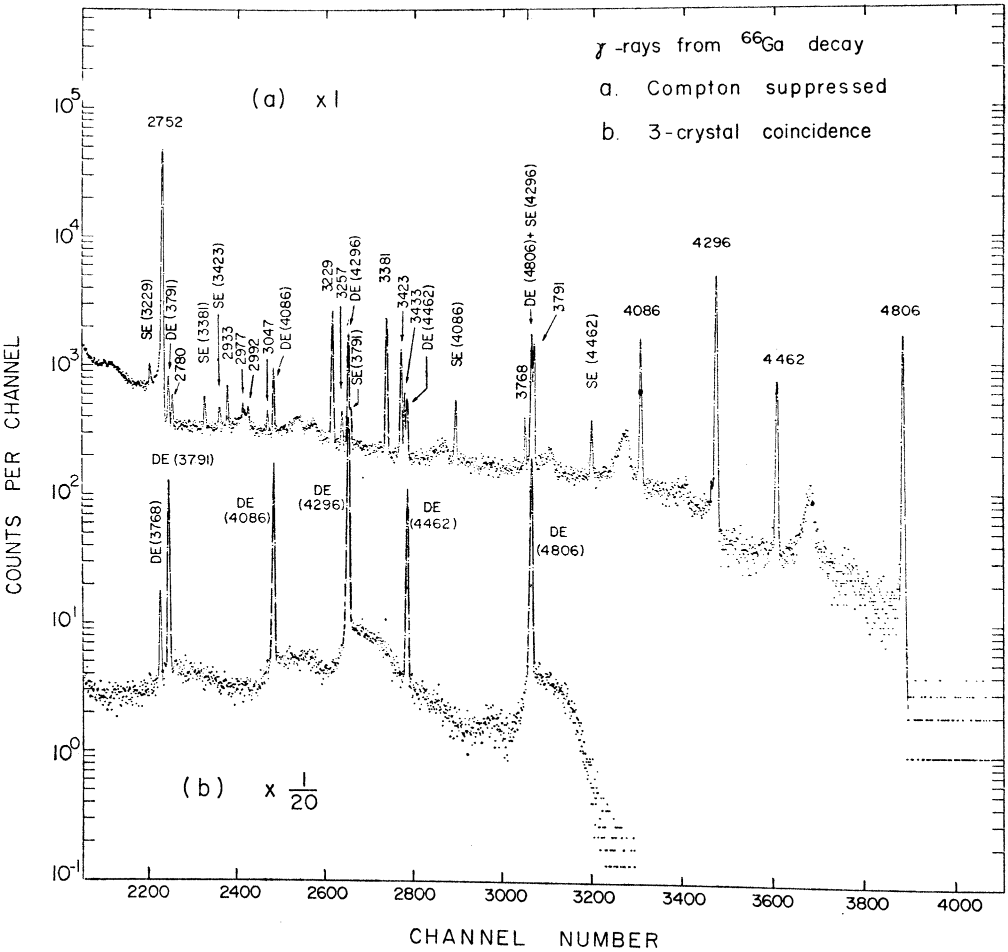

Fig. 8. Typical spectra of the higher-energy γ-rays from ^{66}Ga decay. The upper part (a) displays a typical Compton suppressed singles spectrum and the lower part (b) shows a (511-γ-511) escape spectrum of the singles γ-rays from ^{66}Ga obtained with the same gain.

The proposed decay scheme is shown in fig. 13 and the arguments for it are summarized below.

The definite levels discussed below are based on observed γ-γ coincidence relationships and are for most cases further supported by energy sums or nuclear reaction information.

The 1039.24 keV *level*: The 1039.24 keV γ-ray is the most intense one; it is in strong coincidence with a wealth of γ-rays (table 4) and certainly populates the ground state.

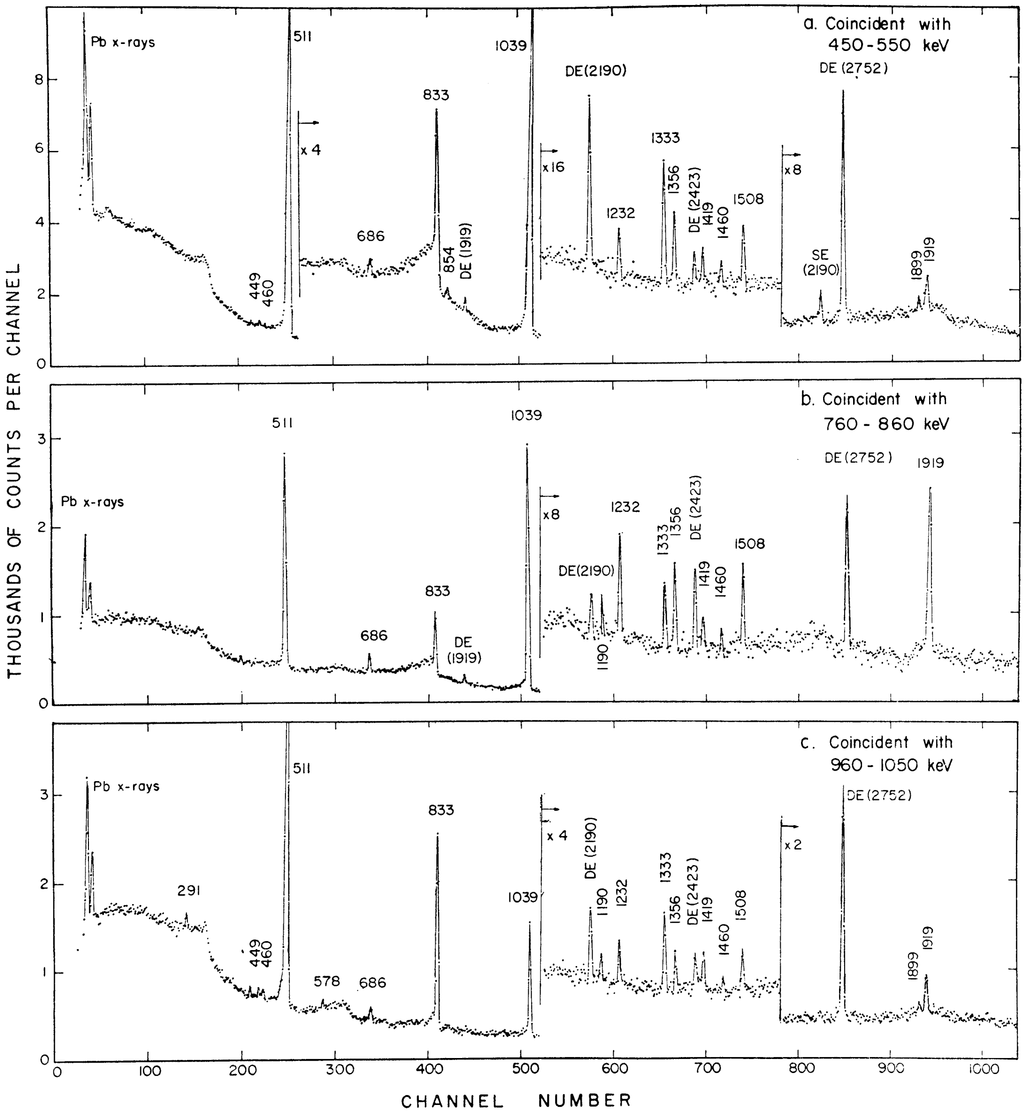

Fig. 9. Spectra of the lower energy γ-rays from ^{66}Ga decay observed with a 25 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the NaI(Tl) detector. Parts (a), (b), and (c) emphasize the coincidences with the 511 keV annihilation radiation, the 833.46 and the 1039.24 keV γ-rays, respectively.

The 1872.70 keV *level*: The population of this level in the decay of ^{66}Ga via γ-transitions from higher lying states is established on the basis of the strong coinci-

TABLE 3

Energy and intensity of the γ-rays from ^{66}Ga decay

Transition	E_γ (keV) measured [b])	E_γ (keV) from scheme [c])	I_γ measured [b])
7 → 5	290.1 1(2)	290.65 14(5)	1.5 1(3)
12 → 9	410.1 2(6)	410.0 2(6)	3.0 2(2)
7 → 4	448.9 1(8)	448.9 2(4)	2.9 1(2)
11 → 7 [a])	459.8 1(5)	459.8 2(1)	2.4 1(2)
13 → 7 [a])	578.4 2(2)	578.4 2(1)	1.6 1(2)
12 → 6	686.22 6(7)	686.22 13(6)	6.9 2(3)
2 → 1	833.46 4(10)	833.46 4(1)	162 7(6)
4 → 2	907.0 3(2)	907.5 2(3)	3.0 2(2)
16 → 9	913.9 4(2)	914.20 14(6)	1.9 1(2)
15 → 6	980.8 2(3)	981.12 13(5)	1.5 2(3)
9 → 3	1009.6 2(3)	1009.08 13(3)	1.83 10(2)
1 → 0	1039.24 5(5)	1039.24 5(1)	1000
15 → 5	1147.9 2(5)	1147.79 13(5)	2.2 3(3)
16 → 6	1190.28 13(5)	1190.45 14(6)	4.2 4(3)
6 → 2	1232.2 2(5)	1232.37 12(2)	11.4 20 [d])
17 → 7	1232.2 2(5)	1232.40 21(3)	4 2 [d])
3 → 1	1333.00 6(9)	1333.00 6(1)	32.8 5(8)
7 → 2	1356.35 11(5)	1356.35 12(5)	8.3 30 [d])
17 → 6	1356.35 11(5)	1356.43 22(4)	3 1 [d])
16 → 5	1356.35 11(5)	1357.12 14(6)	7 2 [d])
12 → 3	1418.79 6(9)	1419.05 11(6)	16.5 3(8)
8 → 2 [a])	1459.5 2(4)	1459.5 2(1)	2.5 7(4)
9 → 2	1508.29 9(9)	1508.62 12(3)	14.8 9(8)
4 → 1	1741.7 7(1)	1741.0 2(3)	1.9 4(1)
5 → 1	1899.16 9(9)	1899.16 9(1)	11.5 3(9)
12 → 2	1918.63 6(4)	1918.59 10(6)	56.5 2(4)
6 → 1	2066.8 4(2)	2065.83 11(2)	0.98 16(2)
14 → 2 [a])	2173.8 2(4)	2173.8 2(1)	3.8 3(4)
7 → 1	2189.85 6(12)	2189.81 11(5)	150 3(9)
15 → 2	2213.4 2(2)	2213.49 11(5)	3.8 5(4)
10 → 1	2393.5 2(4)	2393.84 11(2)	6.4 2(4)
16 → 2	2422.75 6(9)	2422.82 12(6)	50.6 10(8)
12 → 1	2751.92 6(13)	2752.05 11(6)	609 8(9)
4 → 0	2780.30 16(3)	2780.2 2(3)	3.3 2(4)
18 → 2	2933.4 12(8)	2933.7 2(3)	5.7 3(8)
15 → 1	3046.9 2(2)	3046.95 10(5)	1.7 2(3)
7 → 0	3229.16 6(8)	3229.05 10(5)	38.5 6(8)

TABLE 3 (continued)

Transition	E_γ (keV) measured [b])	E_γ (keV) from scheme [c])	I_γ measured [b])
16 → 1	3256.55 17(4)	3256.28 11(6)	3.1 3 (4)
9 → 0	3381.34 6(15)	3381.32 10(3)	36.8 4 (9)
17 → 1	3422.77 10(10)	3422.26 20(3)	21.0 9(10)
10 → 0	3433.02 15(3)	3433.08 10(2)	7.3 3 (4)
18 → 1	3767.5 2(3)	3767.16 20(3)	3.7 2 (4)
12 → 0	3791.38 10(3)	3791.29 12(6)	26.3 11(4)
15 → 0	4086.27 10(8)	4086.19 9(5)	29.1 6 (8)
16 → 0	4295.88 10(6)	4295.52 10(6)	92 2 (6)
17 → 0	4461.93 15(6)	4461.5 2(3)	18.4 4 (8)
18 → 0	4806.58 20(6)	4806.4 2(3)	39.6 6 (8)

Intensities are given relative to the 1039.24 keV γ-ray taken as 1000.
[a]) Transitions assigned tentatively to de-excite levels established in nuclear reaction studies.
[b]) The numbers in parentheses indicate the number of spectra from which the reported value was obtained as a weighted average.
[c]) This is the transition energy deduced from the ^{66}Zn level energies assigned in fig. 13. The level energies are weighted averages of energy sums the number of which is given in parentheses.
[d]) Estimated from the coincidence spectra and from the intensity balance.

TABLE 4

Summary of the observed γ-γ coincidence relationships in the decay of ^{66}Ga

Fig.	Gate in NaI (keV)	γ-rays in coincidence (keV)
9a	450- 550	449, 460, 686 [a]), 833, 854, 1039, 1333 [a]), 1356 [a]), 1460, 1508, 1899, 1919
10a	450- 550	2190, 2394, 2752, 2780, 3229, 3381, 3433, 3791, 4086
9b	760- 860	686, 1039, 1190, 1232, 1356, 1460, 1508, 1919
10b	760- 860	2174, 2423, 2933
9c	960-1050	291, 449, 460, 578, 686, 833, 1190, 1232, 1356, 1419, 1460, 1508, 1899, 1919
10c	960-1050	2174, 2190, 2394, 2423, 2752, 2933, 3423
[b])	1160-1300	686, 1190, 1356
11a	1300-1370	833, 1010, 1039, 1232 [a]), 1419, 1899
11b	1370-1440	833, 1039, 1232 [a]), 1333, 1899
11c	1505-1570	833, 1039
12a	1840-1970	833, 1039, 1147, 1356 [a])
12b	1970-2110	833, 1039, 1356 [a])
[b])	2110-2250	460, 1232 [a])
[b])	2790-2930	449
[b])	3200-3330	460

[a]) Weak coincidence. [b]) Not shown in illustrations.

dence of the 833.46 keV γ-ray with the 1039.24 keV γ-ray and a wealth of observed additional coincidences (table 4).

The 2372.24 keV *level*: The population of this level is established from the observed coincidence of the 1333.00 keV γ-ray with the 1039.24 keV γ-ray and not with

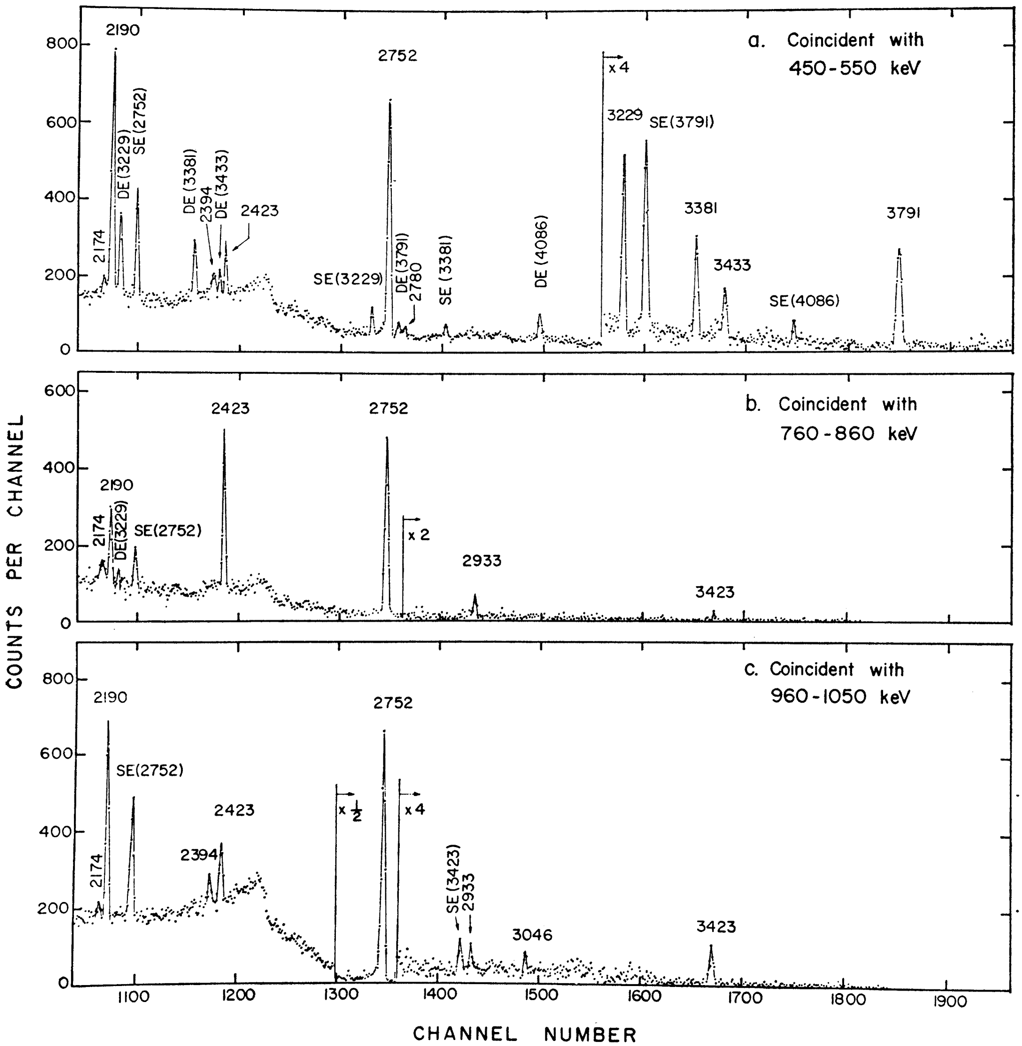

Fig. 10. Spectra of the higher energy γ-rays from ^{66}Ga decay observed with a 25 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the NaI(Tl) detector. Parts (a), (b) and (c) emphasize the coincidences with the 511 keV annihilation radiation, the 833.46 and the 1039.24 keV γ-rays, respectively.

the 833.46 keV γ-ray (fig. 9b,c). The additional coincidence between the 1333.00 and 1418.79 keV γ-rays (fig. 11a,b) firmly establishes this level since the 1418.79 keV γ-ray depopulates a well established level at 3791.29 keV (see below).

The 2780.2 keV *level.* This level is well established on the basis of three γ-rays at 2780.3, 1741.7 and 907.0 keV assigned to populate the ground and the two first excited states by good energy agreement. Further evidence is provided by the 448.9 keV

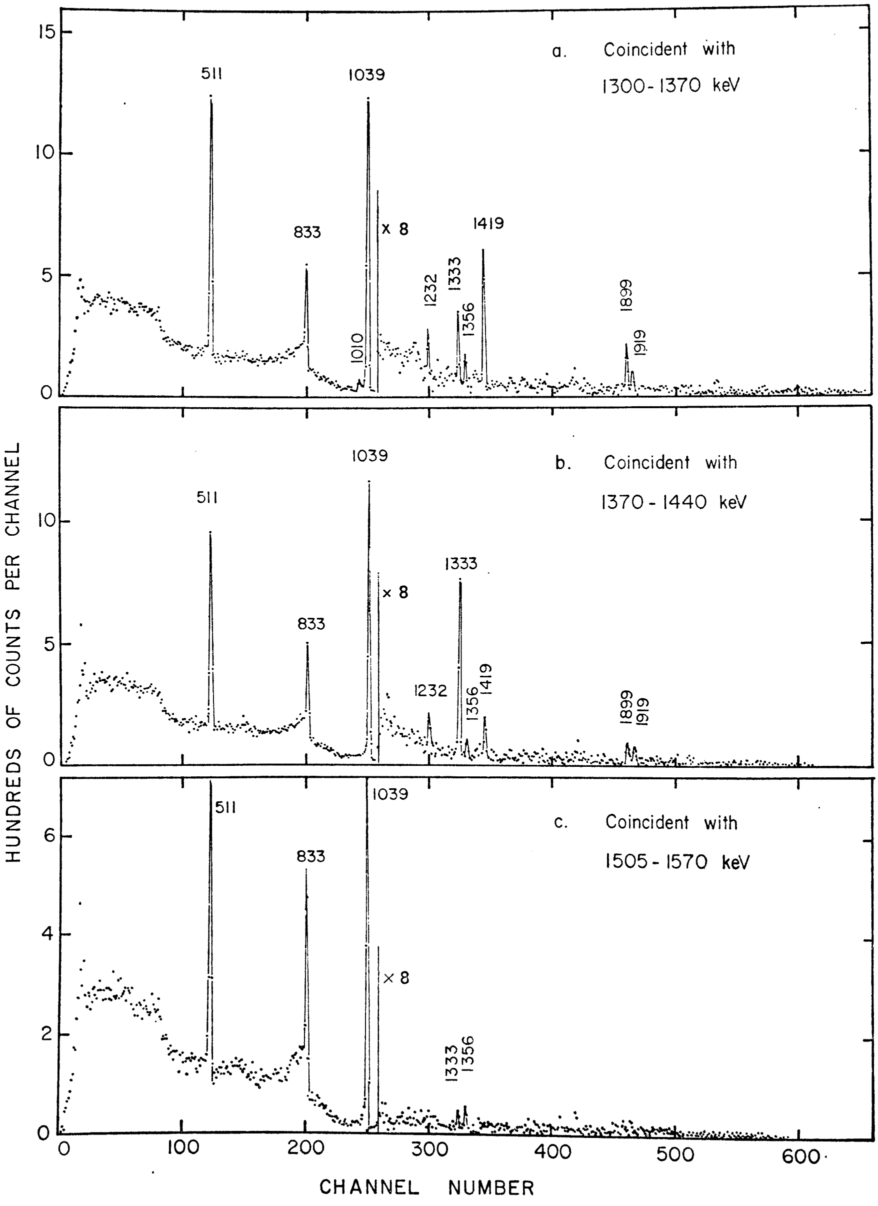

Fig. 11. Spectra of the γ-rays from ^{66}Ga decay observed with a 25 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the NaI(Tl) detector. Parts (a), (b) and (c) emphasize the coincidences with the 1356.35, the 1418.79 and the 1508.29 keV γ-rays, respectively.

γ-ray seen in coincidence with the 2790-2930 keV region in the NaI detector which includes a major part of the 2780.3 keV γ-ray.

The 2938.4 keV *level*: This level is established by the observed strong coincidence of the 1899.16 keV γ-ray with the 1039.24 keV γ-ray but not with the 833.46 keV γ-ray (fig. 9b,c). Additional evidence is provided by the 1147.9 and 1356.4 keV γ-rays observed in coincidence with the 1840-1970 keV region in NaI (fig. 12a) which connect

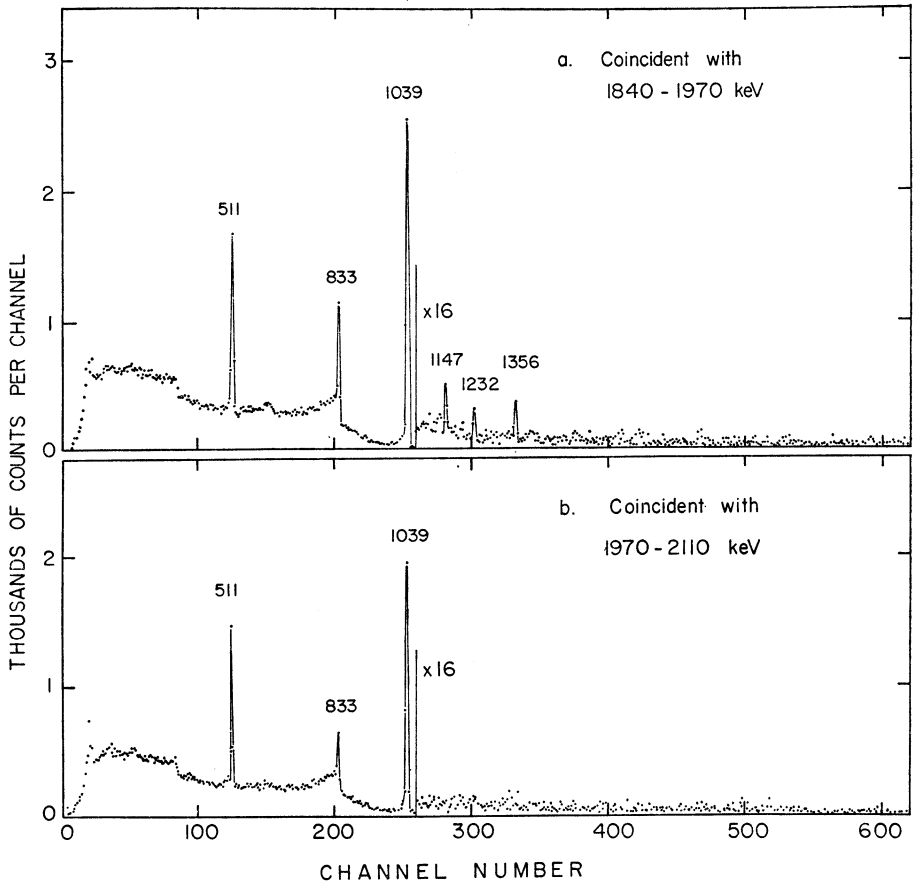

Fig. 12. Spectra of the γ-rays from ^{66}Ga decay observed with a 25 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the NaI(Tl) detector. Parts (a), and (b) emphasize coincidences with the 1899.16, 1918.63 and the 2066.8 keV γ-rays, respectively.

this level with levels at 4086.19 and 4295.52 keV, respectively. This level is identified with the 2941 $\pm$ 2 keV level from the $^{66}Zn(p, p')$ study of Katsanos and Huizenga [22]).

The 3105.07 keV *level*: Previous authors [32,34,35]) have assigned the 1232 keV γ-ray to depopulate a level at 4461.5 keV on the basis of good energy agreement between energy sums leading to that level. A level at 3106 keV which is de-excited by a

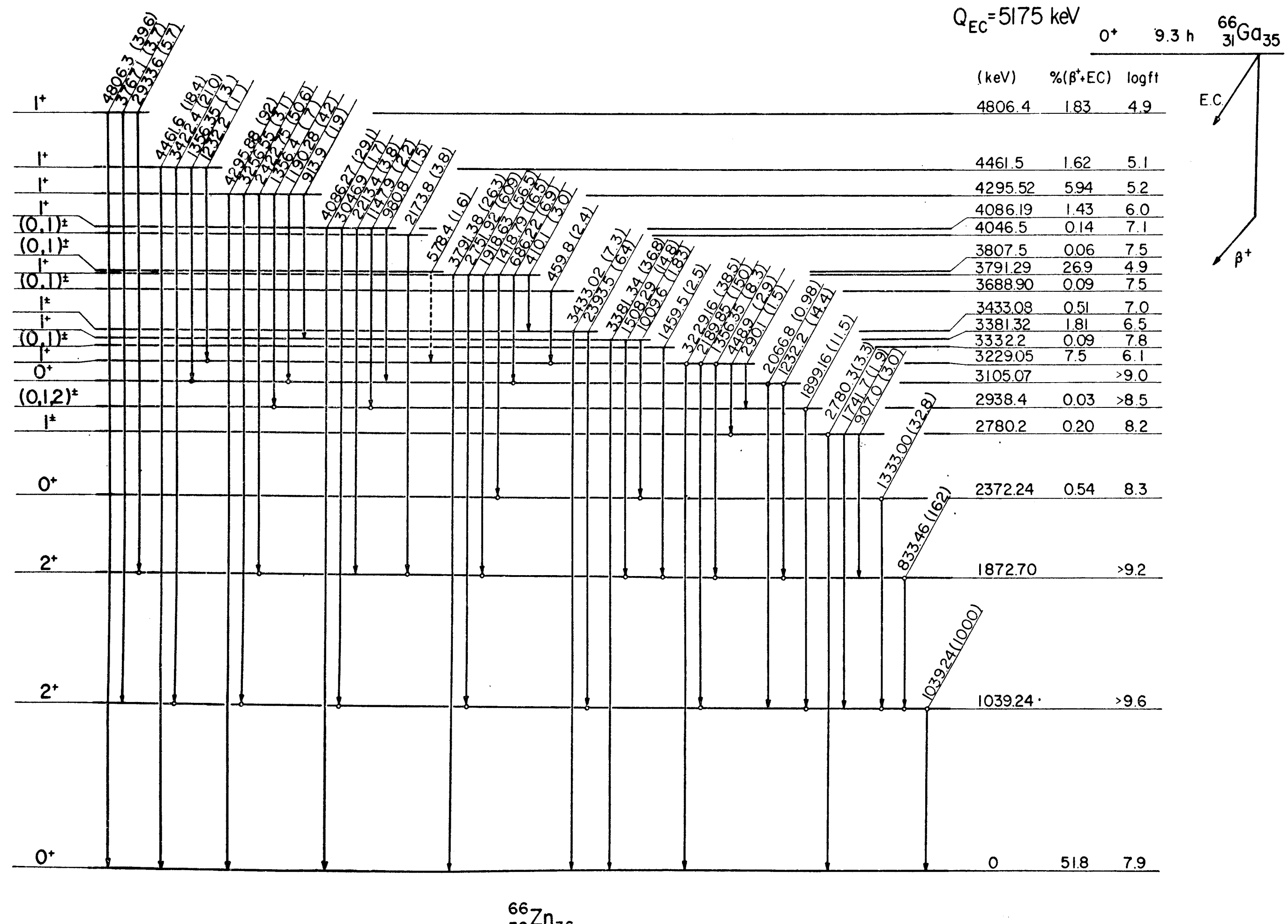

Fig. 13. Proposed decay scheme for 9.3 h ^{66}Ga. The energies are given in keV and the γ-ray intensities in parentheses are relative to the intensity of the 1039.24 keV γ-ray taken as 1000.

1234 and a possible 2067 keV γ-ray was reported by Shikazono and Kawarasaki [26]) in their photoexcitation study of the 7368 keV level of ^{66}Zn by lead capture γ-rays. A level at 3107 ± 2 keV is also reported from (p, p′) studies [22]). In this work a strong coincidence of a 1232 keV γ-ray was observed both with the 1039.24 and 833.46 keV γ-rays (fig. 9b, c). This suggests the presence of a level at 3105.07 keV which is de-excited by the 1232.2 and 2066.8 keV γ-rays and is populated by the 686.22, 1190.28 and a 1356.35 keV γ-ray as evidenced by observed strong coincidences of the latter three γ-rays with the 1160-1300 keV region of the NaI detector (see table 4 and fig. 13).

The 3229.05, 3433.08, 3791.29, 4086.19, 4295.52 *and* 4461.5 keV *levels*: The population of these levels in the ^{66}Ga decay is suggested by the observed strong coincidences of the 2189.85, 2393.5, 2751.92, 3046.9, 3265.55 and 3422.4 keV γ-rays with the 1039.24 keV γ-ray (figs. 9c and 10c) and not with the 833.46 keV γ-ray (figs. 9b and 10b). These levels are further confirmed by the presence of the crossover γ- transitions to the ground state with several additional γ-rays populating established lower-lying levels. The 448.9 keV γ-ray was observed in coincidence with the 2790-2930 keV region in the NaI detector, which suggests a coincidence with the 2780 keV γ-ray and is assigned to populate the 2780.2 keV level. The 290.1 keV γ-ray is assigned to de-excite the 3229.05 keV level and populate the 2938.4 keV level on grounds of good energy agreement. The assignment of the 1356.4 keV line in the scheme deserves detailed discussion. At first it should be pointed out that by energy difference the observed line could be accommodated well within experimental error to de-excite either of the two levels at 4461.5 or 3229.05 keV and perhaps the 4295.52 keV level (see table 3, column 3). The 1356.4 keV line was observed in coincidence with the 1039.24 and 833.46 keV γ-rays and at least in part with the 1232.2, 1899.16 and perhaps the 2066.8 keV γ-rays (figs. 9b,c; 10b,c; 12a, b). The coincidence with the 1899.16 keV γ-ray requires that at least part of the γ-intensity in the 1356.4 keV complex peak be assigned to the transition from the 4295.52 keV level to the 2938.4 keV level. The coincidence between the 1232.2 and 1356.4 keV γ-rays requires further that part of the intensity of the 1356.4 keV complex peak be assigned to a transition from the 4416.5 keV level to the 3105.07 keV level. Only a small fraction of the decays from the 4461.5 keV level proceeds through a 1232.2 keV transition to the 3229.05 keV level as established from the lack of substantial coincidence intensity between the 1232.2 keV line and the 2189.85 keV γ-ray. The assigned intensities of the 1232.2 and 1356.4 keV γ-rays from the 4461.5 keV level and of the 1356.4 keV γ-ray from the 4295.52 and 3229.05 keV levels is based on the present coincidence data subject to restriction from intensity balance.

The assignment of the 1918.63, 1418.79 and 686.22 keV γ-rays to de-excite the 3791.29 keV level is based on observed coincidences with the 833.46, 1333.00 and 1232.2 keV γ-rays, respectively (see figs. 9b, 11a and table 4). The 410.1 keV γ-ray was assigned to de-excite the 3791.29 keV level on the basis of energy agreement.

The 1147.9 keV γ-ray was seen in coincidence with the 1899.16 keV γ-ray (fig. 12a) and thus de-excites the 4086.19 keV level. The 2213.4 and 980.8 keV γ-rays are too weak to be seen in the present coincidence experiment and were assigned to depopulate the 4086.19 keV level on grounds of good energy agreement.

The 1190.28 keV γ-ray was observed in coincidence with the 1160-1300 keV region in the NaI detector which indicates that it is coincident with the 1232.2 keV γ-ray and on this basis it is assigned to de-excite the 4295.52 keV level. The 913.9 keV γ-ray was assigned to de-excite the 4295.52 keV level by energy agreement.

The 3381.32 *and* 4806.4 keV *levels:* The 1508.29 and 2933.6 keV γ-rays were observed in coincidence with the 833.46 and the 1039.24 keV γ-rays (figs. 9b,c and 10b,c) and this suggests levels at 3381.32 and 4806.4 keV. The population of these levels is further substantiated by the 3381.34 and 4806.3 keV γ-rays which are assigned to populate the ground state. The 1009.6 keV γ-ray was observed in coincidence with the 1333.00 keV γ-ray (fig. 11a) and was assigned to populate the 2372.24 keV level. The 3767.1 keV γ-ray was too weak to be observed in the present coincidence experiment but from energy agreement it was assigned to populate the 1039.24 keV level.

The 3332.2 *and* 4046.5 keV *levels*: The 1459.5 and 2173.8 keV γ-rays were observed in coincidence with both the 1039.24 and 833.46 keV γ-rays. This suggests levels at 3332.2 and 4046.5 keV. Of these the 3332.2 keV level may be identified with the 3332 ± 2 keV level observed in the (p, p′) excitation [22]) of ^{66}Zn. The level at 4046.5 keV, which has not been observed before, can be rationalized by (i) the fact that the 2173.8 keV γ-ray was not observed in coincidence with any other γ-ray and (ii) observing that the only other level that could be populated by the 2173.8 keV γ-ray which is consistent with the 833.46 keV coincidence is the level at 2780.2 keV, which in turn can be excluded because the small branching of the 907.0 keV γ-ray in the de-excitation of the 2780.2 keV level would have rendered the coincidence of the 2173.8 keV γ-ray with the 833.46 keV γ-ray undetectable in the present experiment.

The 3688.90 keV *level*: The 459.8 keV γ-ray was observed in coincidence with the 1039.24, 2189.85 and 3229.16 keV γ-rays, but not with the 833.46 keV γ-ray (figs. 9b, c and table 4). All of these observations are consistent with a level at 3688.90 keV de-excited by the 459.8 keV γ-ray. This level may be identified with the level at 3691 ± 2 keV observed in the (p, p′) reaction [22]).

A tentative level at 3807.5 keV: This tentative level is assigned on the basis of an energy agreement with a level at 3809 ± 2 observed in the (p, p′) reaction [22]), and the fact that the 578.4 keV γ-ray was observed in coincidence with the 1039.24 keV γ-ray.

3.3. ASSIGNMENT OF J^π VALUES IN ^{66}Zn AND DISCUSSION

The levels in ^{66}Zn which are believed to be populated in the decay of ^{66}Ga are summarized in table 5. The percent population of these levels by $\beta^+ + $EC as obtained from the γ-ray intensity balance is given in columns 3 of table 5 and is based on a 51.8 % population to the ground state [29]). Corrections due to internal conversion have not been applied since the low-energy γ-rays for which this correction may be noticeable are very weak. The log *ft* values determined in this work are given in the fifth column of table 5 and are based on the EC/β^+ ratios given in the fourth column as calculated from fig. 3 of appendix IV in ref. [39]).

TABLE 5
Levels in ^{66}Zn populated in the decay of ^{66}Ga

Level no.	Level energy (keV)	% population by (β^++EC)	EC/β^+	log *ft*	J^π
0	0	51.8 [a])	0.00074	7.9	0^+
1	1039.24 5	−0.15 41	0.0175	> 9.6	2^+
2	1872.70 6	−0.13 30	0.045	> 9.2	2^+
3	2372.24 8	0.54 4	0.095	8.3	0^+
4	2780.2 2	0.20 2	0.22	8.2	$1^\pm$
5	2938.4 1	0.03 8	0.32	> 8.5	$(0,1,2)^\pm$
6	3105.07 10	−0.008 20	0.52	> 9.0	0^+
7	3229.05 10	7.3 2	0.77	6.1	1^+
8	3332.2 2	0.093 26	1.13	7.8	$(0, 1)^\pm$
9	3381.32 10	1.81 4	1.43	6.5	1^+
10	3433.08 10	0.51 2	1.8	7.0	$1^\pm$
11	3688.90 12	0.090 4	8.2	7.5	$(0, 1)^\pm$
12	3791.29 12	26.9 3	20	4.9	1^+
13	3807.50 12	0.060 4	25	7.5	$(0, 1)^\pm$
14	4046.5 2	0.14 1	3200	7.1	$(0, 1)^\pm$
15	4086.19 12	1.43 3	> 10000	6.0	1^+
16	4295.52 12	5.94 11	∞	5.2	1^+
17	4461.5 2	1.62 8	∞	5.1	1^+
18	4806.4 2	1.83 3	∞	4.9	1^+

[a]) From ref. [27]).

The decay of ^{66}Ga to the ground state of ^{66}Zn is $0^+ \rightarrow 0^+$, a pure Fermi transition, which is isospin forbidden with a log *ft* value of 7.9 and an isospin $T = 3$ admixture in the $T = 2$ ground state of ^{66}Zn of $(4.00 \pm 0.08) \times 10^{-5}$ as measured by Camp and Langer [29]). The J^π value of the 1039.24 and 1872.70 keV levels is 2^+ as determined in the γ-γ directional correlation work of Schwarzchild and Grodzins [28]) and in the photoexcitation correlation work of Shikazono and Kawarasaki [26]). This assignment is consistent with the lower limits of 9.6 and 9.2 for the log *ft* values of these two levels.

The level at 2372.24 is very weakly populated by beta decay with a log *ft* value of 8.3. This value limits J^π for this level to $0^\pm$, $1^\pm$ or 2^-. An upper limit of 0.8 for the intensity of a 2372.24 keV γ-ray to the ground state can be placed from the present experiments relative to the 1039.24 keV γ-ray taken as 1000. The absence of this γ-ray favors a 0^+ assignment. This level has been observed in recent (p, p′) and (p, α) studies [22]) rather strongly. Sen Gupta and Van Patter [27]) have assigned a level at 2383 keV as 0^+ from (p, p′γ) angular correlation studies on ^{66}Zn. These findings strongly suggest that this 2372.24 keV level is indeed 0^+. The high log *ft* value for this $0^+ \rightarrow 0^+$ transition must be explained as due to an isospin forbidden transition.

The level at 2780.2 keV is only weakly populated by β-decay and the log *ft* value of 8.2 suggests $0^\pm$, $1^\pm$ or 2^- as possibilities. The strong γ-transition to the 0^+ ground state helps eliminate $0^\pm$ or 2^- as possibilities. This level at 2780.2 keV with a most probable assignment as $1^\pm$ should be distinguished from the 2.81 MeV level assigned as 3^- by Sen Gupta and Van Patter [27]).

The level at 2938.4 keV does not appear to be populated by β-decay and a log *ft* value of 8.9 has been estimated for this decay. A level at 2941 ± 2 keV has been observed in the ^{66}Zn(p, p′) reaction [22]) and a level at 2940 keV has been reported [26]) in the photoexcitation of ^{66}Zn. The de-excitation of the 2940 keV level was postulated by Shikazono and Kawarasaki [26]) to proceed by γ-rays at 1899 and 2941 keV with relative intensities 2.1 and 1.5, respectively. In the present experiments we find no evidence for a 2938.4 keV γ-ray and an upper limit of 1.0 relative to the 1039.24 keV γ-ray taken as 1000 can be placed from the present data. The present information suggests $(0, 1, 2)^\pm$ as possibilities for this level. The strong decay to the 2^+ level at 1039.24 keV may be used to exclude the 0^- value as a possibility for this level.

The level at 3105.07 keV is not populated by β-decay and a lower limit of 9.0 can be placed for the log *ft* value to this level. A level at 3107 ± 2 keV that is possibly double has been observed [22]) in the (p, p′) and (p, α) study of ^{66}Zn. A level at 3106 keV deexciting primarily by a 1234 keV γ-ray has been reported [26]) from photoexcitation studies of ^{66}Zn in agreement with the present results, and has been assigned as 0^+ on the basis of angular distribution measurements [26]). An upper limit of 0.8 for 3105.07 keV γ-ray to the ground state can be placed from the present data. If the J^π value for this level is indeed 0^+ then this would be a third case of an isospin forbidden $0^+ \rightarrow 0^+$ pure Fermi transition in this nucleide with a log *ft* value at least as high as 9.0.

The levels at 3229.05, 3381.32, 3791.29, 4086.19, 4295.52, 4461.5 and 4806.4 keV are strongly populated by allowed β^+ or EC decay (log $ft < 6.5$). This limits the J^π value of these levels to $(0, 1)^+$. All of these levels have been observed to decay to the 0^+ state by γ-ray emission and this excludes the 0^+ as a possibility.

The levels at 3332.2, 3688.90, 3807.50 and 4046.5 keV are weakly populated by $\beta^+ +$EC with log *ft* values suggesting allowed or first forbidden transitions and this limits the J^π value of these levels to $(0, 1)^\pm$.

Finally, the level at 3433.08 keV was observed to be weakly populated by $\beta^+ +$EC decay with a log *ft* value of 7.0 which suggests an allowed or first forbidden transition. This limits the J^π value to $(0, 1)^\pm$. Of these the $0^\pm$ value can be excluded since this level was observed to decay to the 0^+ level by γ-ray emission.

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