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Gamma Rays from Ga^{65} Decay and Half-Life of the 54-kev Level of Zn^{65}†

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The energies and intensities of the gamma rays following the positron and electron capture decay of Ga^{65} have been determined by means of scintillation spectrometry techniques. At least twenty gamma rays de-excite proposed levels in Zn^{65} at the following energies (in kev): 53.95 ± 0.01, 115.13 ± 0.02, 206 ± 2, 773 ± 10(?), 863 ± 10, 1040 ± 15, 1310 ± 20, 1480 ± 20, 1970 ± 40, and ~2300. A consistent cascade scheme for Zn^{65} is presented which incorporates all of the observed gamma transitions. The first excited state of Zn^{65} has been found to be isomeric with a half-life of 1.65 ± 0.05 μsec.

I. INTRODUCTION

A NUMBER of investigators in the past five years have studied the low-lying levels in Zn^{65} by observing either the radiations following the beta decay[1–4] of Ga^{65} or the neutrons,[5–8] protons,[9] gammas,[10] or conversion electrons[11] from the reactions $Cu^{65}(p,n)Zn^{65}$ and $Zn^{64}(d,p)Zn^{65}$. The agreement among these different studies is quite good for the first three excited states, but there is disagreement at higher energies. Up to 1955, it had been reported[12–16] that Ga^{65} decays predominantly by positron emission with a half-life of 15 minutes. Only a few levels in Zn^{65} were established in this earlier work. The status of this problem as of September, 1959, has been summarized by Way *et al.*[17]

Preliminary results on studies of the decay of Ga^{65} performed at this Laboratory[3,4] indicated that there were probably no gamma rays with energies greater than 1 Mev, but the utilization of improved techniques and apparatus has shown this assumption to be incorrect.

Limitations on the accuracy and completeness of the results obtained in the present work were imposed by a number of experimental difficulties. The principal difficulties were: the considerable complexity of the gamma-ray spectrum as obtained by scintillation techniques, the presence of strong coincident annihilation radiation from the positron decay, the necessity of using the relatively weak sources produced by Van de Graaff irradiation, and the previously undetected presence of a delayed transition from the first excited state of Zn^{65}.

In spite of these difficulties, it has been possible by careful analyses of singles spectra to obtain the energies and intensities of most of the gamma-ray transitions and, by coincidence techniques, to observe the principal cascades. Other weaker cascades have been postulated on the basis of the energy and intensity data. The half-life of the isomeric state has been measured and certain features of the cascade scheme investigated by delayed coincidence measurements. From the results of these studies and the published reports of other investigators, it has been possible to arrive at a reasonably consistent level scheme for Zn^{65}.

II. EXPERIMENTAL PROCEDURES AND APPARATUS

Ga^{65} sources were produced from the $Zn^{64}(p,\gamma)Ga^{65}$ reaction by bombarding thick (10.8 mg/cm^2), isotopically enriched Zn^{64} targets[18] (89.6% Zn^{64}, 10.2% Zn^{66}, 0.2% Zn^{67}, and ~0.01% Zn^{68}) with 1.8-Mev protons from the Radiation Division 2-Mv Van de Graaff accelerator. The Zn was electroplated from a cyanide bath onto a 4-mil Ag foil. The only extraneous activities found to be detectable were from two longer-lived Ga isotopes. It was possible to reduce to negligible amounts the radiation from the Ga^{67} ($T_{\frac{1}{2}}=78$ hr) and Ga^{68} ($T_{\frac{1}{2}}=68$ min) activities by irradiating successively 12 Zn^{64} targets (used directly as sources after irradiation) and by keeping total bombarding times usually less than 30 min/day for each target. All of the nuclear gammas listed in Table I were found to decay with the 15-min half-life of Ga^{65}.

The gammas from the decay of Ga^{65} were studied with a conventional scintillation spectrometer. Both 3-in.×3-in. NaI(Tl) crystals potted in rather thick

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† A preliminary report on the latter part of this work was given at the Houston meeting of the American Physical Society, March, 1960 [L. S. August, Bull. Am. Phys. Soc. **5**, 101 (1960)].

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[18] Obtained from the Stable Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

aluminum cans and $1\frac{1}{2}$-in.$\times$1-in. NaI(Tl) crystals with 1-mil thick aluminum windows were used in these studies. A $1\frac{1}{2}$-in.$\times\frac{1}{2}$-in. anthracene crystal covered with 1-mil aluminum foil was used in working with the higher energy positrons from Ga^{65}. The 3-in.$\times$3-in. crystals were mounted on Du Mont 6363 photomultiplier tubes, and the smaller crystals were mounted on Du Mont 6292 tubes. The photomultipliers were selected such that they showed a negligible change in gain with changes in counting rate that were several times larger than those changes in rate which occurred during the experiments on Ga^{65}. The detectors were unshielded when singles spectra were taken below 700 kev. In obtaining high-energy singles spectra, a 3-in.$\times$3-in. NaI detector was placed in a Pb shield with a conical snout, the shield providing at least a 2-in. thickness of Pb in all directions except for a small solid angle including the source. In obtaining coincidence spectra, two such shielded detectors were used at 90° with respect to each other.

Pulse-height spectra were obtained with a 100-channel analyzer built at this Laboratory.[19] Nonoverloading amplifiers with both differential and integral discriminators were used in the various experimental arrangements. Energy calibrations were made with the gamma rays, x rays, and coincidence radiation from the following sources: Na^{22}, Mn^{54}, Co^{57}, Co^{60}, Ba^{133}, and Cs^{137}. These sources provided calibration peaks at the following energies (in kev): 30, 81, 122, 511, 662, 840, 1173, 1276, 1333, 1787, and 2506. After the very precise bent crystal spectrometer work of Chupp *et al.*[10] was reported, the 115.13-kev transition in Zn^{65} provided an excellent internal calibration point, and the 53.95- and 61.20-kev transitions (unresolved by scintillation techniques) yielded yet another.

The analyses of the singles gamma spectra were carried out in the usual way described in the report by Heath.[20] The crystal response functions for monoenergetic gammas were obtained from the observed pulse-height distributions of the calibration sources listed in the previous paragraph. In obtaining the pulse-height spectra from both the Ga^{65} and the standard sources, an attempt was made to reproduce the same experimental conditions in taking both types of spectra. When a response function with an energy differing from those available was required, the function was obtained by a linear, graphical interpolation between two adjacent ones which were available. The total absolute efficiencies and peak to total ratios for 3-in.$\times$3-in. crystals were taken from Heath's graphs. The corresponding values for the $1\frac{1}{2}$-in.$\times$1-in. size have been determined from Bell's data.[21] The absorption of the gammas by intervening material was also taken into account. In taking a number of singles spectra the source was sandwiched between two 1-in.$\times$1-in.$\times\frac{9}{32}$-in. slabs of Lucite in order to obtain complete annihilation of the positrons near the source. This procedure permitted the intensities of the more prominent nuclear gammas to be expressed in terms of the number of gammas/positron. In obtaining other spectra the minimum amount of absorber necessary to prevent the positrons from reaching the crystal was used in order to obtain incomplete annihilation at the source. This condition was desirable since there were fewer annihilation quanta incident on the crystal which could produce spurious summing effects. Intensities (in γ's/β^+) could be determined for spectra taken without complete annihilation by using the intensities of the more prominent gammas as normalization values.

TABLE I. Energies and intensities of gamma rays following the decay of Ga^{65}.

Results of present work		Results of Mayer-Kuckuk[c]	
Energy (kev)	γ's/100 β^+	Energy (kev)	γ's/100 β^+
[61+54][a]	21.5±1.5[b]		
91±2	$\leq$1.5		
115[a]	60.3±1.8	118±3	65±20
152±2	10.6±1.7		
206±2	3.9±0.8		
511	200	511	200
(658±10)?	$\leq$2.2		
748±8	11.2±1.1	738±6	14±7
863±15	0.7±0.3		
925±10	3.4±0.5	906±8	1.3±0.8
(985±15)?	$\leq$0.3		
1040±10	1.4±0.3		
(1104±15)?	$\leq$0.6		
1195±15	1.4±0.2		
1310±20	0.7±0.3		
1365±15	1.8±0.3	1378±30	6±5
1480±20	0.8±0.3		
1764±40	~0.11		
1855±30	~0.17	1858±30	<1
1970±30	~0.05		
2180±30	~0.15		
2330±50	~0.07		

[a] Energies from reference 10.
[b] The number of 61-kev gammas is 1.5 ±0.5 times the number of 54-kev gammas.
[c] See reference 2.

Delayed coincidence measurements were made with a simple time-to-pulse-height converter that was developed at this Laboratory[22] for use with the 100-channel analyzer. For this experiment two detectors were used with associated amplifiers and differential discriminators. A selected radiation feeding the delayed state was detected by one cyrstal and, by means of an output pulse from the first differential discriminator, ΔE_1, initiated the action of the converter. The selected delayed radiation was detected by a second crystal and, by means of the output pulse from the second discriminator, ΔE_2, terminated the action of converter. The amplitude of the output pulse from the converter was proportional to the time interval between the initiating and terminating pulses.

The time-to-pulse-height conversion system was cali-

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[19] P. R. Shifflett, J. Brotzman, and G. F. Wall, Naval Research Laboratory Report (to be published).
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[21] P. R. Bell (private communication).
[22] J. Brotzman, Rev. Sci. Instr. **31**, 467 (1960).

brated with a suitable double-pulse generator. The relationship between channel number and delay time was found to be linear to within a few tenths of a percent. The calibration of the system, therefore, involved determining the slope of a line by a least squares fit to the channel versus delay time data. The system was calibrated before and after each run, and the values so determined usually varied by less than 1%. Prior to each slope determination the double-pulse generator was calibrated with a crystal-controlled, time-mark generator which had an accuracy of at least ±0.001 cps.

III. GAMMA-RAY SPECTROSCOPY

A. Singles Spectra

Since the pulse-height spectrum from the Ga^{65} gammas extended up to 2.3 Mev, four partial spectra are shown to present the desired detail. Room background has been subtracted in all of the spectra. Figure 1 presents the pulse-height spectrum up to 680 kev taken under conditions which produced complete annihilation near the source. The dashed line is the Compton plus backscatter distributions from all of the gammas whose energies are greater than 500 kev, although the predominant contribution is from the annihilation radiation. The shape of the dashed curve was obtained from a Na^{22} spectrum for which the experimental conditions were the same as that for the Ga^{65} spectrum.

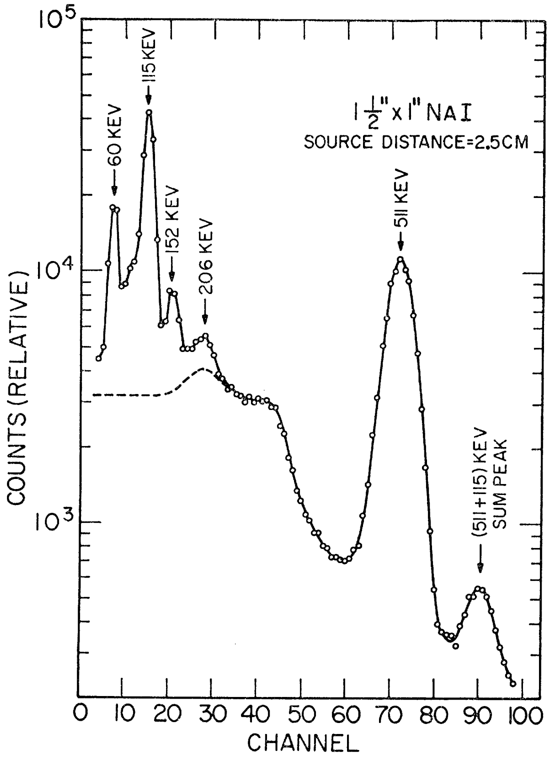

FIG. 1. Low-energy pulse-height spectrum of gamma rays from Ga^{65} decay. The source was surrounded by a sufficient amount of Lucite to insure complete annihilation near the source.

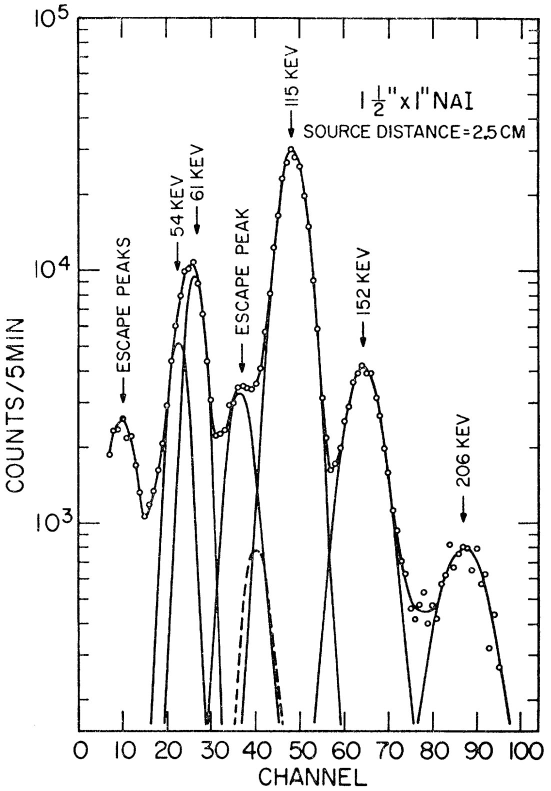

FIG. 2. Low-energy pulse-height spectrum of Ga^{65} gamma rays taken with sufficient absorber to prevent positrons from entering crystal but not enough to produce complete annihilation near the source. The Compton and backscatter distributions from higher energy gamma rays have been subtracted from original spectrum.

In Fig. 2 is shown the spectrum of the lower energy gammas with approximately three times the gain used in taking the data for Fig. 1 and with the Compton and backscatter distributions from higher energy gammas subtracted from the original spectrum using a Na^{22} source in the same geometry. The 54-, 61-, and 115-kev values are from the work of Chupp *et al.*, with their precise values reduced to the number of significant figures that are consistent with the accuracy of the scintillation spectrometer. The peak labeled 60 kev in Fig. 1 is shown resolved into the two lowest energy gammas of Chupp *et al.* From the spectrum of Fig. 2, it is reasonably evident that this peak is composed of more than one gamma because the half-width at half-maximum is only 6% less than the corresponding value for the 115-kev peak whereas it should be 25% smaller. A 90-kev transition has been reported by Bernstein and Lewis[11] in their $Cu^{65}(p,ne)Zn^{65}$ work. Because of the large intensity of the 115-kev gamma and the energy (87 kev) of the escape peak, it is not clear from the data in Fig. 2 that a 90-kev gamma exists in the spectrum. From the present data, only an upper limit to the intensity of a gamma of such energy may be given. The dashed peak in Fig. 2 represents such a limit.

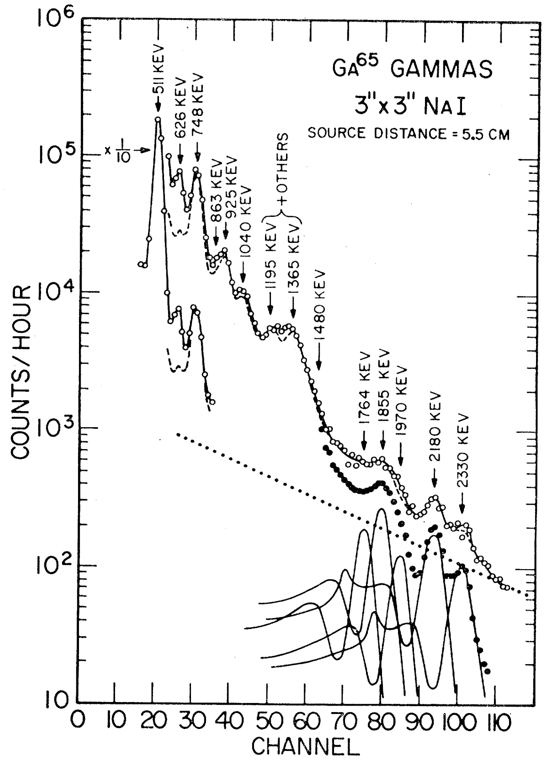

FIG. 3. High-energy pulse-height spectrum of Ga^{65} gamma rays taken with the detector in a Pb shield and with sufficient absorber to prevent positrons from entering the crystal but not enough to produce complete annihilation near the source. The dashed curve is for another spectrum for which the gamma rays were collimated with a piece of lead $\frac{1}{4}$-in. thick with a $\frac{1}{8}$-in. hole through it. The dotted line represents the presumed distribution due to positron bremsstrahlung and annihilation in flight which after subtraction from the original spectrum (open circles) yielded the spectrum shown by the filled circles.

Figure 3 shows the remaining part of the pulse-height spectrum obtained with a shielded detector under conditions which gave somewhat less than complete annihilation. Spectra have been taken at half the gain used for the data shown in order to investigate whether any radiation exists with an energy greater than 2.3 Mev. From such spectra the conclusion is that some radiation of very low intensity does exist beyond 2.3 Mev, but the intensity decreases exponentially with energy and becomes indistinguishable from the room background at about 3.2 Mev. Since no photopeaks were observed above 2.3 Mev either in normally obtained spectra or in those in which the sources were brought to within 1 cm of the crystal in order to enhance sum peaks, this part of the spectrum is regarded as resulting from bremsstrahlung and the annihilation of positrons in flight. A correction to the data of Fig. 3 for this exponential distribution was obtained by extrapolating to lower energies from the points in excess of 2.3 Mev as shown by the dotted line below the original spectrum (open circles). The considerable uncertainty of the slope of this line could have introduced an error of at least a factor of two into the intensity values for gammas with energies greater than 1700 kev. The filled circles show the spectrum that results when this contribution presumed to be due to the positron bremsstrahlung and annihilation in flight is subtracted from the original spectrum. For clarity, only the response functions used to fit the high-energy part of the spectrum are shown.

One further point needs to be discussed in connection with Fig. 3. The dashed curve which falls below the solid one at certain energies represents the spectrum which results when the gammas were additionally collimated with a piece of lead $\frac{1}{4}$-in. thick with a $\frac{1}{8}$-in. hole through it. Decreases in intensity noted in the dashed spectrum suggest coincidence summing exists between 115-kev gammas and others with the following energies (in kev): 748, 925, 1365, 1850, and 2180. The two other decreases in intensity noted at 626 and 1260 kev apparently result from summing between annihilation quanta and 115- and 748-kev gammas, respectively.

Figure 4 shows the pulse-height spectrum obtained

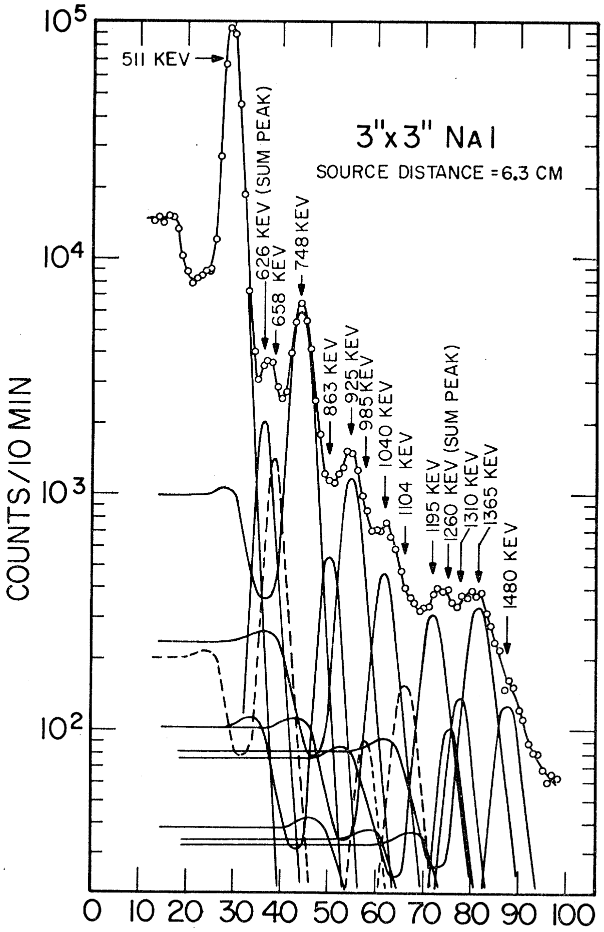

FIG. 4. High-energy pulse-height spectrum of Ga^{65} gamma rays taken with the detector in a Pb shield and with minimum absorber necessary to prevent positrons from entering the crystal.

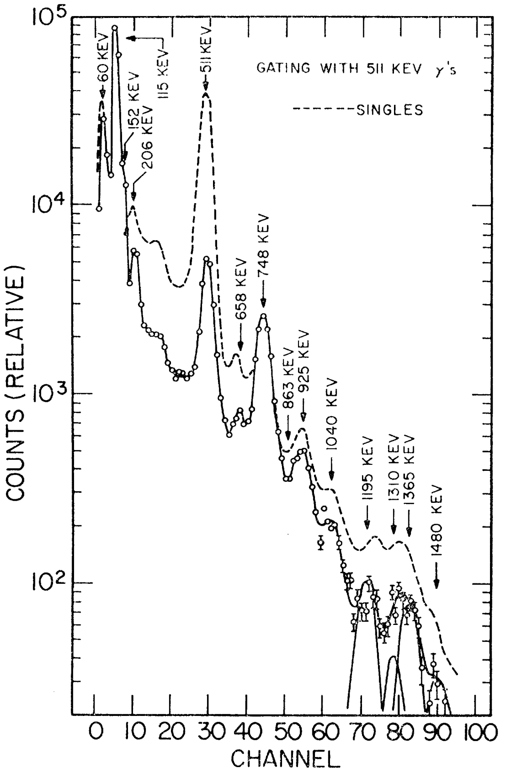

FIG. 5. Coincidence spectrum of Ga^{65} gamma rays gated with annihilation radiation. The singles spectrum (dashed curve) and the coincidence spectrum have been arbitrarily normalized at the 748-kev peak.

in a geometry which provided minimum absorber consistent with preventing the positrons from entering the crystal. There was ~30% less annihilation near the source than occurred for the previous spectrum. The existence of most of the gammas indicated by the solid response functions in Fig. 4 may be inferred from peaks in the experimental spectrum. However, a number of response functions are fitted to the spectrum which do not correspond to obvious peaks but are necessary to account for the observed distribution. Those less apparent transitions that are corroborated by other experiments are shown by solid curves, while the ones less strongly supported by other data are drawn as dashed curves in order to indicate their doubtful nature.

The intensities and energies which have been determined from a number of spectra for each of the various gammas are given in Table I. Mayer-Kuckuk[2] has made the only other known investigation of the gamma rays following the decay of Ga^{65} with scintillation spectrometry techniques. The results of this investigation are also included in the table for comparison. The errors shown in the table for the work done at this Laboratory are estimated errors. These estimates were arrived at by examining the spread in the values of a given quantity from the various spectra, and these values were averaged to yield the tabulated result. Usually the errors quoted are sufficiently large that both the smallest and largest individual values are included within the limits established by the estimated errors. This method leads to large error estimates, but considering the complexity of the problem and the rather large systematic errors which can easily be introduced, this method seems to be more realistic than a statistical approach.

B. Coincidence Spectra

It proved practical to obtain coincidence spectra only for the intense 115-kev gamma rays and annihilation radiation. The 100-channel analyzer accepted pulses from one detector which were in coincidence (within a resolving time of $\sim 2\ \mu$sec) with gate pulses from a differential discriminator used with the other detector. The coincidence spectra obtained with the differential discriminator set over the 511-kev and 115-kev peaks are shown by the solid curves of Figs. 5 and 6, respectively. A singles spectrum (dashed curves) is shown in each figure for comparison. The singles spectrum was taken in the same experimental arrangement as the coincidence spectra. The two spectra in each figure have been arbitrarily normalized at the 748-kev peak. The errors indicated are the calculated probable errors based upon counting statistics.

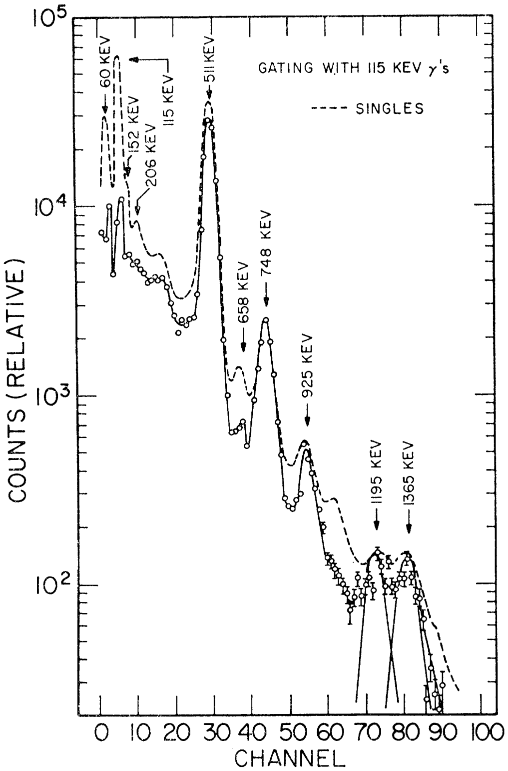

FIG. 6. Coincidence spectrum of Ga^{65} gamma rays gated with 115-kev gamma rays. The singles spectrum (dashed curve) and the coincidence spectrum have been arbitrarily normalized at the 748-kev peak.

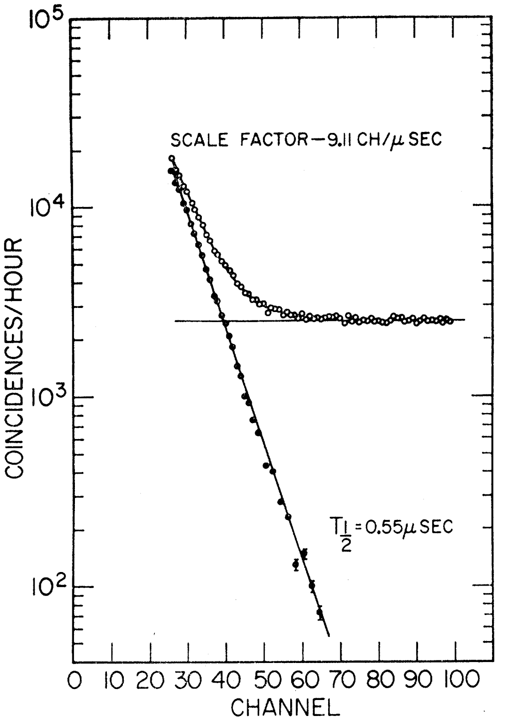

FIG. 7. Delayed coincidence decay curve for 206-kev level of Re^{187}. The system was triggered by 480-kev gamma rays feeding the delayed 206-kev level which is de-excited strongly by 72-kev gamma rays. The decay curve (filled circles) was obtained by subtracting the background from the original data (open circles).

The coincidence spectra gated with the annihilation radiation (Fig. 5) serves as an indication of which levels are fed by positron decay from Ga^{65} in contrast to electron capture. All of the previously observed gamma rays below 1500 kev appear to be in coincidence with the annihilation radiation, as indicated in Table II. One unscattered 511-kev annihilation quantum cannot be in true coincidence with the other in this case because of the 90° geometry. The magnitude of the annihilation peak in Fig. 5 is, therefore, an upper limit to the accidental coincidence rate in this case. The absence of true coincidences between unscattered annihilation quanta and other strong transitions contributes a significant improvement to the spectrum in that the true sum peaks involving annihilation radiation are eliminated. It is evident from Fig. 5 that such summing occurs in the singles spectra at 626 kev and at 1260 kev.

TABLE II. Summary of conclusions from gated spectra.

Gamma energy (kev)	Coincident with 511-kev quanta	Coincident with 115-kev γ's
~60	Yes	No
115	Yes	No
152	Yes	No
206	Yes	No
511	No[a]	Yes
658	Yes?	Yes?
748	Yes	Yes
863	Yes	No
925	Yes	Yes
1040	Yes	No
1195	Yes	Yes
1310	Yes	No?
1365	Yes	Yes?
1480	Yes?	No?

[a] Detectors heavily shielded and at 90° with respect to each other.

The results obtained by gating with 115-kev gammas (Fig. 6) are also listed in Table II. Coincidences involving a possible 658-kev gamma are indicated as doubtful in the table because of the unfortunate position at which the peak occurs in the spectrum. The uncertainties indicated for the higher energy transitions are a reflection of the poor statistics obtainable at this region of the spectrum. It seems clear that coincidences are present, but the energies are somewhat doubtful. The values listed appear to give the most reasonable interpretation of the data.

IV. DELAYED COINCIDENCE STUDIES

In order to test the reliability of the delayed coincidence circuit and to check the accuracy of the data obtained with it, two radioisotopes known to decay to isomeric states were produced and the half-lives of these states measured. The 206-kev state in Re^{187} is known to

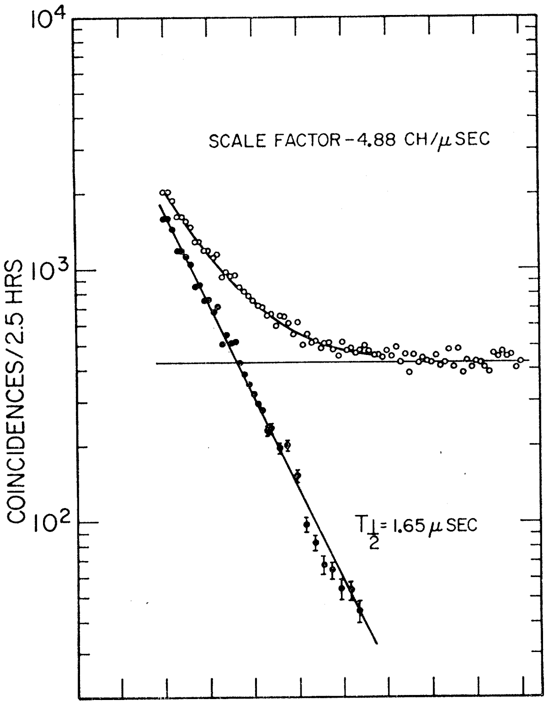

FIG. 8. Delayed coincidence decay curve for the 54-kev level of Zn^{65}. The system was triggered by high-energy positrons which may feed directly and/or indirectly the delayed 54-kev level which is de-excited by 54-kev gamma rays. The decay curve (filled circles) was obtained as explained for Fig. 7.

TABLE III. Summary of delayed coincidence work.

Nuclide	Level energy (kev)	Half-life (μsec) Present work	Half-life (μsec) Previous work	Reference for previous work
Re^{187}	206	0.55 ± 0.02	0.65	23
			0.526 ± 0.012	24
			0.5	25
Zn^{67}	93	9.5 ± 0.5	8.8 ± 1.0	26
			9.4 ± 0.3	27
			9.5 ± 1	28
			8.5	29
			9.3 ± 0.2	30
Zn^{65}	54	1.65 ± 0.05		

be isomeric.[23–25] A W^{187} source was sandwiched between two NaI detectors and the first differential discriminator, ΔE_1, was placed over the 480-kev peak which is produced by one of the strong gammas feeding the 206-kev level. The second differential discriminator, ΔE_2, was placed over the intense 72-kev peak which results from a gamma that de-excites this state. Counts were recorded for one hour, and the resulting distribution is shown in Fig. 7. The open circles are for the original data, which are composed of true delayed coincidences and background. This background is indicated by the horizontal line and results from random pulses that fall into the window ΔE_2 after a trigger pulse has occurred. The background to be subtracted has been determined from the last forty channels of data by a simple iterative process of successive approximations to achieve a flat background and a linear decay on the semilog plot.

The filled circles in Fig. 7 are the delayed coincidences from Re^{187} which are obtained from the original data after the background has been subtracted. The errors indicated on the experimental points are the calculated probable errors based on the counting statistics. A weighted, least squares fit has been applied to the data. The weighing was done according to the statistics of the points. The value obtained (from two runs) for the half-life of the 206-kev level in Re^{187} is 0.55 ± 0.02 μsec.

A similar experiment to that described above was also performed to determine the half-life of the 93-kev isomeric state[26–30] in Zn^{67}. The source used was Ga^{67}. The first differential discriminator, ΔE_1, was placed over the peak produced by the relatively strong 280-kev gammas feeding the 93-kev level, and the other differential discriminator, ΔE_2, was placed over the strong 93-kev peak. The resulting data (from three runs) were analyzed in the same manner as described above, and the half-life of the 93-kev state in Zn^{67} was found to be 9.5 ± 0.5 μsec. The results from both the Re^{187} and Zn^{67} experiments are compared in Table III with the results of other investigators. The comparison shows that the agreement is good and, therefore, that the technique and circuitry are reliable.

The fact that a low-energy excited state in Zn^{65} is isomeric was first established at this Laboratory by placing both differential discriminators over the (54+61)-kev composite peak. The resulting distributions were like the one shown in Fig. 8 with the exception that it was not possible to obtain equally good statistics in runs of reasonable length. The low counting rates were necessitated by the fact that for spectra where most of the pulses have amplitudes above both discriminator levels, a distortion of the delayed coincidence distribution is observed with high counting rates which is thought to be due to a paralyzing effect in the discriminators. It was found that data could be collected more rapidly without distortion by using the higher energy positrons with energies greater than ~800 kev as the initiating radiation. In obtaining the data shown in Fig. 8, a small NaI crystal and an anthracene crystal were used. The first differential discriminator, which was used in conjunction with the anthracene detector, covered the energy region from about 800 kev to 2000 kev. Experiments conducted with and without aluminum absorbers demonstrated that for the region covered by the first differential discriminator, most of the pulses were produced by positrons. The data of Fig. 8 were obtained without absorbers. The positrons entering the NaI crystal through the silver target backing did not appreciably affect the intensity of the relatively strong (54+61)-kev peak for which the second differential discriminator was set.

Two additional delayed coincidence runs were made also using the positrons to trigger the system. For one of these a thin window NaI crystal was used to detect the positrons. By averaging the values from these different runs, the final value for the half-life of the isomeric state in Zn^{65} was found to be 1.65 ± 0.05 μsec. The error assignment is the probable error of the statistically weighted mean. Calibration errors were negligible compared to the statistical errors. The final value also agrees to within the stated errors with the earlier work done with poorer statistics for the case in which the system was triggered by pulses from the (54+61)-kev gammas, thus indicating that no significant systematic error is introduced by gating with positrons.

Delayed coincidences were also observed between 152-kev and ~60-kev gammas. The number of delayed transitions obtained when triggering with either 152-kev or ~60-kev gammas were roughly the same. This result implies that the intensities of the 54-kev and 61-kev gammas are not very different since the intensity of the 152-kev peak is $\sim\frac{1}{2}$ of that due to the (54+61)-kev composite peak.

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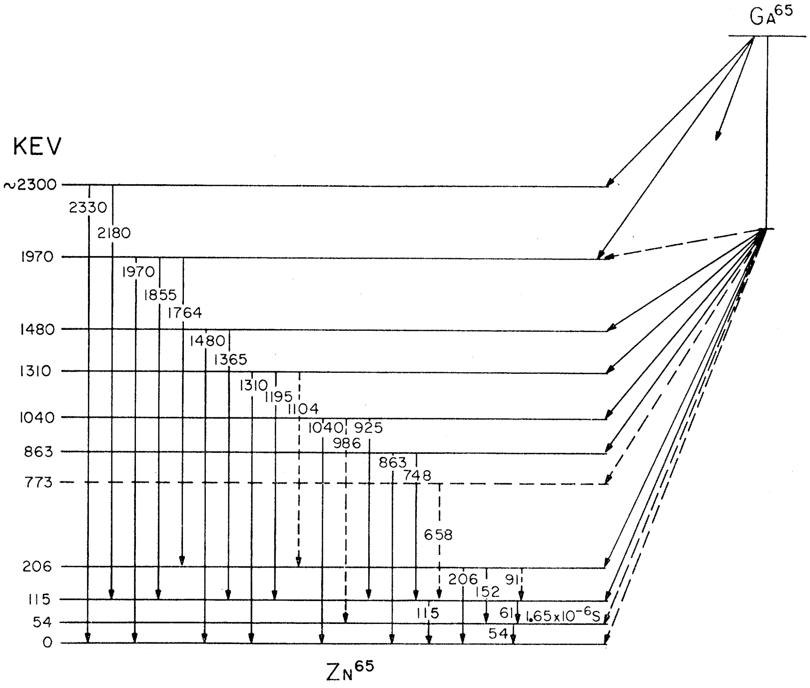

FIG. 9. Level scheme for Zn^{65} with the possible positron and electron-capture branching indicated.

V. DISCUSSION

The proposed level scheme for Zn^{65} which has been inferred from the data that were previously discussed is shown in Fig. 9. The work that has been considered in this report and that of the other investigators mentioned is relatively conclusive for the level scheme up to 1040 kev. At higher energies, however, the level arrangement and the various modes of gamma de-excitation by the numerous transitions reported become more tenuous. The only gammas that have been shown in Fig. 9 are those for which some experimental evidence (see Table I) has been obtained. There could be others that are weak and which are not observable because of the complexity of the spectrum. In the remarks that follow, the evidence for proposing the various levels are given as well as other information pertinent to them.

Levels at $\sim$2300 kev and 1970$\pm$40 kev are proposed entirely on the basis of data such as that shown in Fig. 3. It was not practical because of the very low intensities involved to attempt to get any normal coincidence data at these energies. The coincidence summing arguments mentioned in connection with the discussion of Fig. 3 indicate that the proposed scheme for these levels is a reasonable interpretation. The energy of the 2300-kev level is shown only as approximate because it is not particularly clear that the 2180-kev and 2330-kev gammas go to the lower levels indicated. The 115-kev and ground states are selected mainly because there appears to be coincidence summing at 2300 kev. Nevertheless, it cannot be considered unreasonable to propose that the 2180-kev gamma goes to the 206-kev level and that the 2330-kev gamma goes to the 54-kev level. In the latter case, however, one would not expect much summing at $\sim$2300 kev because of the relatively lower intensity of the 54-kev transition and because it is delayed. The assignment of a level at 1970 kev appears to be reasonable in spite of the complexity of the pulse-height spectrum from 1700 to 2000 kev. These two levels apparently are fed almost exclusively by electron capture. From the measured maximum energy of the proposed ground-state positron group reported by Daniel,[1] a positron transition would be expected to occur to the 1970-kev level with a maximum energy of roughly a few hundred kilovolts. For such a transition, however, it is expected theoretically[31] (for an allowed case) that only about 1% of the disintegrations to this state would be by positrons. The levels lower than these two are fed by both electron capture and positrons. The proposed levels at 1.97 and 2.30 Mev are possibly the same ones reported by Shull and Elwyn[9] at 1.85 Mev and 2.40 Mev from their $Zn^{64}(d,p)Zn^{65}$ work. The assigned percentage errors for the various Q values measured by Shull and Elwyn range from 1% to 2%. Brugger *et al.*[6] reported a level at 1.93$\pm$0.02 Mev, and Mayer-Kuckuk proposes one at 1.98$\pm$0.03 Mev. These last two values probably refer to the same level reported in the present paper at 1.97$\pm$0.04 Mev.

The 1.48$\pm$0.02-Mev and 1.31$\pm$0.02-Mev levels are proposed on the basis of the spectra discussed in Sec. III. Mayer-Kuckuk reports a single level at 1.38$\pm$0.03 Mev, Brugger *et al.* report a level at 1.26$\pm$0.03 Mev,

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[31] G. J. Nijgh, A. H. Wapstra, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (Interscience Publishers, Inc., New York, 1959), Chap. 5, p. 65.

and Shull and Elwyn report one at 1.28 Mev. The 1.31-Mev level proposed in the present paper is apparently the same level reported by Shull and Elwyn as well as the one reported by Brugger *et al.* The existence of a 1.49-Mev level could account for the level energy reported by Mayer-Kuckuk, if an unresolved average of the gamma transitions from the two levels proposed in the present report were observed. The coincidence summing at 1.26 Mev makes the study of this energy region difficult.

A (1040±15)-kev level has not been reported by other investigators. It is proposed in the present work on the bases of analyses of singles and coincidence spectra as have been shown, and on the energy addition of the 925-kev and 115-kev gammas which were found to be in coincidence. Intensity considerations were also of importance, especially with regard to the change in intensity noted for the 1040-kev peak when spectra were taken with and without a collimator. Mayer-Kuckuk reports a (906±8)-kev gamma which is presumably the same gamma that has been reported as 925 kev in this paper. Mayer-Kuckuk does not place the 906-kev gamma in the decay scheme which is given.

The (863±10)-kev level is proposed as a result of considerations which are the same as those discussed in connection with the 1040-kev level. The implications of the coincidence experiments are clear for this level, and the addition of the 748-kev and 115-kev gammas, which are in coincidence, strongly support the existence of an 863-kev state. The results of Mayer-Kuckuk agree reasonably well with the present work for the 863-kev state. Mayer-Kuckuk reports a level at 856 kev as a result of coincidence measurements between a (738±6)-kev gamma and a (118±3)-kev gamma. Considering the errors given by Mayer-Kuckuk and those shown in Table I of this report for the 748-kev gamma, the two investigations are clearly in agreement for this level.

The difficulties concerning the possible existence of a 658-kev transition were mentioned in the previous discussion. The coincidence data (Figs. 5 and 6) indicate that such a gamma feeds the 115-kev level directly, implying a possible level at 773±10 kev. The maximum upper limit on the intensity that a crossover gamma could have from a possible level at 773 kev appears to be roughly 10% of the intensity of the 748-kev gamma, or $\sim 1\ \gamma/100\beta^+$. Brugger *et al.* report a (780±30)-kev level in Zn^{65} in their final data, although in a preliminary account of this work[5] given in 1954 an energy of 860 kev was assigned to a Zn^{65} level. Shull and Elwyn report a level at ~820 kev and further suggest that two levels are probably involved. Considering what has been written above about a possible 773-kev state in Zn^{65}, the existence of levels at 863 kev and 773 kev seems reasonable and appears to be a likely explanation for the large difference in energy between the 780-kev value of Brugger *et al.* and the other reported values of 856 kev and 863 kev.

The delayed coincidence work clearly indicates that the first excited state of Zn^{65} is isomeric. The 54-, 115-, and (206±2)-kev energy assignments for the first three excited states and the cascade scheme for these states are proposed as a result of the energy measurements of the 152- and 206-kev transitions given in Table I, the observed delayed coincidences between (1) ~60- and ~60-kev gammas, and (2) 152- and ~60-kev gammas, and the precise energy measurements of Chupp *et al.* The proposed scheme for the first three excited states is essentially the same as that given by Bernstein and Lewis.

The positron and electron capture transitions to the various levels of Zn^{65} are indicated only qualitatively in Fig. 9 because of uncertainties which persist concerning some of the details of the decay of Ga^{65}. The positron transitions about which some doubt clearly exists are indicated by dashed lines. The uncertainties involving possible transitions to weakly fed 1970- and 773-kev levels follow from previous comments. The indicated confusion involving positron transitions to the ground state and first excited state of Zn^{65} results from the fact that the total conversion coefficient for the 54-kev transition is obviously large (see Table I). Others[1,11,15] have also reported this coefficient as being large, but an accurately measured value is not available. The half-life measurement of the 54-kev level does not clarify the situation since the value determined, 1.65 μsec, is compatible with either an $E2$ or $M1+(E2)$ transition.[32] The total conversion coefficient for an $E2$ transition is ~7.0 while that for an $M1$ is ~0.5.[33]

From the intensities (Table I), the decay scheme (Fig. 9) Daniel's measurement of the energy of the ground-state positron transition, and the theoretical electron capture/positron ratios for allowed transitions, it is possible to give the following estimates for the fraction of positrons which go to the levels at 1480, 1310, 1040, 863, 206, and 115 kev, respectively: ~0.01, ~0.01, 0.036, 0.094, 0.14, and 0.50. The remaining positrons (~20%) are divided in some way between the ground state and the 54-kev level.

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