Decay Scheme of Gallium-72†

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The decay of Ga^{72} has been investigated with scintillation spectrometers, both single and in coincidence. Evidence has been found for the existence of levels in Ge^{72} at 0.69, 0.84, 1.46, 1.73, 2.06, 2.39, 2.51, 2.82, 3.04, 3.32, and 3.34 Mev. The 0.3-μsec isomeric state has been definitely determined to be the first excited level at 0.69 Mev and, as previously indicated, requires a spin of 0 and even parity. Spins and parities of the other levels of Ge^{72} are discussed.

I. INTRODUCTION

THE first excited states of even-even nuclei are known[1–4] to have predominately a spin of two and even parity. Four of the five known exceptions to this general rule (O^{16}, Ca^{40}, Zr^{90}, Pb^{208})[5–8] apparently occur when both neutrons and protons form closed shells.[3] The other possible exception is Ge^{72}.

While studying the decay of Ga^{72}, Bowe *et al.*[9] found an isomeric state, since confirmed,[10,11] which they assigned to a 0^+ first excited state in Ge^{72} on the basis of its half-life (0.3 μsec), its decay energy (0.7 Mev), the lower limit of conversion coefficient (>2), and the apparent absence of delayed gamma rays. Because of the unusual nature of this transition, we believed that it was important to assure its position in the level scheme of Ge^{72} by studying the decay of Ga^{72} and As^{72}. The detailed results on As^{72} will be reported at a later date.

When the present work was begun, the most extensive investigation of Ga^{72} had been completed by Mitchell *et al.*[12] and by Haynes.[13] Except for some detailed studies of the high-energy gamma rays from Ga^{72},[14,15] no further work had appeared on Ga^{72} until the recent exact measurements of the beta- and gamma-ray spectra by Johns *et al.*,[16] which were done concurrently and independently of our work. These measurements have helped to clarify for us some of the finer details of the Ga^{72} decay, as will be mentioned below.

II. SOURCE PREPARATION

Several Ga^{72} (14.2-hr) sources were obtained by slow neutron irradiation of natural gallium oxide using moderated neutrons from the 60 in. cyclotron of the Crocker Radiation Laboratory, University of California, Berkeley. Bombardments were carried out for three or four hours and sufficient time elapsed before use of the sources to allow for the decay of the 20-min Ga^{70}. There was no detectable radiation left in these sources after approximately two weeks.

Other Ga^{72} sources were obtained from the Oak Ridge National Laboratory, where natural gallium oxide was irradiated for one week. After one week these sources showed the presence of a predominantly beta-emitting contaminant (end-point energy about 1.8 Mev) with a half-life of 15 days. The presence of this activity had a negligible effect on our measurements.

III. APPARATUS

The gamma-ray counters consisted of NaI(Tl) cylinders, $1\frac{1}{2}$ inches long and $1\frac{1}{2}$ inches in diameter, mounted commercially[17] with magnesium oxide reflectors and placed on DuMont 6292 photomultipliers. The resolution of these detectors was 8 to 9 percent full width at half-maximum for the 0.661 Mev gamma ray of Cs^{137}. Our beta-ray detectors were $\frac{1}{4}$ inch to $\frac{1}{2}$ inch thick, 1 inch diameter anthracene cylinders mounted on DuMont 6292 photomultipliers. These detectors had approximately 15 percent resolution for the conversion electrons of the Cs^{137} gamma ray.

The electronic equipment consisted of nonoverload amplifiers,[18] a conventional fast-slow coincidence circuit

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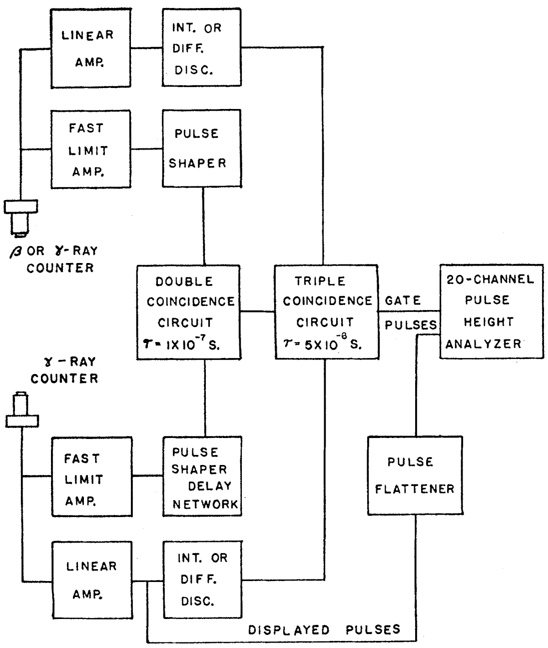

FIG. 1. Arrangement of coincidence circuitry.

with variable delay and a gated 20-channel pulse-height analyzer.[19] A block diagram of the apparatus is shown in Fig. 1. A Higinbotham-type stabilized high-voltage supply,[20] was used for the photomultipliers.

IV. EXPERIMENTAL METHOD AND RESULTS

In order to understand the decay scheme of Ga^{72}, we determined (a) the gamma-ray spectrum, (b) the beta-gamma coincidence spectrum, (c) the gamma-gamma coincidence spectrum, (d) the conversion electron-delayed gamma coincidence spectrum. We assumed that the beta-ray spectra had been measured with sufficient precision and consistency by other investigators.[12,13,16] Table I gives a summary of these beta-ray spectra.

TABLE I. Beta-ray spectra of Ga^{72}.

End point energies (Mev)			Intensities (percent)			Log*ft*[a]
Johns *et al.*[b]	Haynes[c]	Mitchell *et al.*[d]	Johns *et al.*[b]	Haynes[c]	Mitchell *et al.*[d]	
3.166	3.15	3.17	8.3	9.5	8	8.9
2.529	2.52	2.57	9.2	8	8	8.6
...[e]	...	1.74	...	...	3	...
1.508	1.48	1.45	10.0	10.5	7	7.5
0.959	0.955	1.00	30.8	32	26	6.3
0.637	0.64	0.74	41.7	40	23	5.5
...	...	0.56	...	...	25	...

[a] The energies and intensities of Johns *et al.* have been used in computing the log*ft* values.
[b] See reference 16.
[c] See reference 13.
[d] See reference 12.
[e] The possibility of a weak beta-ray spectrum between 1.5 and 2.5 Mev has not been excluded by the work of Johns *et al.* (M. W. Johns, private communication).

In Fig. 2 is presented the proposed decay scheme. Although justification of this scheme will follow in Sec. V, it is presented here to facilitate discussion of the measurements.

A. Gamma-Ray Spectrum

The gamma-ray spectrum was determined both with a single crystal of NaI(Tl) and with a three-crystal pair spectrometer.[21] In the case of the single crystal, the gamma rays from the source were collimated by a 4 inch long channel in lead, $\frac{3}{8}$ inch in diameter. Beta rays were eliminated by a $\frac{1}{16}$ inch thick copper absorber and by the $\frac{1}{32}$ inch thick aluminum crystal container. Figure 3 shows the complete gamma-ray spectrum, as measured with the 20-channel pulse-height analyzer, using overlapping energy ranges and various gains. Table II gives the results of an analysis of the gamma-ray spectrum, which was performed in the customary way of fitting previously determined single gamma-ray spectra to the measured curve. The areas of the photoelectric peaks were then measured and corrected for the ratio of peak area to the total area under the spectrum and for the detection efficiency of NaI.[22] Agreement with other workers[12,13,16] is for the most part quite good. According to our results a possible 0.69-Mev gamma ray could not be present to an intensity greater than 2 percent of that of the 0.835-Mev gamma ray.

Table III gives the analysis of the pair spectrometer data. The intensity of the 2.21-Mev gamma ray has been normalized to 41 in order to facilitate comparison with Table II.

B. Beta-Gamma Coincidence Spectrum

For these measurements sources of Ga^{72} were mounted on cellophane tape and placed between an anthracene crystal and a NaI(Tl) crystal, the latter being shielded by $\frac{1}{16}$-inch copper. The 20-channel analyzer was gated by triple coincidences of the circuit shown in Fig. 1. In order to find out which gamma rays were in coincidence with the various beta rays (see Table I), the anthracene detector was set successively to record electrons with energies greater than (a) 0.05, (b) 0.80, (c) 1.10, (d) 1.65, (e) 2.60 Mev. Because of the finite resolution of the anthracene counter (approximately 15 percent at 0.62 Mev), electrons with energies slightly smaller than the nominal values given above were detected at each setting.

Figure 4 shows the beta-gamma coincidence spectra,

[19] We are very indebted to A. Ghiorso and B. Larsh for providing us with detailed circuit diagrams for this analyzer.
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[22] The calculations of M. J. Berger and J. A. Doggett, Phys. Rev. 99, 663(A) (1955); Rev. Sci. Instr. (to be published), were most helpful in the analysis of our data. We are very indebted to Dr. M. J. Berger for furnishing us these calculations prior to publication.

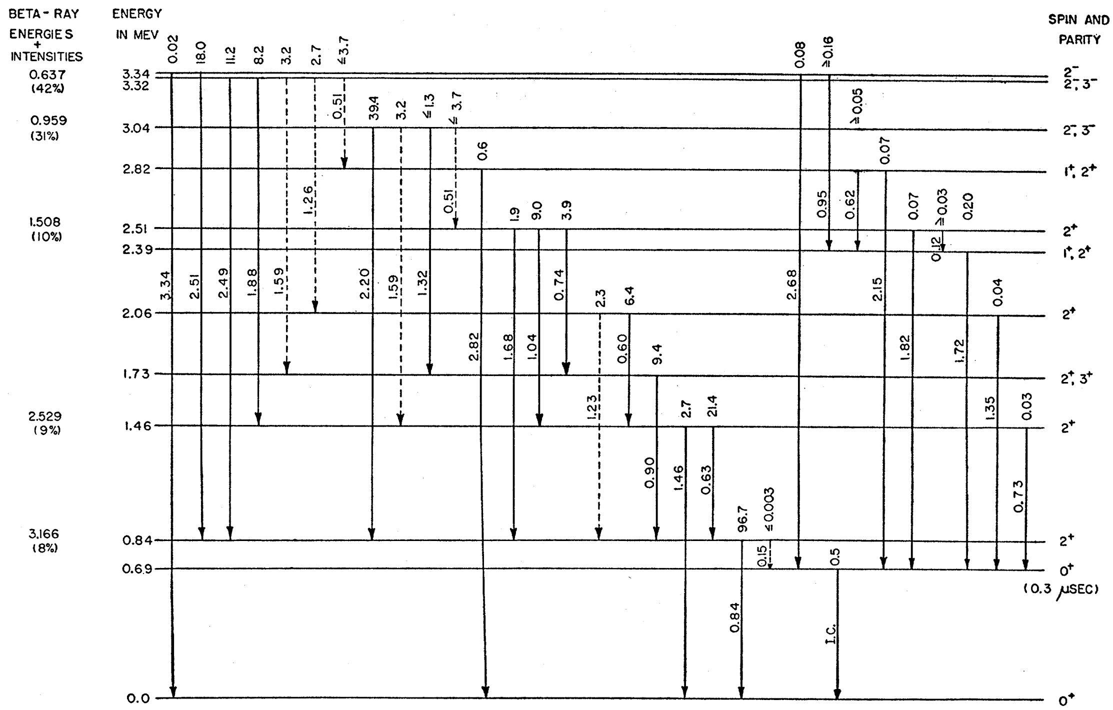

FIG. 2. Proposed level scheme of Ge^{72}. Beta-ray energies and intensities are those of Johns, Chidley, and Williams (see reference 16). For each gamma ray the energy in Mev and intensity in percent decay is shown. The intensities of gamma rays shown in dotted lines are uncertain. Except for the two lowest states, spin assignments are tentative.

each taken in several overlapping ranges and normalized to the same source strength. Table IV gives the analysis of the relative coincident gamma-ray intensities at each setting. Gamma-gamma coincidences contributed at most 10 percent of the total coincidences, which was considered negligible for this work. Chance coincidences were also negligible in every case. On the other hand, because of the close geometry, there was a certain amount of solid angle addition in the gamma-ray counter of 0.63 plus 0.84 Mev, 0.63 plus 1.05 Mev, 0.84 plus 1.05 Mev gamma rays giving rise to increased intensities of the 1.47-, 1.68-, and 1.89-Mev lines. Corrections for this effect have been included in Table IV. Furthermore, there was a certain amount of solid angle addition of the Compton electrons of the 0.84-Mev gamma ray and beta rays in the beta counter. Therefore at a given beta discriminator setting some beta rays of energies up to 0.64 Mev less than the nominal bias energy were detected in the beta counter. We believe that this accounts for the appearance of some of the high-energy gamma rays in the >0.80 Mev and >1.10 Mev beta-gamma coincidence experiments (see Table IV).

C. Gamma-Gamma Coincidence Spectrum

By reference to Figs. 2 and 3 it can be seen that more information about the decay scheme could be gained from gamma-gamma coincidence experiments. Sources of Ga^{72} were placed in the center of absorbers consisting on both sides of $\frac{1}{16}$ inch copper, to absorb beta rays, and of $\frac{3}{64}$ inch lead to attenuate backscattered gamma rays. This sandwich was mounted between two $1\frac{1}{2}$ inch diameter, $1\frac{1}{2}$ inch long, NaI(Tl) counters. Using the circuitry of Fig. 1, the discriminating gamma-ray

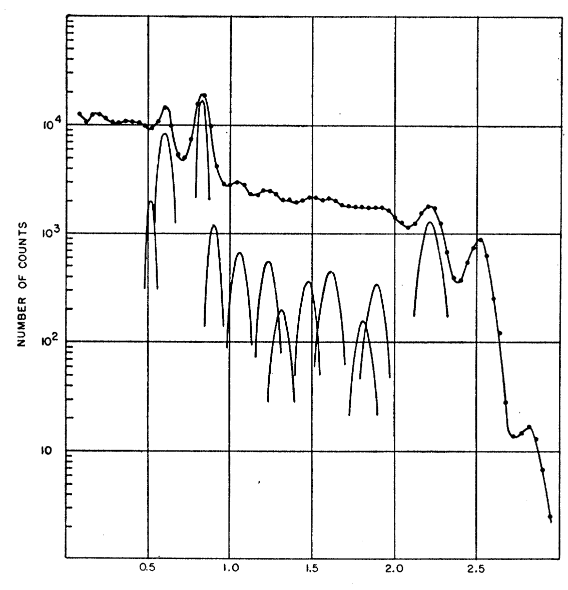

FIG. 3. Gamma-ray spectrum obtained with single NaI(Tl) crystal spectrometer. The analysis of the spectrum yielded the photopeaks as shown.

TABLE II. Analysis of single-crystal gamma-ray spectrum.

Gamma-ray energy (Mev)	Relative intensity	Gamma-ray energy (Mev) Johns *et al.*[a]	Haynes[b]	Mitchell *et al.*[c]	Relative intensity Johns *et al.*[a]	Haynes[b]	Mitchell *et al.*[c]
0.32±0.01	≤0.8						
0.39±0.01	≤1.1						
0.44±0.01	≤1.8						
0.51±0.01[d]	3.7±0.8						
		0.6006			8		
0.63±0.01[e]	28.5±1.4	0.6302	0.63	0.631	24.5	24	54
0.72±0.02	2.0±1.0	0.7862		0.676	3.7		5
		0.812			3.5		
0.835[f]	100	0.8345	0.84	0.835	100	100	100
0.91±0.02	7.0±2.0	0.8943			11		
1.04±0.01	9.2±1.0	1.0495	1.05	1.05	7	4.5	15
		1.231			1.4		
1.24±0.02	5.2±1.0	1.268	1.20		1.7	<2	
1.32±0.03	≤1.3			1.30			
1.46±0.01	2.8±0.6	1.465		1.47	4.6		}23
1.59±0.02	7.8±0.8	1.598	1.59	1.57	6.4	4.5	
1.79±0.03	≤2.0						
1.88±0.01	8.4±0.4	1.860	1.87	1.81	6.8	7.8	10
2.20[f]	40.8±2.1	2.201	2.21	2.18	34.5	33	33
2.40±0.02	≤2.0						
		2.490			11.5		
2.50[f,g]	30.2±1.5	2.508	2.51	2.50	19.5	26.5	15
2.82±0.01	0.6±0.1	2.849			0.5		
		3.100[h]			0.04		
		3.340[h]			0.02		

[a] See reference 16.
[b] See reference 13.
[c] See reference 12.
[d] This could be annihilation radiation produced in the lead collinator by the high-energy gamma rays.
[e] The shape of this line indicates that it is definitely complex. The data is compatible with lines at 0.60 and 0.63 Mev with intensities of 6.5 and 22.0 percent, respectively.
[f] The energies of these gamma rays has been assumed for calibration purposes.
[g] This line has been resolved by Hedgran and Lind (see reference 15) to be two lines of 2.508 and 2.491 Mev with an intensity ratio of 8 to 5 respectively.
[h] Bishop, Wilson, and Halban (see reference 14) have found gamma rays of 3.05±0.1 and 3.35±0.1 Mev with intensities of 0.13 and 0.03 percent per disintegration. The 3.100-Mev gamma ray found by Johns *et al.* (reference 16) may indicate another level in Ge^{72} at 3.100 Mev.

counter was set differentially at the energies (a) 0.63, (b) 0.84, (c) 0.95, (d) 1.47, (e) 1.72, (f) 2.20, (g) 2.50 Mev. The channel width of the differential discriminator was approximately 5 percent of each energy.

Figure 5 shows the coincident gamma-ray spectra, except for case (g) which appeared to be identical with case (f). All the curves were normalized to the same source strength. It is well known that at each discriminator setting, not only the photopeak of the appropriate gamma ray, but also the Compton electrons from higher energy gamma rays give rise to coincidences. In order to obtain the "pure" 0.84-Mev gamma-gamma spectrum, curve *c*, Fig. 5, was subtracted from curve *b*. The result is shown in Fig. 6, curve *a*. Similarly the "pure" 0.63-Mev gamma-gamma coincidences were obtained by subtracting curve *c*, Fig. 5, and an appropriate fraction of curve *a*, Fig. 6 (to take into account the effect of Compton electrons from the 0.84-Mev gamma ray under the 0.63-Mev photopeak) from curve *a*, Fig. 5. Even with these corrections, the 0.63-Mev curve contains some contributions from the 0.60 Mev gamma ray. However the result is shown in Fig. 6, curve *b*. Analysis of the "pure" 0.84- and 0.63-Mev gamma-gamma coincidences yields the results shown in Table V, which have been corrected for solid angle addition and absorption in the lead. Chance coincidences were negligible.

TABLE III. Analysis of gamma-ray spectrum from pair spectrometer.

Gamma-ray energy (Mev)	Relative intensity
1.6 ±0.1	8±2
1.8 ±0.1	10±2
2.20±0.02	41[a]
2.40±0.05	≤2
2.50±0.02	29±2
2.80±0.05	≤0.5

[a] The intensity of the 2.20-Mev gamma ray has been normalized to 41 in order to facilitate comparison with Table II.

Curves *c* to *e* of Fig. 5 were not analyzed into "pure" curves, because of the excessive contribution of Compton electrons from higher energy gamma rays. Qualitatively it can be shown from the curves of Fig. 5 that the 1.47-Mev gamma ray (curve *d*) is in coincidence with the 1.90-, 1.59-, 1.30-, and 1.05-Mev gamma rays. The 1.72-Mev curve (*e*) indicated coincidences with the 1.46-Mev gamma ray, presumably due to the Compton electrons of the 1.90-Mev gamma ray. The 2.20-Mev gamma ray (curve *f*) is in coincidence with the 0.84-Mev gamma ray, as is the 2.50-Mev gamma ray (not shown).

D. Beta-Delayed Gamma Coincidence Spectrum

In order to find the position of the isomeric state in the level structure of Ge^{72}, we searched for gamma rays

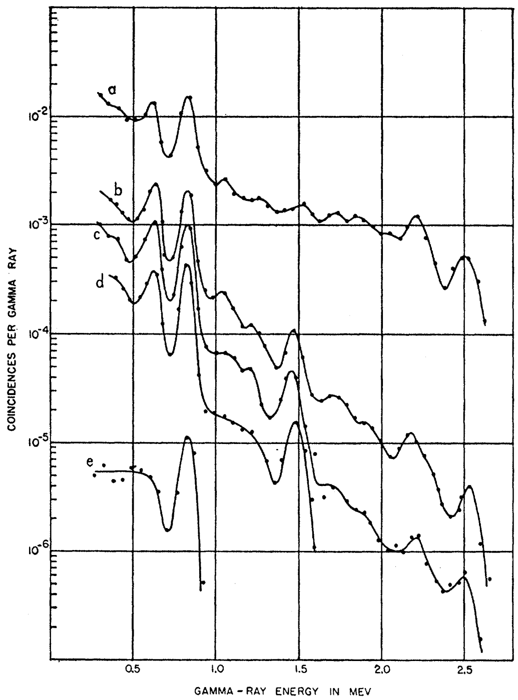

FIG. 4. Beta-gamma coincidence spectrum. The different curves were taken with the beta discriminator set to record beta rays whose energies were greater than or equal to (a) 0.05, (b) 0.80, (c) 1.10, (d) 1.65, (e) 2.60 Mev. The curves were normalized to the same source strength.

preceding or following this state. It is well known[9,12,13,16] that this state decays by emission of 0.68-Mev conversion electrons. Thin sources of Ga^{72} were placed between an anthracene and a NaI(Tl) counter, as described in Sec. IV B (also see Fig. 1). The beta-ray detector was biased differentially to detect only pulses around 0.68 Mev with 10 percent channel width. At first the gamma-ray counter was delayed by different times, giving a typical delayed coincidence curve and indicating an isomeric state of half-life consistent with 0.3 μsec.[9–11] With the gamma counter delayed by

TABLE IV. Analysis of beta-gamma coincidence spectrum.

Gamma-ray energy (Mev) \ Beta-ray energies	Relative gamma-ray intensities (a) >0.05 Mev	(b) >0.80 Mev	(c) >1.10 Mev	(d) >1.65 Mev	(e) >2.60 Mev
0.63	30±4	61 ±10	50 ±10	35±5	···
0.72	7±3	···	···	···	···
0.84	100	100	100	100	100
0.90	10±3	···	···	···	···
1.05	14±2	10 ±2	3 ±1	···	···
1.24	8±2	3.0 ±0.6	3 ±1	···	···
1.47	2±2	5.7 ±1.0	8.5 ±1.5	5.7±1	···
1.59	4±2	···	···	···	···
1.68	···	1.7 ±0.8	0.8 ±0.3	···	···
1.90	8±2	0.7[a]±0.4	<0.1[a]	···	···
2.20	39±5	3.1 ±0.5	0.7[a]±0.3	···	···
2.50	32±3	1.8[a]±0.4	0.5[a]±0.2	···	···

[a] The appearance of these gamma rays is probably due to beta-gamma solid angle addition in the beta counter. (See text.)

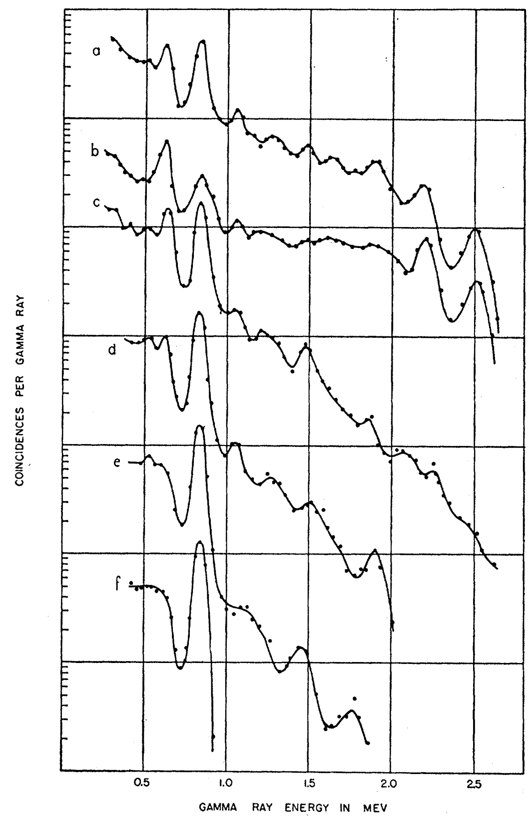

FIG. 5. Gamma-gamma coincidence spectrum. The curves correspond to settings of the gamma-ray discriminator at (a) 0.63, (b) 0.84, (c) 0.95, (d) 1.47, (e) 1.72, and (f) 2.20 Mev. The number of coincidences per gamma ray at 0.84 Mev were (a) 5.3×10^{-4}, (b) 2.9×10^{-4}, (c) 1.6×10^{-4}, (d) 1.6×10^{-4}, (e) 1.6×10^{-4}, (f) 1.3×10^{-4}.

0.5 μsec with respect to the beta counter, which eliminated the detection of all prompt coincidences, the coincident gamma-ray spectrum was measured. Several measurements all normalized to the same source strength, were taken and the average is shown in Fig. 7, curve *a*. The coincident gamma-ray spectrum was then measured again, this time with the beta counter

TABLE V. Energies and relative intensities from the 0.84- and 0.63-Mev gamma-gamma coincidence spectra.

0.84-Mev gamma-gamma coincidence spectrum Energy (Mev)	Intensity[a]	0.63-Mev gamma-gamma coincidence spectrum Energy (Mev)	Intensity[b]
0.63±0.02	29.1±2.5	0.62±0.02	2.6±1.4
0.77±0.04	5.3±0.8	0.84±0.01	24 ±3
0.89±0.02	11.1±1.4		
1.05±0.02	8.0±1.0	1.05±0.02	5.3±1.4
1.30±0.05	2.5±1.2	1.30±0.05	3.5±1.0
1.62±0.05	3.4±2.1	1.48±0.02	3.0±1.0
1.87±0.02	6.1±2.0	1.64±0.05	2.3±1.1
2.20±0.02	39.2±5.5	1.79±0.05	2.7±1.3
2.50±0.02	31.8±3.3	1.90±0.03	8.4±1.5

[a] The intensities have been normalized using the intensity of the 2.20-Mev gamma ray from the collimated gamma-ray spectrum.
[b] The intensities have been normalized using the fraction of the 0.84-Mev gamma-ray intensity which is in coincidence with the combined 0.63- and 0.60-Mev gamma ray.

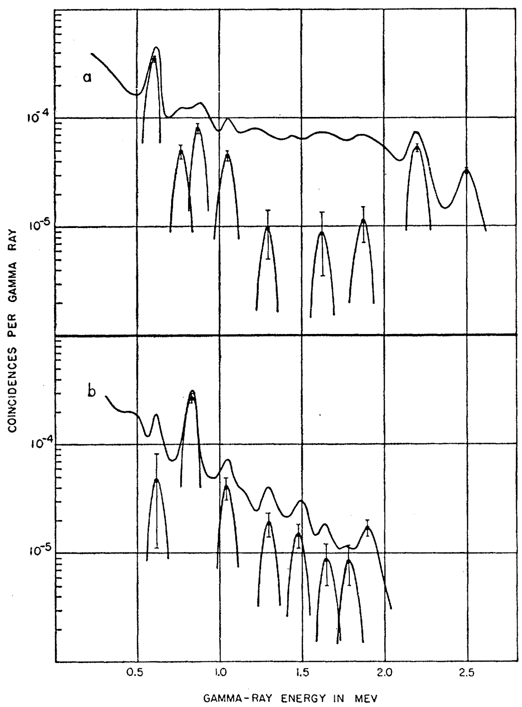

FIG. 6. Pure gamma-gamma coincidence spectra. Curves *a* and *b* represent the "pure" 0.84-Mev and 0.63-Mev gamma-gamma coincidence spectra, respectively. Analysis of the spectra yielded the photopeaks as shown.

delayed by 0.5 μsec with respect to the gamma counter. The resulting spectrum is shown in Fig. 7, curve b. This curve is identical with the singles spectrum. Also the total number of these coincidences is just equal to the number of calculated chance coincidences within an expected error of 10 percent. We take this to indicate that no gamma-rays follow the delayed state. Curve b, Fig. 7 is then just the chance-coincidence spectrum for

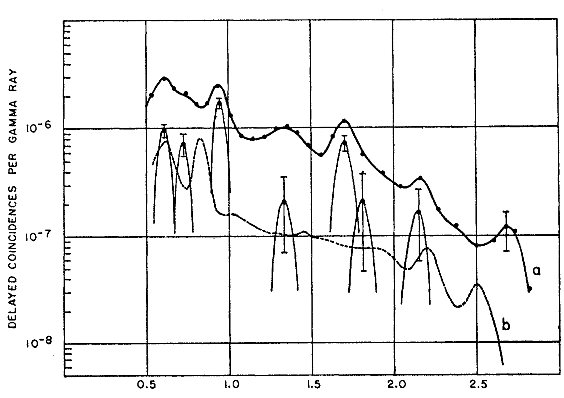

FIG. 7. Delayed beta-gamma coincidence spectra. Curve *a* is the 0.68-Mev beta-delayed gamma-ray spectrum. Curve *b* is the gamma-delayed 0.68-Mev beta-ray spectrum which is also the same as the chance spectrum. After subtraction of curve *a* from *b*, the result was analyzed yielding the photopeaks as shown.

curve *a*, Fig. 7. The difference spectrum was analyzed in the usual way and the results are given in Table VI. Because of poor statistics, the energies and intensities of the higher-energy lines are somewhat uncertain. For example, the presence of a 2.35-Mev gamma ray cannot definitely be excluded by our data.

Figure 8 gives the low-energy part of the delayed gamma-ray spectrum corresponding to Fig. 7, curve *a*. A delayed gamma ray in the region of 0.1 Mev had been observed previously.[11] Because of severe overloading of the gamma amplifier, an energy calibration was made by first adding to the Ga^{72} source a weak source of Ce^{144}, providing a calibration point at 0.134 Mev, and then by placing $\frac{1}{16}$ inch lead under the Ga^{72} source to provide a calibration point at 0.074 Mev (Pb K α_1 and α_2 x-rays). This calibration was made both before and after the 12-hour measurement necessary to obtain the data shown in Fig. 8. The entire experiment was repeated twice and indicated that the

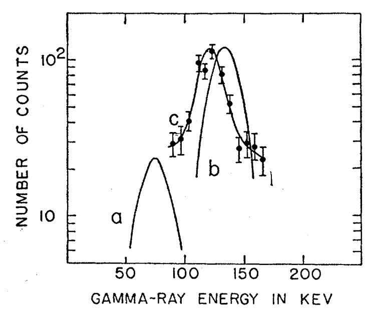

FIG. 8. Parts of the low-energy end of the 0.68-Mev beta-delayed gamma-ray spectrum. Curve *a* is the Pb K_α x-rays and curve *b* is the 0.134-Mev line from Ce^{144} used for energy calibration. Curve *c* is Ga^{72} 0.115-Mev line. The chance coincidence distribution in the same energy region was flat.

energy of the low-energy delayed gamma ray is 0.115 ± 0.004 Mev. There was a suggestion of a gamma ray at 0.145 Mev (not shown in Fig. 7), but if present, its absolute intensity must be equal to or less than 0.003 percent.[23,24]

V. DECAY SCHEME

The final decay scheme is shown in Fig. 2. Its gross features are very similar to the schemes proposed by Mitchell *et al.*[12] and especially by Haynes,[13] which were based on Ge^{72} levels near 0.84, 1.47, 2.52, 3.05, and 3.35 Mev obtained from beta-ray end points (see Table I). In order to shorten the discussion of the additional features of the decay scheme, which we have found, we summarize in Table VII the pertinent experi-

[23] The half-life of the 0.84-Mev state has been determined by N. P. Heydenburg and G. M. Temmer [Phys. Rev. **99**, 617(A) (1955) and verbal report] to be 1.3×10^{-12} sec. This, together with our limit on the branching ratio, would give a partial half-life for the 0.145-Mev $E2$ transition as equal to or greater than 4×10^{-8} sec.

[24] *Note added in proof.*—Remeasurement of the 0.68-Mev beta-delayed gamma-ray spectrum between 0.05 and 0.50 Mev shows the presence of only the 0.115- and possibly the 0.145-Mev gamma rays in this energy region.

mental evidence for each level. Only certain features are worth discussion.

The 3.33-Mev level is apparently double, because the two gamma rays of 2.491 and 2.508 Mev (intensity ratio 1:1.6), having been resolved by others,[15,16] are both in coincidence with the 0.84-Mev gamma ray. Indeed, comparing the intensity of our composite 2.50-Mev gamma ray with that of the 2.20-Mev gamma ray, we find 0.74 ± 0.05 in the singles spectrum (Table II) and 0.81 ± 0.14 in the 0.84-Mev gamma-gamma coincidence spectrum (Table V). Furthermore, comparison of the intensity of the 2.50-Mev gamma ray with that of the 1.04-Mev gamma ray, yields 3.3 ± 0.4 in the singles gamma-ray spectrum (Table II), but less than 0.18 in the >0.80- or >1.10-Mev beta-gamma coincidence experiments (Table IV), showing that the major, if not the total, part of the 2.50-Mev gamma ray leaves the 3.33-Mev level.

Comparison of the 1.59-Mev gamma-ray intensity with the 1.88-Mev gamma-ray intensity in the singles spectrum (Table II) and in the 0.63-Mev gamma-gamma coincidence spectrum would indicate the gamma rays around 1.59 Mev leave both the 3.33 and 3.04-Mev levels with roughly equal intensities. We have no definite information about a possible split-up of the 1.24-Mev gamma rays, although this has been found by Johns *et al.*[16] (See Table II. These gamma rays leave the 3.33- and 2.06-Mev levels respectively.) Our >1.65-Mev beta-gamma coincidence spectrum, Fig. 4(d), and the 1.72-Mev gamma-gamma coincidence spectrum, Fig. 5(e), give possible indications of this effect.

A 1.68-Mev gamma ray, not found in the singles spectrum, is seen to go from the 2.51-Mev to the 0.84-Mev level both in the >0.80-Mev and >1.10-Mev beta-gamma coincidence experiments (Tables IV and V). The intensity of the 1.68-Mev gamma ray is approximately 2 percent of that of the 0.84-Mev gamma ray.

The 0.32-Mev gamma ray (intensity ≤ 1.8 percent), listed in Table II can be accommodated in four different places in the decay scheme and the 0.44-Mev gamma ray (intensity ≤ 1.8 percent), in two places, so they are not shown in the decay scheme. The other two uncertain lines at 0.39 and 1.79 Mev remain unassigned. The intensities shown in the decay scheme are averages, whenever possible of the singles and coincidence data. The choice between starting lines at the 3.32- or 3.34-Mev level has been done entirely on the best energy fit.

In order to accommodate four of the gamma rays (0.115, 0.65, 0.95, and 1.72 Mev) appearing in the 0.68-Mev beta-delayed gamma spectrum, we propose a level in Ga^{72} at 2.39 Mev. Our results indicate that the 0.122-Mev gamma ray is definitely not the transition between the 0.84-Mev and 0.69-Mev levels. The sum of the intensities of the 0.122-, 0.65-, and 0.95-Mev gamma rays is very nearly equal to the intensity of the 1.72-Mev gamma ray (Table VII), indicating at most a very small beta-ray feeding of the 2.39-Mev level.

TABLE VI. Analysis of beta-gamma delayed coincidence spectra.

Energy (Mev)	Relative intensity[a]
0.115 ± 0.004	0.03 ± 0.01
$0.62\ \pm0.02$	0.05 ± 0.01
$0.73\ \pm0.03$	0.04 ± 0.01
$0.95\ \pm0.02$	0.16 ± 0.02
$1.34\ \pm0.06$	0.04 ± 0.02
$1.71\ \pm0.02$	0.20 ± 0.03
$1.82\ \pm0.04$	0.07 ± 0.05
$2.15\ \pm0.04$	0.07 ± 0.04
$2.69\ \pm0.03$	0.08 ± 0.02

[a] The sum of the intensities of the lines of energy 0.73, 1.34, 1.71, 1.82 2.15, 2.69 Mev has been normalized to equal 0.50 percent.

Only a lower limit can be placed on the absolute intensities of the radiations feeding the 2.39-Mev level because, although a limit of 2 percent has been placed (Tables II and III) on the intensity of the 2.39-Mev ground state transition, other transitions may leave this level. Approximate calculations taking into account solid angles, etc., indicate that the gamma rays feeding the 0.69-Mev level account completely for the known 0.5 percent branching ratio[9,12,13,16] of the 0.68-Mev conversion electrons. We used this value to calculate the intensities of the radiations feeding the 0.69-Mev state directly.

Referring to Fig. 2, it can be seen that the intensity balance of the radiations arriving at and leaving the various levels of Ge^{72} is in moderately good agreement with the beta spectra (see Fig. 1). The discrepancies that occur can most likely be attributed to a slight overestimation of the intensities of the high-energy gamma rays. A weak beta branch may be indicated to

TABLE VII. Evidence for level structure of Ge^{72}.

Level (Mev)	Evidence
3.33	$0.637\beta^{a}$; $3.34\gamma^{b}$; $>0.05\beta-\gamma^{c}$; $0.84\gamma-2.50\gamma^{d,e}$; $0.63\gamma-1.90\gamma$; $0.68\beta-d2.69\gamma^{f}$
3.04	0.959β; $>0.80\beta-\gamma$; $0.84\gamma-2.20\gamma$; $0.63\gamma-1.64\gamma$
2.82	2.82γ; $0.68\beta-d2.15\gamma$
2.51	1.508β; $>1.10\beta-\gamma$; $0.84\gamma-1.62\gamma$; $0.63\gamma-1.05\gamma$; $0.68\beta-d1.82\gamma$
2.39	$0.68\beta-d1.71, 0.95, 0.62, 0.115\gamma$
2.06	$1.24\gamma^{g}$; $0.63\gamma-0.62\gamma$; $0.68\beta-d1.34\gamma$
1.73	0.90γ; $0.84\gamma-0.89\gamma$
1.46	2.529β; 1.46γ; $>1.65\beta-\gamma$; $0.84\gamma-0.63\gamma$; $0.68\beta-d0.73\gamma$
0.84[h]	3.166β; 0.84γ; $2.20, 2.50\gamma-0.84\gamma$; $>2.60\beta-0.84\gamma$
0.69	$0.68\beta-d\gamma$, no $d0.68\beta-\gamma$ found

[a] 0.637β means that a 0.637-Mev beta ray is known to lead to level in question.
[b] 3.34γ means that a 3.34-Mev gamma ray is known and presumably goes to the ground state.
[c] $>0.05\beta-\gamma$ means there is evidence for this level from a beta-gamma coincidence experiment with beta rays of energy greater than 0.05 Mev.
[d] $0.84\gamma-2.50\gamma$ means that 0.84-Mev gamma rays have been found in coincidence with 2.50-Mev gamma rays.
[e] The 2.50-Mev gamma ray is known to be a doublet (see references 15 and 16) indicating levels at 3.32 and 3.34 Mev.
[f] $0.68\beta-d2.69\gamma$ means that 0.68-Mev beta rays or conversion electrons are in coincidence with delayed gamma rays of 2.69 Mev.
[g] This line has been resolved into two lines at 1.231 Mev and 1.268 Mev (see reference 16), of which the first represents the transition between the 2.06- and 0.84-Mev levels.
[h] Evidence for this level has been found also from inelastic neutron scattering [R. M. Sinclair, Phys. Rev. **99**, 621(A) (1955)] and Coulomb excitation (see reference 23) on Ge^{72}.

the 2.06-Mev level. This would not be in disagreement with Johns *et al.*[16] (see Table I).

VI. DISCUSSION

A. The Isomeric State of Ge^{72}

The delayed coincidence work (Sec. IV D) shows (1) that the isomeric state of Ge^{72} is the first excited state, (2) that not more than 5 percent of the isomeric transition proceeds by gamma rays.[25] Therefore one now knows that the half-life of the isomeric state is 0.3 μsec,[9–11] its decay energy is 0.69 Mev,[9,12,13,16] and its conversion coefficient greater than 20. The only transition compatible with these properties is a $0-0$ transition[26] without parity change. Since the ground state of Ge^{72} is presumably 0^+, the transition involved is 0^+-0^+.

Calculations of the lifetime of $0-0$ (no) transitions have been made under various assumptions for the electronic wave function occurring in the transition matrix element.[27–32] Assuming electronic Dirac wave functions and approximating the nuclear matrix element by the square of the nuclear radius ($1.2A^{-\frac{1}{3}}\times10^{-13}$ cm), a lifetime is obtained, in good agreement with the experimental value.[33]

The reason for the violation of the general rule concerning the spin and parity of the first excited states of even-even nuclei[1–4] at $_{32}Ge_{40}{}^{72}$ is at present not understood. The near degeneracy of the $p_{3/2}$ and $f_{5/2}$ nucleon configurations may be associated with this phenomenon. It is interesting to note that in Ge^{70} a 0^+ level is found[34] just 0.175 Mev above the first excited state at 1.04 Mev, which has the normal spin of 2 and even parity.

The possibility of a 0^+ level appearing above or below the first 2^+ state in Ge^{74} and Se^{74} is currently being investigated at this laboratory by studying the decay of As^{74}. As yet no state of this nature has been detected.

[25] This follows from a comparison of the upper limit of the delayed beta-gamma coincidences [Fig. 7(b)] which could not be accounted for by chances with the true beta-delayed gamma coincidences (Fig. 7, curve *b* minus curve *a*).

[26] The limit on this conversion coefficient is exceedingly higher than that expected for even $E5$ (2.2×10^{-2}) or $M5$ (4.8×10^{-2}) radiation, while the lifetime is about what one expects for $M2$ radiation. A $0-0$ transition with change of parity is forbidden for monoenergetic conversion electrons.

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B. The Higher Excited Levels of Ge^{72}

No direct information exists on the spins and parities of the levels of Ge^{72} other than the ground and first excited states. Unfortunately, the complexity of the level scheme precludes an unambiguous angular correlation experiment.

The shell model prediction[35] for the ground state $_{31}Ga_{41}{}^{72}$ is $p_{3/2}$ state for the proton and a $g_{9/2}$ state for the neutron. One may expect[35] from the coupling of these two odd nucleons an odd-parity state with a spin of 4, 5, or 6. A high spin assignment of this nature is in agreement with the fact that no beta transition to the ground state of Ge^{72} is observed. The second-excited state of Ge^{72} would appear to have a 2^+ assignment both from the decay of As^{72} and the systematics of even-even nuclei.[1–4] This information, coupled with the fact that the two most energetic beta transitions of Ga^{72} have very nearly the same $\log ft$ value (see Table I) and can be classified most naturally as first forbidden, restricts the spin assignment of Ga^{72} to 3^- or 4^- and suggests that the spin of the third excited state of Ge^{72} is 2^+. The pattern of the transitions between the ground, second, and third or fourth excited states of Ge^{72} is similar to the $0^+-2^+-2^+$ pattern of some other even-even nuclei noted elsewhere.[36,37]

The beta transitions to the 3.04-, 3.32-, 3.34-Mev levels seem to be in the allowed category. Of the various possible spin assignments for these three levels, 2^- or 3^- appears necessary because of the strong gamma-ray transitions going from these levels to the second excited state. The possible absence of transitions to the ground and first-excited states from the 3.04- and 3.32-Mev level may speak for 3^- assignment for these levels and a 2^- assignment to the 3.34-Mev level, which would restrict the Ga^{72} spin and parity to 3^-, in violation of the strict application of Nordheim's rules.[33]

The levels at 2.06, and 2.51 Mev would appear to have even parity and spins close to 2 because transitions to the 0^+ first-excited state are observed from these levels. The cross-over gamma rays to the ground state would be expected to be of the order of one percent intensity and hence could easily have been missed in our analysis. The level at 2.39 Mev which is mainly responsible for the feeding of the isomeric state could have either a 1^+, or 2^+ assignment, as could the level at 2.82 Mev.

The most likely spin and parity assignments based on considerations of gamma-ray intensities for single-particle transitions[38] and of the beta spectra are shown in Fig. 2.

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C. Decay of As^{72} to Ge^{72}

The decay of As^{72} has been studied by several investigators.[39–42] As^{72} decays primarily by positrons of end-point energies of 3.339 (19.3 percent), 2.498 (61.6 percent), 1.844 (12.1 percent), 0.669 (5.0 percent), and 0.271 (2.0 percent) Mev.[39] Gamma rays of energy 0.835 and 1.05 Mev were resolved. The $\log ft$ value (8.3) and the shape of the 3.339-Mev ground state positron branch indicated[39] that the transition was first forbidden ($\Delta J=\pm 2$, change of parity). A 2^- spin and parity was then implied for As^{72}, possibly accounted for by an $f_{5/2}$ proton and a $g_{9/2}$ neutron configuration.

We have started to investigate the decay of As^{72} using scintillation spectrometers. Although the results will be reported in more detail at a later date, it is worthwhile noting that the decay scheme is at least as complex as that of Ga^{72}, but more difficult to study because of the relatively lower intensity of the gamma rays above 0.84 Mev. From preliminary results it appears that most of levels observed in the decay of Ga^{72} are also populated in the decay of As^{72}. In addition a level at 2.90 Mev and apparently levels above 3.34 Mev are required. The 2.90-Mev level seems to participate in populating the 0.69-Mev level. At present no decisive information concerning the spins and parities of the excited levels of Ge^{72} can be obtained from the decay of As^{72}, beyond what is known from the decay of Ga^{72}.

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Fission Theory and Semiempirical Mass Formula

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The fission theory of Bohr and Wheeler employs the semiempirical mass formula with the following constants: E_s(=surface energy)$=14A^{\frac{2}{3}}$ Mev; $x=E_{\text{Coulomb}}/2E_s=(1/47.8)(Z^2/A)$; nuclear radius=Coulomb radius$=1.47\times10^{-13}A^{\frac{1}{3}}$ cm. The experimental masses deviate systematically from the values calculated using this formula. In the present note it is shown that these differences may severely influence the results of the fission theory.

A reduction of the standard error in the mass formula from 8 to 2 mMU has been achieved by using the following constants: $E_s=17.8A^{\frac{2}{3}}$ Mev; Coulomb radius$=1.216\times10^{-13}A^{\frac{1}{3}}$ cm; $x=(1/50.1)(Z^2/A)$. The smaller x-value and Coulomb radius, in addition to possible shell effects in the two halves of the deformed nucleus, decrease the stability of a symmetric deformation of the nucleus.

SINCE the publication of the original liquid drop theory,[1] a considerable amount of new experimental data on exact masses has been obtained.[2,3] To fit these values more satisfactorily the constants in the semiempirical mass formula[4,5] have to be altered. This change affects the liquid drop theory of fission. With the revised values the critical form of the nucleus is more strongly deformed than hitherto assumed and tends more to asymmetry.

In the fission theory of Bohr and Wheeler the following constants are employed: E_s(=surface energy) $=14A^{\frac{2}{3}}$ Mev; $x=E_c/2E_s=(1/47.8)(Z^2/A)$ (E_c=Coulomb energy, Z=charge number, A=mass number); nuclear radius=Coulomb radius$=1.47\times10^{-13}A^{\frac{1}{3}}$ cm. As mentioned, the semiempirical mass formula in which these values are used,[5] results in large systematic deviations from the experimental masses.

To show the extent to which these errors may affect the results of the theory, we have plotted the energy necessary for the deformation of a U^{238}-nucleus into two touching spheres with charges proportional to their masses, as a function of the sphere masses (Fig. 1). From the liquid drop theory, with the original constants mentioned above, one finds curve I.[6] Curve II is calculated from the experimental mass values[3] of nuclei with the same mass numbers as the spheres. These masses have been corrected with the following formula

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