Gamma Rays from Ga^{66}

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Twenty-four gamma-rays up to 4.8-MeV energy in the decay of 9.5-h Ga^{66} have been measured to an accuracy of 1.5 keV with a lithium-drifted germanium detector, and are assigned to a level scheme in close agreement to that of Schwarzschild and Grodzins. Prominent gamma-rays, useful in Ge(Li) calibration are: 4.8059, 4.4616, 4.2950, 4.0862, 3.7915, 3.3812, 3.2294, 2.7524, and 2.4231 MeV. The four highest energy values are 0.7–2.3 keV lower than the values of Coté *et al.*

I. INTRODUCTION

THERE is current interest[1,2] in the higher energy (up to 4.8-MeV) gamma rays in the decay of 9.5-h Ga^{66} as convenient high-energy calibration standards in lithium-drifted germanium gamma-ray spectroscopy. This is a thoroughly studied decay,[3] in which most of the high-energy transitions had been resolved, identified and assigned by a combination of NaI–three-crystal pair spectrometry, NaI singles spectrometry, magnetic conversion-electron-spectrometry up to the 4.8-MeV transition, and coincidence analysis. We considered it worth examining with the higher resolution of a Ge(Li) spectrometer, as we had a radiochemically separated gallium source available as a byproduct of our study of Ga^{67}. This served to identify the transitions in Ga^{66}. When the interest in accurate energy values came to our attention, we repeated the measurements on a source prepared without chemical purification after irradiation with particular attention to matters of calibration, linearity, and rate effects.

II. SOURCE PREPARATION

Ga^{66} was made by $(d,2n)$ and $(d,3n)$ reaction on a 99.999+% pure natural-zinc 10-mil foil in the Argonne cyclotron. The 22-MeV deuterons were attenuated in energy by a covering window of 6-mil aluminum.

In the preliminary study the gallium activity was extracted[4] and purified by solvent extraction after 3 days of cooling. Ample 9.5-h Ga^{66} activity remained for Ge(Li) spectroscopy from the 450-μA-h irradiation.

A 2-mm^2 piece cut from an identical zinc foil several hours after a 70-μA-h irradiation was used as the source for the precision experiment with no chemistry. We observed gamma rays corresponding to known intense transitions in 3.3-h Cu^{61} [made by the $Zn^{64}(d,\alpha n)$ reaction], 3-h Zn^{71m} [$Zn^{70}(d,p)$]; 68-min Ga^{68} [$Zn^{68}(d,2n)$]; 14-h Zn^{69m} [$Zn^{68}(d,p)$]; and 78-h Ga^{67} [$Zn^{66}(d,n)$]. All other gamma-rays observed were assigned to the Ga^{66} decay.

III. APPARATUS

Harry Mann of the Argonne Laboratory constructed the 22-mm diam×6-mm drifted-depth Ge(Li) detector, which is operated at 500-V bias. The preamplifier, designed by Irvin Sherman, Argonne Model PASD-1, has an inherent noise figure of 1.8 keV full width at half-maximum (FWHM), and a noise slope of 0.04 keV/pF. Ortec Multimode solid-state amplifier Model 401 and biased amplifier Model 408 drove the Packard Model 45 1024-channel analyzer.

The stability of this system is excellent. An overnight 10-h run showed no widening of the peak at 4.8 MeV (5.1-keV FWHM), without the use of gain stabilization. At 570 keV (Bi^{207}) the resolution width is 2.5 keV. From these widths one derives an effective Fano factor of $\sim$0.26 at the 500 V operating bias.[5]

A precision pulser was used to determine the amplitude response function of the over-all electronic system by a method (described in a later section) in which the assumption of exact proportionality between pulser setting and pulse amplitude is relied on. The pulser signal is introduced at the preamplifier input along with the Ge(Li) signal. Output level of the pulser is $\sim$10 V/MeV. The pulser reference voltage divider consists of a General Radio decade resistor bank and an interpolating 0.05% linear Helipot. The measured maximum deviation of the pulser reference-supply divider resistors from uniformity is 2.5 in 10^4 over the range used in this experiment. Zero offset is $\sim$1 part in 10^4 of the mean pulser range. No correction for these known deviations was made; the omitted corrections are less than 1 keV, and scatter randomly in sign and magnitude.

Germanium detectors have been shown[6] to have proportional response to within $\pm$4 keV at 6 MeV.

IV. EXPERIMENT

Seventeen gamma rays of Ga^{66} were found in the preliminary "radiochemically purified" experiment. We describe here only the details of the second experiment.

* Based on work performed under the auspices of the U. S. Atomic Energy Commission.

[1] R. E. Coté, R. Guso, S. Raboy, R. O. Carrigan, Jr., A. Gaigalas, R. B. Sutton, and C. C. Trail, Nucl. Phys. **77**, 239 (1966). Values given in present article, Table I, are revised from those in the publication, by private communication.

[2] H. L. Acker, G. Backenstoss, C. Daum, J. C. Sens, and S. A. DeWit, Nucl. Phys. **87**, 1 (1966).

[3] A. Schwarzschild and L. Grodzins, Phys. Rev. **119**, 276 (1960).

[4] M. S. Freedman, F. T. Porter, and F. Wagner, Jr., preceding article (Phys. Rev., **151**, 886 (1966).

[5] H. M. Mann, Bull. Am. Phys. Soc. **11**, 127 (1966).

[6] R. E. Berg and E. Kashy, Nucl. Instr. Methods **39**, 169 (1966).

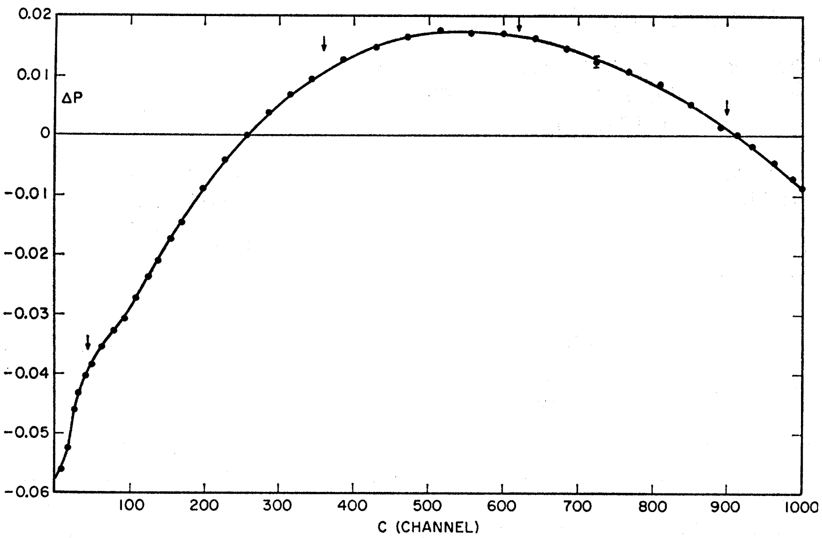

FIG. 1. Gain correction term ΔP for system including preamplifier, amplifier, window amplifier, and 1024-channel analyzer, measured with pulser, for high-energy run. The pulser range is 1.875–5.400 dial units. The deviations are with respect to a straight line through $(P,c)=(2.700, 258.0)$ and $(5.000, 907.2)$. The arrows mark main decade switch points. A typical error bar is shown.

Eight hours after irradiation a 1-h run was made at ~2.7 keV per channel covering the range 0.25–2.8 MeV, followed by a 10-h run at ~3.0 keV/channel covering the range 1.7–4.9 MeV. A 1.9-g/cm² beryllium absorber stopped all positrons. In each run we observed both the full-energy ("photopeak") and the single- and double-annihilation radiation escape peaks of the intense 2.7524-MeV gamma ray, which are unresolvable from the corresponding peaks of the calibration standard,[7] the 2.75392±0.00012 MeV gamma ray from 15-h Na^{24}. Therefore the Na^{24} source was not run simultaneously with the Ga^{66} source.

The necessity to run the standard separately, and the fact that the sample decayed by more than a half-life during the runs raised consideration of the influence of counting rates on the line shapes and positions. We observe shifts in line position of ~0.5 channel and toeing out on the high-amplitude side of the line at 10% analyzer dead time, but not at 5%, with respect to very low rates. Therefore both runs and the Na^{24} standard and pulser runs were taken at a dead time adjusted close to 5%, as indicated on the analyzer-dead-time meter. This alone does not ensure the absence of rate-dependent shifts between sample and standard, since the preamplifier sees also the much more numerous low-amplitude pulses which are biased out in the biased amplifier, especially in the high-energy run. Thus, pulse pile-up effects may distort spectra before the electronic subtraction, and as the relative intensity of small pulses differs in sample and standard, relative shifts may occur at a given analyzer dead time. To reduce this effect the high-energy run, which gave the calibration of the 2.7524-MeV Ga^{66} line with respect to the 2.7539-MeV Na^{24} line, was taken through a 10-g/cm² Pb plus 3-g/cm² Cu absorber pair, to reduce the intensity of the main low-energy (1.039- and 0.511-MeV) peaks substantially. The same absorber reduced the 1.368-MeV gamma-ray intensity in the Na^{24} standard.

Each run was preceded and followed by a run with the Na^{24} standard and by a pulser run. The latter were taken superimposing the pulser 60-Hz rate on the sample rate. The maximum shift among 38 pulser peaks taken before and after the 10-h high-energy run was 0.5 channel; average shift was ~0.2 channel. The 38 pulser peaks were spread over the 1024 channels, with some concentration in the top and bottom quadrants where the greatest nonlinearity is expected.

The centroid of each peak in the Ga^{66}, Na^{24}, and pulser runs was estimated by eye on the oscilloscopic display of the spectrum at maximum gain (~3 mm per channel) by two observers. For peaks projecting a factor of 2 over background we judge the error in the centroid to be no more than 0.2 channel and for smaller peaks, <0.5 channels (1.5 keV). A digitized intensifier on the Packard analyzer directable to any channel is very helpful in avoiding channel counting errors. Doubtful cases were hand plotted from the printer output. Only 3–4 channels covered the main body of each line.

A background run on the entire irradiated sample (500 times the activity of the sample used for Ga^{66}) after 17 days decay showed no peaks corresponding to those in the Ga^{66} run.

V. COMPUTATIONS

For each run, the average of the pulser-peak centroids before and after the run was taken. The parameters of a straight line, $P_{sl}=Mc+b$, where c is the centroid channel number, passing through two arbitrarily chosen (P,c) points near 250 and 750 channels, were calculated. P is the pulser dial reading. The differences, $\Delta P_i = P_i - P_{sl,i}$, were plotted, as in Fig. 1.

From this plot corrections ΔP_i are read (with an accuracy corresponding to ~0.25 keV) and added to

[7] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **63**, 353 (1965).

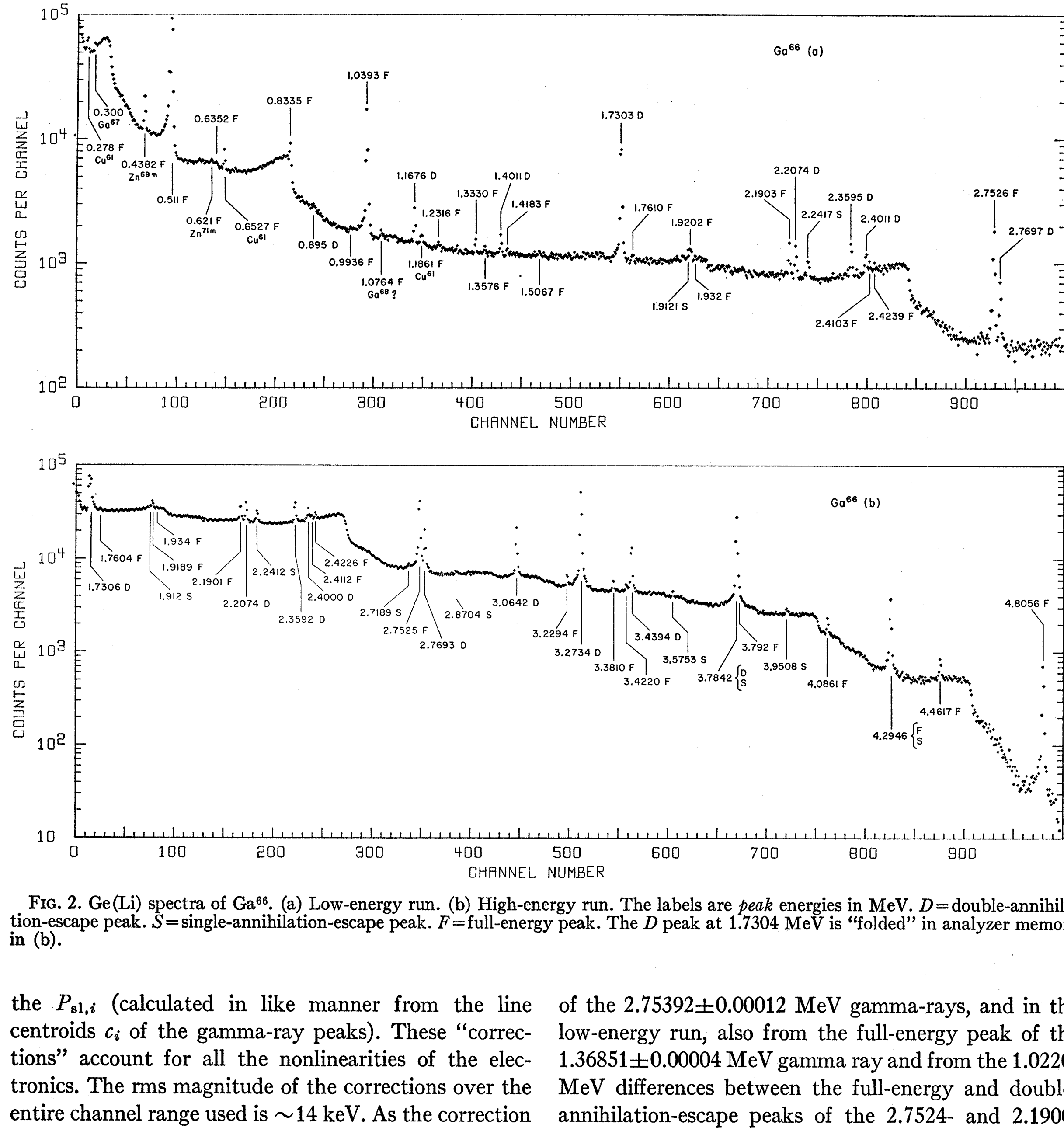

FIG. 2. Ge(Li) spectra of Ga^{66}. (a) Low-energy run. (b) High-energy run. The labels are *peak* energies in MeV. D=double-annihilation-escape peak. S=single-annihilation-escape peak. F=full-energy peak. The D peak at 1.7304 MeV is "folded" in analyzer memory in (b).

the $P_{s1,i}$ (calculated in like manner from the line centroids c_i of the gamma-ray peaks). These "corrections" account for all the nonlinearities of the electronics. The rms magnitude of the corrections over the entire channel range used is ~14 keV. As the correction curve is roughly centered about the chosen line (Fig. 1), the corrections are of comparable values of both signs, and nowhere do they exceed ~30 keV. The correction curves for the two runs are generally smooth, show no breaks at the pulser values corresponding to steps on the pulser main-decade resistor switch, and are of the shape consistent with the expected nonlinearities of the biased amplifier, amplifier and analyzer.

A calibration constant for each run relating the corrected $P_i = P_{s1,i} + \Delta P_i$ and energy was obtained from the P_i for the standard lines in Na^{24}, the full-energy and double- and single-annihilation-radiation escape peaks of the 2.75392±0.00012 MeV gamma-rays, and in the low-energy run, also from the full-energy peak of the 1.36851±0.00004 MeV gamma ray and from the 1.0220-MeV differences between the full-energy and double-annihilation-escape peaks of the 2.7524- and 2.1900-MeV gamma ray in Ga^{66}. These values, weighted by considerations of relative statistical counting uncertainty, were averaged to give a calibration constant for each run.

A point of general interest for Ge(Li) spectroscopy is that the annihilation-radiation peak exhibited the well-known Doppler broadening due to the motion of the positron-electron system at the time of the two-photon annihilation. Compared to the 2.50-keV width observed at 570 keV (Bi^{207}), the annihilation peak showed 3.50 keV, indicating an intrinsic FWHM Doppler contribution of 2.45 keV to the total width. This is in qualitative

TABLE I. Gamma rays in decay of Ga^{66}.

This expt. Observed[d] Peak	This expt. Observed[d] MeV	This expt. Weighted average (MeV)[e]	Schwarzschild and Grodzins[a] MeV	Schwarzschild and Grodzins[a] Observed peaks	Coté *et al.*[b] MeV	Coté *et al.*[b] Observed peaks	Acker *et al.*[c] MeV	Acker *et al.*[c] Observed peaks	Gamma-ray intensities (%) This expt.	Gamma-ray intensities (%) Ref. a
F	4.8056									
D	4.8062	4.8059	4.833±0.03	*E*, *F*, *D*	4.8082±0.0015	*F*, *D*	4.7986±0.0028	*F*, *D*	5.9	5.4
S	(4.8058)[f]									
F	4.4617									
D	4.4614	4.4616	4.45 ±0.06	*D*	4.4623±0.0015	*F*, *D*	4.4530±0.0035	*D*	2.2	2.9
S	4.4618									
F	4.2946									
D	4.2954	4.2950	4.300±0.005	*E*, *F*, *D*	4.2969±0.0015	*F*, *D*	4.2857±0.0027	*F*, *D*	11.2	10.8
S	(4.2952)[g]									
F	4.0861									
D	4.0862	4.0862	4.10 ±0.04	*F*, *D*	4.0871±0.0015	*F*, *D*	4.0793±0.0020	*F*, *D*	4.1	5.0
S	4.0863									
F	3.792									
D	3.7915	3.7915	3.790±0.03	*E*, *F*, *D*					2.6	4.3
F	3.4220									
D	3.4220	3.4220							1.9	
			3.400±0.20[h]	*E*, *F*, *D*						6.8[h]
F	3.3810									
D	3.3812	3.3812								
S	3.3814								4.6	
F	3.2294									
D	3.2294	3.2294	3.24 ±0.04	*F*, *D*					4.1	4.8
S	3.2299									
	···		3.03 ±0.05[i]	*F*, *D*					···	0.7
F	2.7525									
D	2.7524	2.7524	2.748±0.004	*E*, *F*, *D*			2.7493±0.002	*F*[j]	60[k]	60
S	2.7522									
F		2.472[l]	2.470±0.02[i]	*E*					2.1	
F	2.4232									
D	2.4231	2.4231	2.410±0.02	*E*, *F*, *D*					5.5	7.2
S	2.4231									
F[l]		2.4108[l]	···						0.4	
F	2.1903									
D	2.1896	2.1900	2.183±0.004	*E*, *F*, *D*					14.4	13.1
F		1.933[l]	···						1.3	···
F	1.9189									
D	1.917	1.9189	1.915±0.010	*E*, *F*, *D*					6.0	5.4
F[l]		1.7607[l]							0.9	···
F		1.5067	1.54 ±0.04	*D*					1.5	2.1
F		1.4183	1.41 ±0.03	*D*					1.8	1.4
F		1.3576	···						2.4	···
F		1.3330	1.333±0.003	*E*, *F*					3.2	4.0
F		1.2316	···						3.0	···
F		1.0393	1.037±0.002	*E*, *F*					93	76
F		0.9936	···						0.9	···
F		0.8335	0.828±0.002	*E*, *F*					14.9	12
F		0.6352	···						0.9	···
F		1.0764[m]	···						2.9	···
D		3.767[n]	···						≤0.3	···

[a] Reference 3.
[b] Reference 1. Values given here are revised from those in the publication, by private communication.
[c] Reference 2.
[d] *F* is the full-energy peak; *D* is the double-annihilation-escape peak; *S* is the single-annihilation-escape peak; *E* is the conversion-electron peak in magnetic spectrometer.
[e] An error of ±0.0015 MeV is assigned to each gamma-ray energy (see text).
[f] The single-annihilation-escape peak of the 4.8059-MeV gamma ray is an unresolved component, (~1/3 of total intensity) of the full-energy peak of the 4.2950-MeV gamma ray (energy difference =0.5109 MeV).
[g] The *S* peak of the 4.2950-MeV gamma ray is a ~15% component of the *D* peak of the 4.8059-MeV gamma ray.
[h] Noted as a probable doublet in Ref. 3.
[i] Not assigned in Ga^{66} decay scheme.
[j] We believe this peak to be the full-energy peak of the 2.7493-MeV transition, not as assigned in Ref. 2, as the *D* peak of a 3.7713-MeV gamma ray.
[k] Normalized to intensity of Ref. 3, given as intensity per ground state $\beta+$.
[l] See note added in proof on (p,p') and (p,α) reactions. The 2.4108-MeV line is probably a *D* peak with $E_\gamma=3.433$-MeV, and the 1.7607-MeV line is probably a *D* peak with $E_\gamma=2.783$-MeV.
[m] Probably gamma ray in decay of 68-min Ga^{68}.
[n] Unfolded from 2.7524-MeV *F* peak.

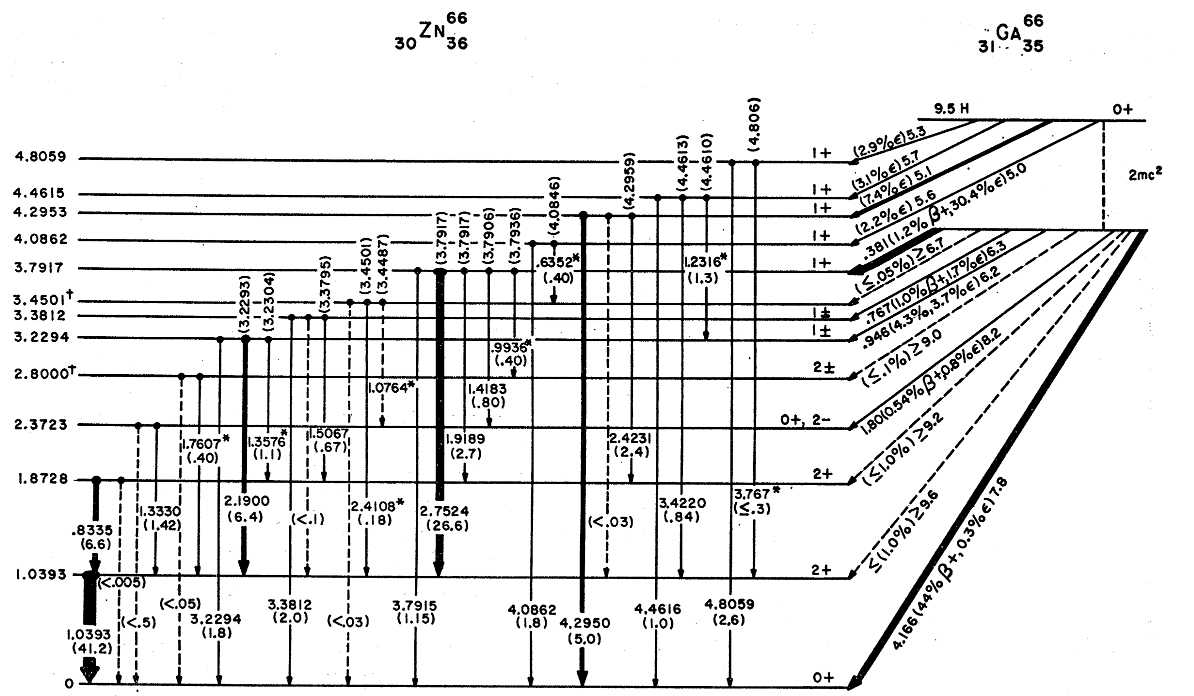

FIG. 3. Decay scheme of Ga^{66}. The numbers in parentheses under energies in MeV are gamma-ray intensities in percent per Ga^{66} decay, assuming a ground-state positron intensity of 44% from Ref. 3. All other $\beta+$ and electron-capture feeds are (slightly) revised for consistency with the gamma-ray intensities. Transitions added to the scheme in this study are marked with an asterisk; levels added are marked with a dagger. The dashed transition (1.0764 MeV) probably occurs in Ga^{68} decay, not in Ga^{66}. The numbers in parentheses above the arrows (except ground-state transitions) are energy sums of the gamma-ray plus the indicated level energy at which the transition terminates, for intercomparison. Level energies are weighted averages. Some gamma-ray intensity limits for transitions not found (dashed) are shown. Log*ft* values are given. See note added in proof for changes.

agreement with the broadening found[8] on external photoelectron peaks from positrons stopped in various condensed materials.

VI. RESULTS

Figure 2 displays the spectrum from the two runs.

The energies of all peaks not assigned to other recognized radioactivities produced by deuterons on zinc are given in Table I, columns 1 and 2. As the energy difference between the 4.8059- and 4.2950-MeV gamma rays is 0.5109 MeV, the single-escape (*S*) peak of the former coincides with the full-energy (*F*) peak of the latter; the *F* peak comprises about $\frac{2}{3}$ of the composite, and so in the energy determination the peak position is assigned to the *F* peak. As the double-escape (*D*) peak of the higher energy gamma ray constitutes about $\frac{5}{6}$ of the composite with the *S* peak of the lower, the peak energy is assigned to the higher energy gamma ray.

Every gamma ray except those at 1.933 and 2.472 MeV is assignable to a transition in the decay scheme (Fig. 3). This is in complete agreement with the scheme of Schwarzschild and Grodzins,[3] with confirmations of every decay-scheme assignment which they suggested as tentative (1.4183, 1.5067, 2.4231, and 3.4220 MeV). Two new levels, marked with a dagger, are proposed, and several gamma rays are added, marked with an asterisk. We observe every gamma ray of Ref. 3 except the weak 3.03-MeV line, which they did not assign. The 1.0764-MeV transition, which fits in the scheme with a discrepancy of 1.4 keV, is probably a gamma ray in the 68-min Ga^{68} decay.

In no case was a member of the *F*, *S*, *D* combination of peaks not observed with about the expected intensity if the local background statistics permitted its observation. The energy correspondences between the *F*, *S*, and *D* peaks make peak identification unambiguous.

The average deviation from the weighted average energy of the *F*, *S*, and *D* peaks is 0.15 keV. Although the calibration constant for the high-energy run was derived only from the Na^{24} 2.75392-MeV *F*, *S*, and *D* peaks, which were in channels below 350, this evidences the accuracy of the constant up to the highest channels. Moreover, the decay scheme has seven cases of two gammas with a crossover gamma ray, five cases of three gamma rays with a crossover, and one case of four gamma rays with a crossover. In these 13 cases, which involve gamma rays from 0.6–4.4 MeV, the maximum discrepancy in any sum-crossover comparison is 1.9 keV (0.9936+1.7607=2.6543 versus 2.7524, both the stop-

[8] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **45**, 117 (1963) find ~3 keV (FWHM) intrinsic width of the annihilation line for positrons stopped in water. D. A. Lind and A. Hedgran, Arkiv Fysik **5**, 29 (1952) find 2.9 keV for positrons in brass. D. E. Muller, H. S. Hoyt, D. J. Klein, and J. W. M. DuMond, Phys. Rev. **88**, 775 (1952) observe intrinsic broadening of ~5 keV for positrons stopped in copper. We find a FWHM broadening of 2.45 keV for both beryllium and lead.

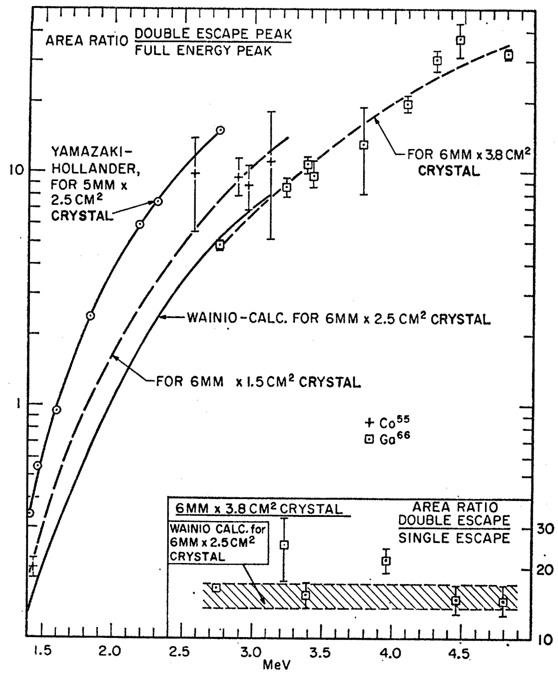

FIG. 4. Ratio of double-annihilation-escape peaks to full-energy peaks and to single-annihilation-escape peaks, as a function of gamma-ray energy, for various Ge(Li) spectrometers.

over lines being very weak lines, with centroid location errors of 1.5 keV), and the average of the absolute values of the discrepancies is 0.7 keV, with no trends with energy. From this evidence and from the uncertainties of the pulser linearity, peak centroid estimation, and ΔP graphing and reading errors, we assign an error of 1.5 keV to every gamma-ray energy. This uncertainty reflects mainly the error in the calibration constant. Although the reading errors in weak lines alone are 1.5 keV, their fit in the level scheme reduces their error relative to strong gammas.

Our values overlap those of Schwarzschild and Grodzins within their larger errors, except for the 2.1900- and 0.8335-MeV gamma rays. Figure 2 of Ref. 3, the conversion electron spectrum of Ga^{66}, shows a pronounced source-thickness line broadening that perhaps accounts for the few-keV lowering of their value for the 0.8335-MeV transition.

In columns 5–8 (Table I) are shown the energies for the four most energetic gamma rays measured recently by two groups[1,2] in connection with Ge(Li) spectroscopy of x-ray spectra from μ-mesonic atoms. Our values are 0.7–2.3 keV below those of Coté *et al.*, but overlap within the combined errors. These measurements also used Na^{24} gamma rays for calibration, and accounted for possible nonlinearities in the system by requiring $2mc^2$ differences between F and D peaks. They find 6.129 MeV for the 6.131±4-MeV peak of O^{16} by extrapolation of their Ga^{66} fitting.

The CERN[2] group's values are 8–15 keV below ours, outside the errors. We believe one of their peaks, at 2.7493 MeV, is incorrectly assigned, as indicated in Table I. They used the pulser technique, but their calibration appears to be based on lower energy (Co^{60}) gammas. They did not use Na^{24}.

VII. GAMMA-RAY INTENSITIES

The determination of the efficiency of this Ge(Li) detector for full-energy peaks, up to 1.3 MeV, has been described.[4] This technique has been extended to 2.75 MeV (Na^{24}), and the log-efficiency-versus-log-energy function is seen to be linearly extended at high energies, within the $\sim$10% uncertainty. Beyond this energy we have evaluated gamma ray intensities based on the calculated relative efficiencies of double-annihilation-escape peaks, from the work of Wainio.[9] Wainio's calculations gave good agreement with the measurements of Ewan and Tavendale.[10] The absolute double-escape efficiency was obtained by normalization to the gamma-ray intensity obtained from the full-energy peak of the 2.7524-MeV gamma ray.

In Fig. 4 we compare the measured ratio of double-escape- to full-energy-peak areas as a function of gamma-ray energy to the results of Yamazaki and Hollander[11] on a 2.5-cm^2×5-mm thick Ge(Li), to our results[12] on a small area (1.5-cm^2)×6-mm thick crystal with Co^{55} gamma rays up to 3.1 MeV, and with Wainio's calculations interpolated for a 2.5-cm^2×6-mm Ge(Li). Our results [3.8-cm^2×6-mm thick Ge(Li)] fit Wainio's calculations and extend the experimental data to 4.8 MeV.

In the insert of Fig. 4 the ratio of double-escape- to single-escape-peak areas is shown together with Wainio's prediction (error band) for our crystal thickness. This ratio should be independent of energy. In calculating gamma-ray intensities we corrected for decay between the two runs using a 9.5-h half-life, and for the absorption in the lead and copper absorbers.

Columns 9 and 10 of Table I compare our gamma-ray intensities to those of Schwarzschild and Grodzins normalized at 2.7524 MeV. In the light of the efficiency uncertainties the agreement is remarkable. In cases where we resolve the composite peaks of Schwarzschild and Grodzins into components (recognized by them), e.g., the 3.4220-, 3.3812-MeV pair and the 2.472-, 2.4231-, 2.4108-MeV triplet, our intensity sums also match theirs. Only the 1.3576- and 1.2316-MeV lines are not not seen by them despite the substantial intensities.

Assessment of the errors in intensity determinations is difficult, and we make no claims for our intensities over those of Ref. 3.

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[9] K. M. Wainio, Ph.D. dissertation, University of Michigan, 1965 (unpublished). We have interpolated, for the 6-mm thick detector, from Wainio's Monte Carlo calculations for 3.5- and 8-mm detector thicknesses.

[10] G. T. Ewan and A. J. Tavendale, Can. J. Phys. 42, 2286 (1964).

[11] T. Yamazaki and J. M. Hollander, Phys. Rev. 140, B630 (1965).

[12] H. Fischbeck, F. T. Porter, M. S. Freedman, F. Wagner, Jr., and H. H. Bolotin, Phys. Rev. 150, 1941 (1966).

In Table II the summed gamma-ray intensities into and out of each populated level are shown with their difference, which represents positron-plus-electron capture feed into the level. Intensities are here given per Ga^{66} decay (in Table I they are per ground-state positron, from Ref. 3). The comparison to the results of Ref. 3 appears in columns 4 and 5 and the agreement is excellent. No decay is predicted to any level for which positrons were not found in Ref. 3, or to the two new levels added.

The decay scheme as given, including the added transitions and levels, is also consistent with the complete coincidence survey of Ref. 3, except for the assignment of the 1.2316-MeV gamma ray feeding the 3.2294-MeV level. The cascades through the 1.3576-, 2.1900-, and 3.2294-MeV gamma rays are in contradiction to the observation that no coincidences of gamma rays exist for both gamma rays above 1.1 MeV except for the 1.333–1.418-MeV pair. A double Ge(Li) coincidence experiment is required here.

We indicate by dashed lines in Fig. 3 a number of interesting transitions on whose gamma-ray intensity we placed the limits shown. We include the very low limit for the ground transition of the 1.8728-MeV level from Ref. 3. The transition from the 4.8059-MeV to the 1.0393-MeV level (*D* peak) is seen as a foot on the low side of the intense 2.7524-MeV *F* peak, by comparison to a nearby peak shape.

TABLE II. Intensities[a] per decay of Ga^{66}.

Level (MeV)	Gamma rays out (*O*) % per decay	Gamma rays in (*I*) % per decay	$(\beta+)$+E.C. $(O-I)$ % per decay	$(\beta+)$+E.C.[b] % per decay
4.8059	2.62	...	2.62±0.3	2.4
4.4615	3.14	...	3.14±0.5	2.3
4.2953	7.4	...	7.4 ±0.8	6.8
4.0862	2.22	...	2.22±0.3	2.2
3.7917	31.6	...	31.6 ±3	31.2
3.4501[c]	0.18±0.09	0.40±0.15	−0.22±0.24	...
3.3812	2.67	...	2.67±0.3	2.5
3.2294	9.3	1.3	8.0 ±1.0	7.1
2.8000[c]	0.40	0.40	0	0
2.3723	1.42	0.80	0.62±0.1	0.69
1.8728	6.6	6.87	−0.2 ±1.0	0
1.0393	41.2	42.44	−1.2 ±2.0	0
G.S.		56.5	43.5[d]±2	44.3

[a] Intensities are given in percent per decay, on the assumption that the ground-state $\beta+$ population is 44% per decay, as given in Ref. b.
[b] Reference 3.
[c] See note added in proof on (p,α) studies.
[d] Comparison of the inferred ground state $(\beta+)$+E.C. intensity to the postulated 44.3% indicates only the internal consistency of the intensity data (E.C. = electron capture). Of course, no prediction of direct feed to the ground state can be derived from gamma-ray measurements.

VIII. DISCUSSION

The spin assignments of Fig. 3 are mainly those of Ref. 3, based on *ft* values, which we closely corroborate, and on angular correlations of the 2.7524- and 0.8335-MeV gamma rays with the 1.0393-MeV gamma ray.

The high log*ft* of 7.8 for the ground-state beta from the measured 0+ spin of Ga^{66} is explained in terms of the change in isotopic spin ($\Delta T=+1$) for this pure Fermi transition.

The log*ft* limits suggest that the decays to the first and second excited states are at least first forbidden unique or (more likely) second forbidden, and the gamma-gamma correlations select spin-2 for both levels. Both 0.833- and 1.039-MeV gamma rays are *E*2 or *M*1 by their conversion coefficients.[3] Thus both levels are 2+. The allowed betas feeding[3] both these levels from Cu^{66} (1+) confirm these 2+ assignments.

For the 2.3723-MeV level, $\log ft(\simeq \log f_1 t)=8.2$ suggests a first-forbidden unique transition, i.e., $J=2-$. However, from the isotropic angular distribution of a 1.34-MeV gamma ray in a $(p,p'\gamma)$ reaction on Zn^{66}, with 4.4–4.9-MeV protons, Sen Gupta and Van Patter[13] propose 0+ for their 2.382±0.009-MeV state. A 0+ state is expected in this region as a member of the 2-phonon vibrational triplet. The same explanation for the high log*ft* for this 0+-0+ transition as that given for the ground-state decay would hold. The absence ($\leq 10^{-6}$ per decay, Fig. 2 of Ref. 3) of *E*0 conversion electrons to the ground state argues against the 0+ assignment, while the ratio of the upper intensity limit of the 2.37-MeV ground-state gamma ray, as an *M*2, to the intensity of the 1.3330-MeV gamma ray, as an *E*1($\leq$0.5/1.4) is not anomalous with the (2−) assignment. The "level" has been seen with poor resolution in (d,t) pickup[14,15] (very weakly) and in (p,p') scattering[16] (weakly); in (α,α') with 43-MeV alpha particles it has been observed[17] fairly strongly. These findings offer no choice between 0+ and 2−. Clarification (0+ or 2− assignment or 2 states) will require 1.33- 1.04-MeV γ-γ angular correlation at high resolution.[18]

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[18] *Note added in proof:* Dr. A. Schwarzschild informs us that he has calculated that the *E*0 conversion electron intensity would be unobservably small in his experiment for reasonable *E*0 transition probabilities. Further, in recent (p,p') and (p,α) high-resolution studies on Zn^{66} levels by A. A. Katsanos and J. R. Huizenga (private communication) the assignment of spin-0 is strongly favored for the 2.371-MeV level. Preliminary data from these experiments do not indicate the existence of levels at 2.8000 and 3.4501 MeV, which we proposed. However, we have found assignments for the four weak lines in the Ge(Li) spectrum (2.4108, 1.7607, 0.9936, and 0.6352 MeV) which we associated with these proposed levels, as well as for the previously unassigned weak 2.472- and 1.933-MeV gamma rays, as transitions between levels observed in the nuclear reactions and levels in the decay scheme of Fig. 3, as follows: [Initial level, gamma-ray, final level]; [2.783, 1.761+2mc^2, 0]; [3.433, 2.411+2mc^2, 0]; [4.427, 0.994, 3.433]; [4.427, 0.635, 3.792]; [3.511, 2.472, 1.039]; and [3.806, 1.933, 1.873]. All level energies obtained in the (p,p') and $(p\alpha,)$ studies up to 4.8 MeV agree within 2 keV with those in this paper, as do also the energies obtained by Ge(Li) spectroscopy on Ga^{66} by David Camp (private communication).

The energy of each of the newly added levels (2.8000 and 3.4501 MeV) is assigned on the basis of one in-out pair. The arbitrary order of the gammas in each pair is chosen so as not to introduce new low-lying levels at (1.039+0.635=)1.674 or (1.039+0.994=)2.033 MeV, which would likely have been observed in nuclear reaction or inelastic scattering studies. A 2.79-MeV level appears[14,15] in the (d,t) reaction, strongly excited.

The existence of ground-state gamma-ray transitions and the allowed logft values feeding the five highest energy levels unambiguously determines a common 1+ spin. From the 1+, 3.7937-MeV state, the 0.9936-MeV gamma-ray to the 2.8000-MeV level would be an $M2$ transition if the spin of the 2.8000-MeV level is 3−, as suggested[19] for a 2.810±0.02-MeV level by (α,α') scattering. As an $M2$ decay, the 0.99-MeV gamma ray would not ordinarily be observable in competition with the more energetic $E1$ and $M1$ transitions from the 3.7917-MeV state. A spin of 2(±) for the 2.8000-MeV level would make the 0.99-MeV gamma ray $E1$ or $M1$, and would also be consistent with the at least first-forbidden logft value (>9.0). If the level seen in (d,t) pickup[14,15] at 2.79 MeV is identified with the 2.8000-MeV state, negative parity is deemed[20] unlikely.

Broek[19] and Chaminade[17] *et al.* find a state strongly excited by (α,α') scattering at just over 2.80 MeV. Such strong excitation suggests the collective character of the level, and Broek assigns it a 3− (octupole-vibration) spin by the angular distribution of the alpha rays. From the preceding discussion it appears that this level is not our 2.8000-MeV state.

For both the 3.2294- and 3.3812-MeV states, the logft values (6.2 and 6.3) are borderline between allowed and first-forbidden transitions. Both states feed ground-state transitions, so they do not have spin-0. The only tenable choice is spin 1 with undetermined parity. A state at 3.24 MeV is seen[15] in (d,t) pickup.

Beta decay to the 3.4501-MeV state is probably not allowed, so 0+ or 1+ are unlikely, as is any spin above 2. The spin possibilities of 0−, 1−, or 2± are all reasonable for the 0.6352-MeV/4.0862-MeV intensity ratio.

To summarize the picture with regard to spin and parity assignments, we find need for high-resolution γ-γ angular-correlation measurements which may become feasible with larger Ge(Li) detectors, and for much higher resolution particle-reaction and scattering studies, to determine whether level characteristics deduced from these are applicable to states populated in the gallium decay.

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