Shape of the $0^+ \rightarrow 0^+$ Positron Spectrum in Ga^{66}†

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A detailed study of the beta spectrum of Ga^{66} with emphasis on the shape of the positron spectrum of the $0^+ \rightarrow 0^+$ transition has been made with a magnetic spectrometer. The ground-state to ground-state transition is found to have a nonstatistical shape. The shape factor is fitted by the equation $S(W)=K(1+0.0328W+0.354/W-0.000419W^2)$ based upon a ratio of matrix elements $\lambda=\langle i\alpha\cdot\hat{r}\rangle/\langle 1\rangle=-21.3$. An additional factor of the form $(1+0.4/W)$ is needed to obtain the best fit. The nonstatistical shape for this group leads to an end-point energy of 4.153 ± 0.003 MeV and an intensity of 51.2%. The logft is 7.903 and from this the amount of $T=3$ admixture in the $T=2$ ground state of Ga^{66} is found to be 4.00×10^{-5}.

I. INTRODUCTION

A DETAILED measurement of the positron spectrum of the highest energy transition in the decay of Ga^{66} is of interest for several reasons. This transition appears to be from a 0^+ initial state to a 0^+ final state and is therefore governed by only the Fermi part of the V-A interaction. It, therefore, offers one of the few opportunities for studying the effect of the vector interaction without the mixture of a pseudovector contribution. In addition, the comparative half-life for this transition is unusually high. This suggests that the matrix element which normally governs the rate of such a transition is being suppressed. One may, therefore, hope to find evidence for the influence of another matrix element which is usually neglected in the allowed approximation. The retardation of this transition can be attributed to a change in the isotopic spin between the initial and final states.

Small deviations from the predictions of the present theory of beta decay have been observed[1–4] in the electron spectra of In^{114}, Y^{90}, and P^{32} and the positron spectra of Na^{22}, Zr^{89}, and Co^{56}. The measured shape factors of these spectra were fitted with an empirical equation of the form $(1+b/W)$ with $0.2<b<0.4$. W is the relativistic energy of the electron in units of mc^2. The sign of b is the same for both positrons and electrons. The first four nuclides decay by pure Gamow-Teller radiation. The last two decay by mixtures of Fermi and Gamow-Teller radiations. It would be significant to examine an isotope which decays by Fermi radiation alone in order to determine if these deviations are also associated with such radiation.

The $0^+\rightarrow0^+$ transition in Ga^{66} proceeds by pure vector radiation according to the V-A law. This transition has been reported[5–8] to have a linear Fermi-Kurie (F-K) plot from its end point (4.15 MeV) down to 1.8 MeV. The decay scheme has been thoroughly investigated[8] and is well established except for a possible positron transition to a 2.75-MeV level in Zn^{66}. Three investigators[5–7] have reported a 1.4-MeV positron group and two[5,6] did not report a 1.8-MeV group while one of the past investigators has reported[8] a 1.8-MeV group and not a 1.4-MeV group.

In addition, the fact that the odd-odd nucleus has spin zero[9] implies that the ground-state transition to Zn^{66} involves a $\Delta J=0$ $(J=0)$ isotopic-spin-forbidden pure Fermi transition. The high ft value for this transition, in addition to supplying information about the mixture[10] of isotopic spin in the Ga^{66} ground state, also suggests the possibility of detecting a small energy dependence in the shape caused by interference of the matrix elements. Any energy dependence in the shape would affect the value obtained for the admixture.

A detailed investigation of the energy dependence of the $0^+\rightarrow0^+$ transition in Ga^{66} has been carried out. The shape of the spectrum and the ft value for this transition have been carefully established in order that a more accurate value for the isotopic-spin admixture in the ground state of Ga^{66} could be obtained. The experimental shape factor may be fitted with a theoretical equation of the form $(1+c_1W+c_2/W+c_3W^2)$, where c_1, c_2, and c_3 are given explicitly in terms of $\lambda\equiv\langle i\alpha\cdot\hat{r}\rangle/\langle 1\rangle$. An additional correction to the shape factor of the form $(1+0.4/W)$ improves the fit. The need for this factor gives support to the previous work which suggested that there are deviations from theory in the shapes of beta spectra and suggests that the cause of the deviation is independent of the mode of generation of the radiation.

II. EXPERIMENTAL PROCEDURES

Magnetic Spectrometer

The positron spectrum of Ga^{66} was measured in a 40-cm radius of curvature, 180-deg focusing, shaped

† Supported by the program of the Office of Naval Research.
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[1] O. E. Johnson, R. G. Johnson, and L. M. Langer, Phys. Rev. **112**, 2004 (1958).
[2] J. H. Hamilton, L. M. Langer, and W. G. Smith, Phys. Rev. **112**, 2010 (1958).
[3] J. H. Hamilton, L. M. Langer, and W. G. Smith, Phys. Rev. **119**, 772 (1960).
[4] J. H. Hamilton, L. M. Langer, and D. R. Smith, Phys. Rev. **123**, 189 (1961).
[5] L. M. Langer and R. D. Moffat, Phys. Rev. **80**, 651 (1950).
[6] A. Mukerji and P. Preiswerk, Helv. Phys. Acta **25**, 387 (1952).
[7] L. G. Mann, W. E. Meyerhof, and H. I. West, Jr., Phys. Rev. **92**, 1481 (1953).
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[10] W. P. Alford and J. B. French, Phys. Rev. Letters **6**, 119 (1961).

magnetic field spectrometer.[11] Modifications of the equipment and the procedures of operation have been discussed in detail previously.[1,2,12] Two additional changes were the use of a transistorized constant current supply for the magnet and a Rawson rotating coil gaussmeter[13] to measure the magnetic field. Both modifications increased the accuracy of the measurements over that of the previous methods employed.

A continuous flow, loop anode proportional counter operated at 15 cm of Hg pressure with an aluminum-coated Mylar window was used as one of the detectors.[12] The counter window has a cutoff energy at about 20 keV and has essentially uniform transmission above 100 keV. This counter was also operated at 20-cm pressure. A new side window counter was designed and used as a further check on the shape of the spectrum (see Sec. III).

An NE 102 plastic scintillator, with a 10-in. light pipe optically coupled to an EMI 9536B photomultiplier tube, was also used as a detector. Because of the increased sensitivity to gamma rays, the background with the scintillator was much larger than with the proportional counters. Hence, the proportional counter was used for most of the experiments.

The spectrometer was calibrated in terms of the K conversion lines of the 661.6-keV gamma ray of Cs^{137}, the 1.064-MeV gamma ray of Bi^{207}, and the 238.6-keV gamma ray of ThB (F line).[14] The Rawson coil measures the magnetic field directly in gauss to an accuracy of better than 0.1%. From the calibrations, an effective radius ρ is determined which when multiplied by the gaussmeter reading gives directly the value of $H\rho$. The calibrations in terms of the three lines gave a value for ρ with a variation of less than 0.02%, thus confirming the excellent linearity of response claimed for the instrument by the manufacturer.

Measurements of the Ga^{66} positron spectrum were made with the usual center defining baffle made of $\frac{3}{4}$-in.-thick aluminum.[11] With positrons of energies up to 4.15 MeV, there is a possibility of partial transmission through the edges of such a thick baffle as well as small angle scattering from the surfaces of the baffle. Additional measurements were made with a baffle constructed of $\frac{1}{16}$-in. tantalum having the same geometrical opening as the aluminum baffle (see Sec. III). No change was observed in the shape of the Ga^{66} positron spectrum. This indicates that the spectrum was not being distorted by the defining baffle system. New detector slits constructed of $\frac{1}{16}$-in. tantalum were used to reduce the thickness of the slit edges. Experiments were performed to determine the effect on the background resulting from bremsstrahlung and annihilation radiation generated in the slit materials.

Source Preparation

The gallium activity was prepared by bombarding a copper probe with 18-MeV α particles in the Indiana University Cyclotron. The probe tip was dissolved in concentrated nitric acid, and this solution was reduced to dryness. The residue was redissolved in $6N$ HCl, and the gallium separated from the copper without the addition of carrier by the ether extraction process. The gallium activity was separated from the ether solution by back extracting into water. The final sources were liquid deposited on 20-μg/cm^2 Zapon films supported by 0.9-mg/cm^2 aluminized Mylar. The sources were covered with 20-μg/cm^2 Zapon films. In all cases the sources were between 4 and 5 mm in width, and the detector slits were fixed at 4 mm in width. The length of the sources and the detector slits were 2.5 cm. Insulin was used to help spread the activity over the source area. The source thickness was estimated at less than 0.5 mg/cm^2.

The necessity for thin sources and backings, demanded by past investigations of low-energy deviations in the shapes of beta spectra, was not required here since the detailed measurements of this study were limited to energies above 1.8 MeV. Previous experience has indicated that the source thickness and backings used in these experiments should have no influence on the interpretation of the data. Liquid deposited sources although somewhat thicker than evaporated ones are much more intense, hence better statistical accuracy is obtained.

III. TREATMENT OF DATA

Bombardment of natural copper with α particles produces both Ga^{66} and Ga^{68}. Ga^{68} has a half-life of 68 min. The data were taken in such a way as to make negligible any distortion of the Ga^{66} spectra by the presence of Ga^{68} activity. The source was placed in the spectrometer 4 to 5 h after bombardment. The first run was started at energies beyond the end point of the Ga^{68} spectrum (1.9 MeV). If the second run were started below the Ga^{68} end point, at least 12 to 15 h had elapsed since production of the Ga. This was sufficient time so that the lower energy spectrum of Ga^{66} was not distorted. A limit on the amount of distortion was obtained with one of the sources by beginning the initial run well below the end point of the Ga^{68} spectrum. From this run, the intensity of Ga^{68} relative to the intensity of Ga^{66} at the time the measurements were begun could be determined. A period of 11 h introduced an error of less than 0.05% in the counting rate of the Ga^{66} spectrum where the peak of the Ga^{68} spectrum occurred. In all cases where low-energy measurements of Ga^{66} were made, more than 11 h had elapsed between the production of gallium and the beginning of the low-energy measurements. This is important if definitive information is to be obtained about the existence and intensity of the 1.4- and 1.8-MeV beta groups in Ga^{66}.

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[12] J. H. Hamilton, L. M. Langer, R. L. Robinson, and W. G. Smith, Phys. Rev. **112**, 945 (1958).
[13] Rawson Lush Type 822 Rotating Coil Gaussmeter, Rawson Electrical Instrument Company.
[14] *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 227.

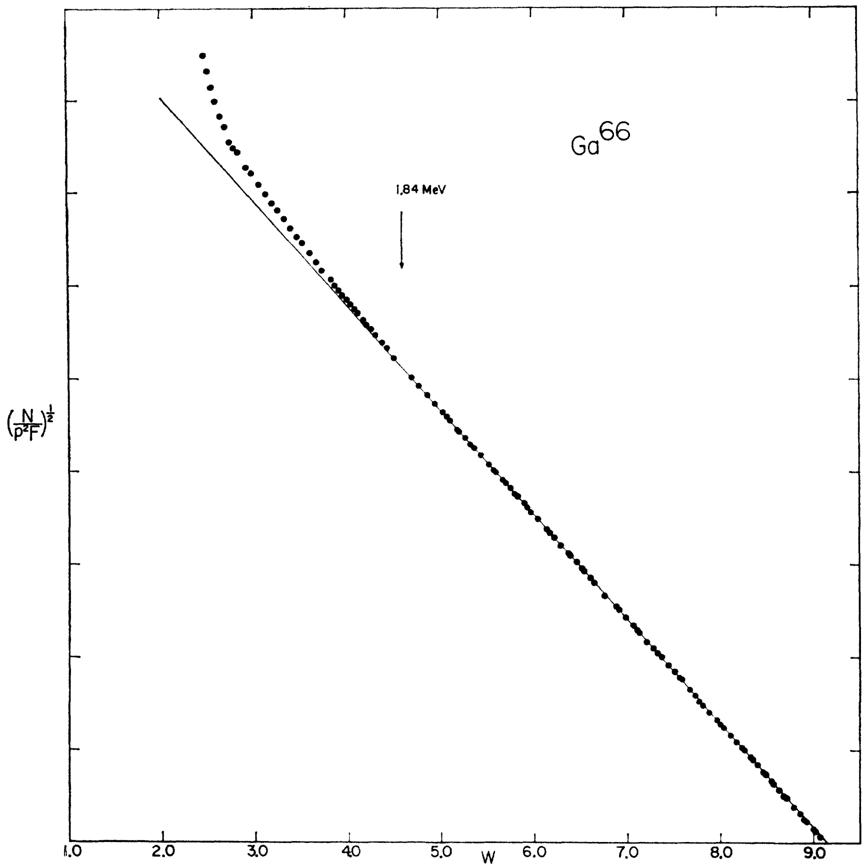

FIG. 1. F-K plot of the Ga^{66} beta distribution.

The sources used had an initial maximum counting rate at the peak of the Ga^{66} spectrum of from 50 000 to 170 000 counts per minute. Counting periods for each datum point were a minimum of 3 min, and in all cases the total number of counts recorded exceeded 10 000. The half-life used to correct the data was 9.40 h.

For the earlier portion of this study, when the shape factor appeared to be statistical, the data for the F-K plot were fitted with a least-squares straight line from $W=4.5$ to the end point. However, when it became evident that the shape factor was nonstatistical, a smooth curve was drawn through the data above $W=7$ in order to obtain a value for the end point. Since a value for the end point must be chosen before a shape factor can be calculated, the exact value was regarded as a parameter so that a smooth variation with energy was obtained for the shape factor. The deviation above $W=7$ from a least-squares straight line through the data is so small that it is not readily apparent on the F-K plot shown in Fig. 1.

The first two sources were measured using a loop anode, proportional counter operated at 10-cm pressure. The efficiency of the counter at this pressure began to fall off at values of $H\rho$ above 11 500. As the magnetic field was increased, more of the ionization produced by the positron radiation failed to be collected at the anode. As a result scintillation techniques were employed to detect the radiation. The first source using the scintillation techniques gave a shape factor consistent with a statistical shape, and these early results were reported at the Mexico City meeting of the American Physical Society.[15] For the first three sources the determination of $H\rho$ was made from a set of calibration equations connecting the voltage picked up by a rotating coil with the direct current generating a reference Helmholtz field.[16] Subsequently, it became apparent after the new gaussmeter was installed that there was an error in the calibration equations. It turned out that the error was just sufficient to remove the energy dependence and result in the erroneous statistical shape reported. The new Rawson coil was used with the next source. A straight line was least-squares fitted to the F-K plot and a tentative maximum energy, W_0, obtained. Using this value of W_0 a shape factor was calculated. It was found that the shape factor increases with energy from $W=5.4$ to $W=7.5$. Above $W=7.5$ there is a rapid falling off with energy.

Because of the higher background which accompanied the use of the scintillation equipment, the proportional counter was again used, but at a gas pressure of 15 cm

[15] L. M. Langer, D. C. Camp, and D. R. Smith, Bull. Am. Phys. Soc. **6**, 334 (1961).
[16] L. M. Langer and F. R. Scott, Rev. Sci. Instr. **21**, 522 (1950).

of Hg. Such an increase in pressure necessitates an increase in the operating voltage of the counter. The increased gas pressure and higher voltage were sufficient to overcome the magnetron effect which existed at 10 cm. A test of the counter at 20-cm pressure showed that 15-cm pressure was more than sufficient to maintain the constant sensitivity over the range of energies examined. Using a Ga^{66} source, plateau checks were carried out on the proportional counter at various energies up to 3.6 MeV. These results indicated that the selected operating voltage was good for the entire range of energies investigated.

A tentative maximum energy release was determined by an extrapolation of a linear least-squares fit to the data. This value of W_0 was then used to calculate a shape factor. Above $W=7.5$, the data fall off rapidly with increasing energy as shown in Fig. 2. When the two sources using the proportional counter and the scintillation equipment are adjusted for differences in intensity, and their shape factors plotted on the same scale, the agreement is excellent. Because of the sharp turn down, the maximum energies was redetermined by drawing a smooth curve through the data above $W=7$. This value of W_0 is lower than that obtained from the linear least-squares analysis. This lower value of W_0 permits one to obtain a shape factor which does not approach zero or infinity as W approaches W_0.

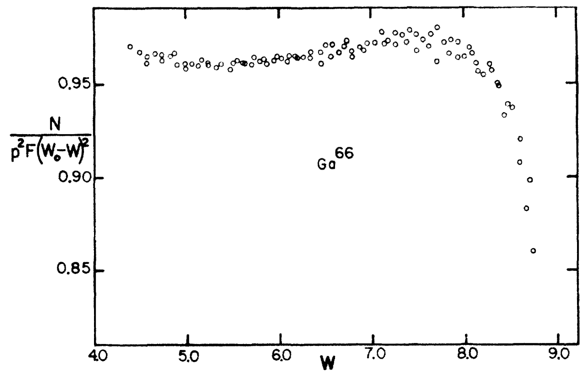

FIG. 2. Shape factor plot of the high-energy positron distribution of Ga^{66}. The tentative value of the end-point energy, $W_0=9.145$, was obtained from the linear extrapolation of a least-squares fit to the F-K plot.

Treatment of Background

The sharp falling off in the region of the end point on the shape factor plot prompted an examination of the methods used to measure the background. The conventional method of using a gate inserted just in front of the detector to obtain the background does not give a sufficiently accurate measure of the background. The background consisted of three contributions: (1) the cosmic background which is independent of source strength; (2) the gamma background which is essentially independent of the variations in the magnetic field and decays with the source; and (3) the secondary radiation background. This third contribution comes from the background produced by radiation which does not go through the slit but strikes the slit material during the actual measurement. For electrons, this contribution would consist only of bremsstrahlung produced by the slit material while for positrons, there is the additional background from the annihilation radiation. This third contribution is a function of the spectrum of positrons. A more representative background was obtained by measuring the distribution of radiation in the focal plane of the spectrometer. This distribution was determined with the help of a movable slit at several different field settings and found to be a constant for any value of the field. Then, the background as a function of $H\rho$ was measured with a solid tantalum $\frac{1}{16}$-in. plate in front of the detector (no slit). From this, that fraction of the background due to radiation striking outside of a 4-mm slit was calculated making use of the known constant distribution of radiation at the spectrometer's focus.

In addition to the background, scattering from the faces of the center defining baffle might cause some distortion of the data. Similarly, partial transmission through the edges of this baffle might also distort the data. The main defining baffle was constructed of $\frac{3}{4}$-in.-thick aluminum. Another baffle of the same geometrical opening was constructed of $\frac{1}{16}$-in. tantalum in order to determine if the thicker baffle was distorting the data. Experimental runs were made with this baffle using the proportional counter operated at a pressure of 15 and 20 cm. In addition, two runs were made at 10-cm pressure using a newly designed side window counter. The result of the analysis using the new tantalum baffle was in excellent agreement with the data taken with the thicker aluminum baffle, indicating that the amount of partial transmission through and scattering off of the thicker center defining baffle is negligible. There was excellent agreement between the 15- and 20-cm pressure runs indicating that the counter was operating safely above the threshold of the magnetron effect. Additional confirmation was obtained from the agreement of both of these different pressure runs with that obtained using the side window counter. *Note added in proof.* Measurements made with a 0.4 cm$\times$2.3 cm surface barrier silicon detector yield the same spectrum shape.

IV. THE THEORETICAL SPECTRUM SHAPE FACTOR

According to the V-A law of beta decay,[17] the $0^+ \rightarrow 0^+$ transitions are generated solely by the vector part of the coupling, measured by a coupling constant C_V. The usual "allowed" approximation to this leads to a statistical shape for the spectrum, proportional to a

[17] E. J. Konopinski, in *Beta-and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, to be published), 2nd ed.

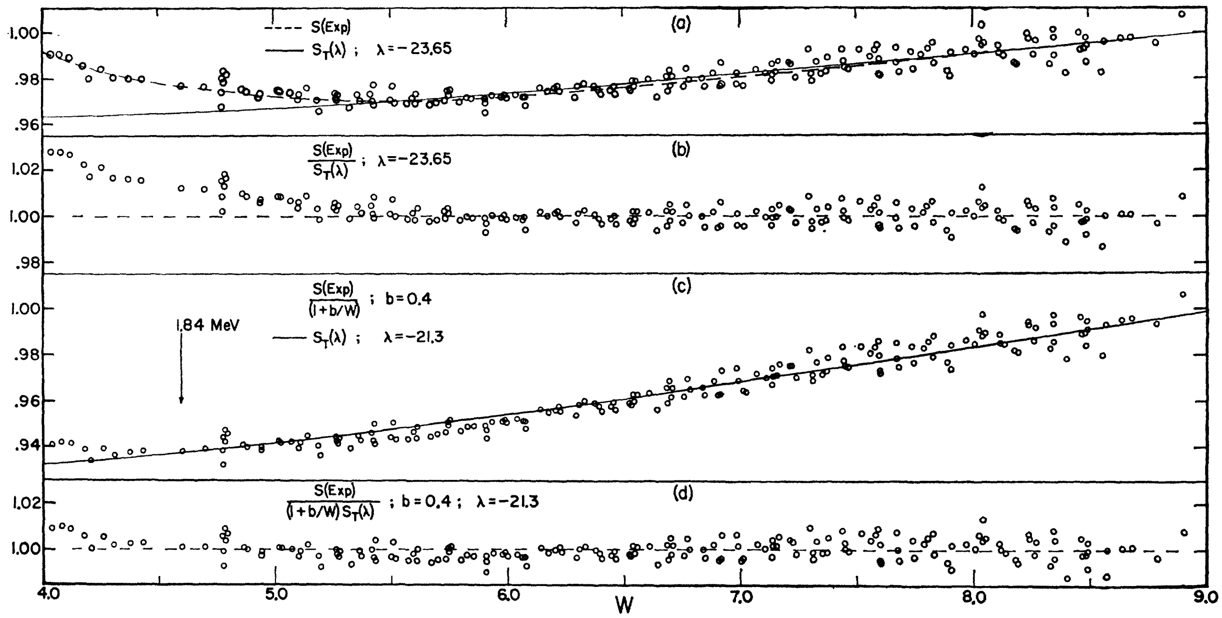

FIG. 3. Theoretical fits to the experimental shape factor distribution for Ga^{66}. The value of the end-point energy is $W_0=9.128$. The solid curve in (a) is the best fit of $S_T(\lambda)$ to the experimental data represented by the dashed curve. The value of λ which gives the best fit is -23.65. (b) shows the experimental shape factor divided by the theoretical fit of (a). The deviation from a constant for values of W less than 5.45 suggests the need for an additional factor of the form $(1+b/W)$. (c) shows the best theoretical fit to the experimental data after the empirical factor $(1+0.4/W)$ has been applied. The theoretical fit is obtained for $\lambda=-21.3$. (d) shows the experimental shape factor divided by both the empirical correction, $(1+0.4/W)$, and the theoretical shape $S_T(\lambda)$ for $\lambda=-21.3$. This quantity is a good constant over the whole range of energies down to $W=4.6$ where the 1.84-MeV beta group becomes evident.

nuclear moment (squared) symbolized by $\langle 1\rangle^2$. Improvements on the allowed approximation bring in contributions from another moment, symbolized by $\langle i\boldsymbol{\alpha}\cdot\hat{r}\rangle$. The corrections arising from this improvement are negligible unless the value of the moment $\langle 1\rangle$ is strongly depressed. In Ga^{66}, the initial and final nuclear states are expected to have different isotopic spins and this serves to suppress $\langle 1\rangle$ while $\langle i\boldsymbol{\alpha}\cdot\hat{r}\rangle$ may not be affected systematically at all.

The consequence for the spectrum is that the shape factor becomes dependent on the energy in a way governed by the size of the parameter $\lambda\equiv\langle i\boldsymbol{\alpha}\cdot\hat{r}\rangle/\langle 1\rangle$. The shape factor is presented as a power series expansion in the nuclear radius R, measured in units of $\hbar/mc$. The number R is of the order 0.012 for Ga^{66}, hence only terms through order R^2 will be kept. With these definitions, the shape factor for $0^+\rightarrow 0^+$ transitions may be written[18]

$$S_0{}^0=C_V{}^2\langle 1\rangle^2\frac{2}{1+\gamma_0}\{[(1-\tfrac{1}{3}q^2R^2)L_0+\tfrac{2}{3}qR\bar{N}_0+\tfrac{1}{9}q^2R^2\bar{M}_0]$$
$$+2\lambda\{[1-(4/9)q^2R^2]\bar{N}_0-\tfrac{1}{3}qR(L_0-\bar{M}_0)\}$$
$$+\lambda^2[(1-\tfrac{1}{3}q^2R^2)\bar{M}_0-\tfrac{2}{3}qR\bar{N}_0+\tfrac{1}{9}q^2R^2L_0]\},\quad (1)$$

where L_0, $\bar{M}_0=M_0R^2$, and $\bar{N}_0=N_0R$ are certain combinations of electron radial wave functions.[19] When these functions are evaluated for a point charge nucleus, they become

$$L_0=\frac{1+\gamma_0}{2}+\frac{\alpha ZR}{2\gamma_0+1}\left[(2\gamma_0+3)W+\frac{\gamma_0}{W}\right]-\tfrac{1}{3}W^2R^2,$$

$$\bar{M}_0=M_0R^2=\frac{1-\gamma_0}{2}-\frac{\alpha ZR}{2\gamma_0+1}\times\left[(2\gamma_0-1)W-\frac{\gamma_0}{W}\right]+\tfrac{1}{9}W^2R^2,$$

$$\bar{N}_0=N_0R=\frac{\alpha Z}{2}-\frac{R}{2\gamma_0+1}\times\left[(2\gamma_0{}^2+\gamma_0-2)W-\frac{\gamma_0}{W}\right]-\frac{11}{18}\alpha ZW^2R^2,\quad (2)$$

through order R^2, and $\gamma_0=(1-\alpha^2Z^2)^{1/2}$. It is convenient to express Eq. (1) in the form

$$S(W)=K(1+c_1W+c_2/W+c_3W^2).\quad (3)$$

In order to obtain expressions for the coefficients of the energy-dependent terms in (3) γ_0 has been set equal to one in the "centrifugal" terms proportional to R, of L_0, $\bar{M}_0$, and $\bar{N}_0$. The set of coefficients are found

[18] E. J. Konopinski (private communication).
[19] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **60**, 308 (1941).

to be

$$K=\left[1+\tfrac{1}{3}W_0R(\alpha Z-W_0R)-\frac{2}{9}R^2\right]+2\lambda\left(\frac{\alpha Z}{2}-\tfrac{1}{3}W_0R\right)$$
$$+\lambda^2\left[\frac{\alpha^2Z^2}{4}-\tfrac{1}{3}W_0R\alpha Z+\tfrac{1}{9}W_0^2R^2-\frac{1}{12}W_0^2R^2\alpha^2Z^2+\frac{2}{9}R^2\right],$$
$$Kc_1=\tfrac{4}{3}R\left[(\alpha Z+\tfrac{1}{3}W_0R)-\frac{\alpha Z\lambda}{2}(\tfrac{1}{4}\alpha Z-\tfrac{2}{3}W_0R)+\tfrac{1}{8}RW_0\alpha^2Z^2\lambda^2\right],$$
$$Kc_2=\tfrac{1}{3}R[\alpha Z+\tfrac{2}{3}W_0R+2\lambda+\lambda^2(\alpha Z-\tfrac{2}{3}W_0R)],$$
$$Kc_3=-\tfrac{1}{3}R^2[\tfrac{4}{3}+\alpha Z\lambda+\tfrac{1}{4}\alpha^2Z^2\lambda^2], \quad (4)$$

where the coefficient K must be positive. The best data were combined and an average value of the end-point energy W_0 determined and used in evaluating the coefficients.

V. RESULTS

The experimental shape factor of the combined proportional counter data is shown in (a) of Fig. 3. The dashed curve represents the experimental data and the solid curve is the best theoretical fit to this data and corresponds to a value of $\lambda=-23.65$. Values of c_1, c_2, and c_3 from this result for λ are:

$$c_1=0.0211,\quad c_2=0.295,\quad c_3=-0.000324.$$

The average end point for these combined data is $W_0=9.128$.

Figure 3(b) shows the experimental data divided by the theoretical shape for $\lambda=-23.65$. The data begin to deviate upward at $W<5.45$. Such a deviation might be interpreted as an inner group, and the value of $W=5.45$ would require an excited state in Zn^{66} in the neighborhood of 1.87 MeV. Since there exists such a level in Zn^{66} which has spin and parity 2^+, this would require that the transition to it be twice forbidden. The outer group may be subtracted and the intensity of the inner group determined. The log ft value which results is 8.0 which is much too low for a twice forbidden transition.

In Fig. 3(c) is shown the experimental data divided by an empirical factor $(1+0.4/W)$, and the solid curve is the best theoretical fit to this data. Such a factor has been found to play a role in other cases of allowed and forbidden decays. The theoretical shape corresponds to a value of $\lambda=-21.3$ and the values of c_1, c_2, and c_3 which result from this value of λ are:

$$c_1=0.03282,\quad c_2=0.354,\quad c_3=-0.000419.$$

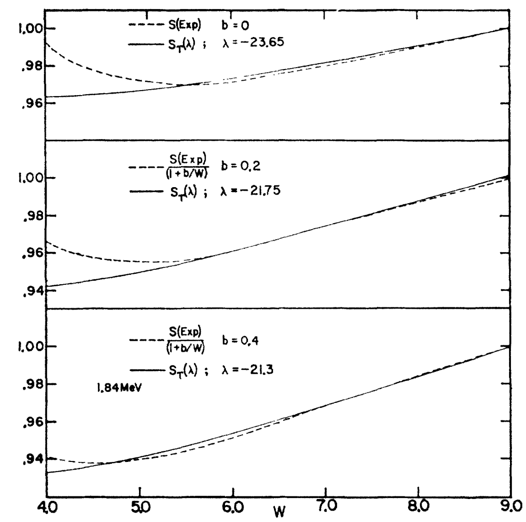

FIG. 4. Best theoretical fits of the shape factor $S_T(\lambda)$ after applying the additional empirical factor $(1+b/W)$ to the experimental distribution for values of $b=0$, 0.2, and 0.4.

Figure 3(d) shows the experimental data divided by both the empirical factor and the theoretical curve for $\lambda=-21.3$. The deviations now begin around $W=4.6$ which is consistent with a transition to an excited state at 2.313 MeV in Zn^{66}. Subtraction of the outer group using the combined shape factor yields a maximum energy of 1.84 MeV, with an error of plus or minus 50 keV. The large error in the end-point determination results from the very low intensity of this group. The intensity, if a statistical shape is assumed for this group, was found to be 0.54%.

The value of b in the empirical factor $(1+b/W)$ was found to be 0.4. The data divided by lower values of b are not fitted as well with a theoretical curve. Attempts at fits with values of b equal to 0.2 and 0.4 along with the value of $b=0$ are shown in Fig. 4. The dashed curves represent the experimental fit to the data. The dashed curve for $b=0$ is the same as the dashed curve in the top section of Fig. 3. The solid curves represent the best theoretical fit to the experimental data after the empirical corrections have been applied. The theoretical fit corresponding to the value of $b=0.2$ fits well for $W>5.6$, but falls low from $W=4.6$ to 5.6, again giving rise to an apparent second forbidden transition to the 1.87-MeV level in Zn^{66}. The deviation upward for $W<4.6$ in the lower section of Fig. 4 corresponds to the 1.84-MeV group.

The Decay Scheme

In the decay scheme shown in Fig. 5 the intensities of the pure electron capture levels are adopted from those given by Schwarzschild and Grodzins. The electron capture end points are figured from the γ-ray energies given by Schwarschild and Grodzins and our value for the total energy release in the decay, 5.175

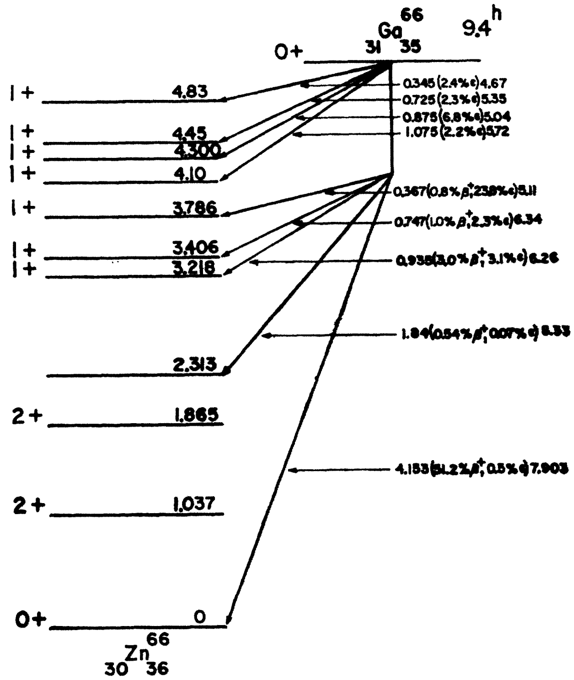

FIG. 5. Level scheme for the decay of Ga^{66}.

MeV. The intensities of the inner groups were determined by successive subtractions, assuming a statistical shape for all but the ground-state transition. Once the intensities of the positron groups were obtained, the electron capture branching ratios to these states were determined from curves giving the K capture to positron ratio.[20] A value of 10% was used for the L to K capture ratio. Table I shows a summary of the beta group energies with respective intensities and log ft values. For comparison, the values obtained for these transitions by Schwarzschild and Grodzins are given.

The $0^+ \rightarrow 0^+$ Transition

The maximum energy release has been determined to be 4.153±0.003 MeV. The quoted error includes both the statistical and the instrumental error. As mentioned in Sec. III the lower end point arises from the requirement that the shape factor behave properly in the neighborhood of the end point. If the spectrum were treated as having a statistical shape and the data least squares fitted to obtain a value for the end point, the average maximum energy becomes 4.160 MeV. This would be in good agreement with the value obtained by Schwarschild and Grodzins.

The intensity of the outer group is found to be 51.2%. This leads to a value for the $\log ft$ of 7.903±0.007. The largest error comes from the uncertainty in the half-life. If the lowest energy group (0.367 MeV) were assumed to have an error of ±10% in its intensity determination (which might arise from such effects as successive subtractions of the various groups and source thickness or backings), this would lead to an error of only ±0.003 in the $\log ft$ value for the $0^+ \rightarrow 0^+$ transition. With this value of $\log ft$, the admixture of the isotopic spin in the ground state of Ga^{66} can be determined. Assuming that the $T=3$ state is admixed into the normal $T=2$ state, we can evaluate the amount of admixture from the known $\log ft$ values of O^{14} and Ga^{66}. For a transition with isotopic spin, T,

$$(ft)^{-1}=C|\alpha|^2(T-T_z)(T+T_z+1), \tag{5}$$

where T_z refers to the third component of isotopic spin of the daughter.[10] The constant C is determined from the O^{14} decay in which $T=1$, $T_z=0$, $\alpha=1$, and the ft value is 3075±10 sec.[21] This then gives for O^{14}

$$(ft)_{O}^{-1}=2C. \tag{6}$$

For the Ga^{66} decay, $T=3$, $T_z=-3$, and α_{32} is the amplitude of the admixture of the $T=3$ state in the $T=2$ state. Thus, for Ga^{66},

$$(ft)_{Ga}^{-1}=6C|\alpha_{32}|^2. \tag{7}$$

However, this last equation must be modified since the spectrum is no longer statistical. One must replace Eq. (7) by

$$(ft)_{Ga}^{-1}=6C|\alpha_{32}|^2\langle S(W)\rangle, \tag{8}$$

where $\langle S(W)\rangle$ is an appropriate average over the spectrum. This spectrum average term would be one for the case of a statistical shape. Here, however, it can be written as

$$\langle S(W)\rangle=\langle S_0(W)\rangle+\langle S_1(W)\rangle\lambda+\langle S_2(W)\rangle\lambda^2 \tag{9}$$

or just Eq. (3) rewritten in a power series of λ rather than W. Combining Eqs. (8), (7), and (5), we find that the coefficient of admixture in the ground state of Ga^{66}

TABLE I. Summary of the beta group energies with respective intensities and $\log ft$ values.

Present investigation				Schwarzschild and Grodzins			
Level	β^+ energy (MeV)	Intensity (%)	$\log ft$	Level	β^+ energy (MeV)	Intensity (%)	$\log ft$
0	4.153	51.2	7.903	0	4.166	44	7.88
2.313	1.84	0.54	8.33	2.370	1.80	0.6	8.2
2.753	1.4	0.1			1.4	1.0	
3.218	0.935	3.03	6.26	3.22	0.946	3.8	6.2
3.406	0.747	0.97	6.34	3.40	0.767	0.9	6.3
3.786	0.367	0.82	5.11	3.785	0.381	1.2	5.0
	Electron capture energy (MeV)				Electron capture energy (MeV)		
4.10	1.075	2.2	5.72	4.10	1.088	2.2	5.6
4.300	0.875	6.8	5.04	4.300	0.888	6.8	5.1
4.45	0.725	2.3	5.35	4.45	0.738	2.3	5.8[a]
4.83	0.345	2.4	4.67	4.83	0.358	2.4	5.4[a]

[a] There is apparently an error in these quoted values.

[20] E. Feenberg and G. Trigg, Rev. Mod. Phys. 22, 399 (1950).

[21] P. K. Bardin, C. A. Barnes, W. A. Fowler, and P. A. Seeger, Phys. Rev. 127, 583 (1962).

can be expressed as

$$|\alpha_{32}|^2 = \frac{(ft)_O}{(ft)_{Ga}} \frac{1}{3} \frac{1}{\langle S(W) \rangle} = \frac{3075}{8\times 10^7 (3\times 0.32)}, \quad (10)$$

which gives

$$|\alpha_{32}|^2 = (4.00\pm 0.08)\times 10^{-5}. \quad (11)$$

The error is calculated from the quoted error in the O^{14} ft value and the error in our ft value for Ga^{66}.

VI. DISCUSSION AND CONCLUSIONS

The highest energy beta group proceeds from the 0^+ initial state of Ga^{66} to the 0^+ ground state of Zn^{66}. The transition is, therefore, governed by only the Fermi coupling constant C_V, and if it were not for the unusually high comparative half-life, one might expect the spectrum to have a statistical shape. This ground state to ground state transition has been carefully examined and found to have a nonstatistical shape (see Fig. 2). The energy dependence presumably arises from the interference of the matrix element $\langle i\boldsymbol{\alpha}\cdot\hat{r}\rangle$ with the normal allowed matrix element $\langle 1\rangle$. The shape factor can be fitted with a theoretically predicted shape of the form $S(W)=K(1+0.03282W+0.354/W-0.000419W^2)$ plus an empirical factor of the form $(1+0.4/W)$. The data cannot be fit as well without the empirical factor. If a fit is attempted without the empirical factor, then when the outer group is subtracted from the total spectrum, there is indication of an inner group which would have an end point of 2.29 MeV. If it is assumed that this corresponds to a transition to the 1.865-MeV level in Zn^{66}, then the comparative half-life which results is 8.0 and this is much too low for a twice forbidden transition.

Since the ground state–ground state transition proceeds by pure Fermi radiation, the necessity for the $(1+b/W)$ term suggests that the deviation found here and those found previously[1–4] in the electron spectra of In^{114}, Y^{90}, and P^{32}, and the positron spectra of Na^{22}, Zr^{89}, and Co^{56} are associated with both the Gamow-Teller and the Fermi parts of the beta interaction.

The intensity found for the outer group is higher than that reported by previous investigators who assumed a statistical shape for this ground-state transition. It is the nonstatistical shape that gives rise to the greater intensity. The nonstatistical shape also affects the determination of the end-point energy. The end-point energy was found to be 4.153 ± 0.003 MeV. When coupled with the intensity of 51.2% and a half-life of 9.4 h, this leads to a $\log ft$ value of 7.903. Using this value for the comparative half-life one can calculate the amount of the $T=3$ admixture in the $T=2$ ground state of Ga^{66}. This was found to be $(4.00\pm 0.08)\times 10^{-5}$. This value is larger than quoted in reference 10 because not all of the decay proceeds through the allowed matrix element $\langle 1\rangle$. Alford and French[10] assumed that the decay was generated solely by the normal allowed matrix element $\langle 1\rangle$, hence neglected the contribution to the decay from the $\langle i\boldsymbol{\alpha}\cdot\hat{r}\rangle$ matrix element.

No evidence for a 1.4-MeV beta group was found. If such a transition exists, its intensity must be much less than 0.1%. The 1.84-MeV transition has an intensity of only 0.54% and consequently its end-point energy cannot be determined to better than ± 50 keV by our data.

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