initial and final states of the nucleus and does not directly reflect the properties of the summed-over intermediate states that constitute the $E1$ giant resonance. The literal connections among all these phenomena arising in a deformed i.h.o. model simply indicate that the model is too simplified (it expresses deformation by one parameter only) for realistic application to nuclei.

The author wishes to acknowledge helpful discussions and correspondence from many sources, particularly Dr. E. G. Fuller, Dr. K. H. Lokan, Dr. B. M. Spicer, and Dr. N. W. Tanner.

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Positron Decay of Y^{88}[†][*]

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The weak positron spectrum in the decay of Y^{88} has been investigated using a 4π-positron-scintillation spectrometer. Two measurements of the spectrum yield experimental shape factors which are consistent above 250 keV with that expected for a unique once-forbidden transition. The average end-point energy obtained in these two measurements is 761±9 keV. The positron branching was measured and found to be 0.20±0.01%. The logft is 9.4, and logf_1t is 8.7. On the basis of recent measurements of the gamma-ray intensities in the Y^{88} decay the electron capture branching to the 1840-keV level is determined to be 5.8±0.7%, which yields an electron capture to positron ratio of 29±4 for this transition.

I. INTRODUCTION

According to the presently accepted decay scheme[1] (See Fig. 1.), Y^{88} decays primarily by an electron-capture transition to the 2740-keV second excited state of Sr^{88}. The 900-, 1840-keV gamma cascade arising in the de-excitation of this level is the most prominent feature in the decay. The existence, also, of a very weak positron group populating the 1840-keV first excited state of Sr^{88} has been known since at least as early as 1948. The results of magnetic spectrometer measurements by Peacock and Jones,[2] reported at that time, indicate that the intensity of the positron group is 0.19±0.04% of the total decay and that the end-point energy is 830±20 keV. Though the Fermi-Kurie plot constructed from their experimental positron distribution appears, roughly, to be linear above about 200 keV, they made no specific assertion about the shape. A positron distribution arising from internal-pair de-excitation of the 1840-keV state in Sr^{88} (populated in more than 90% of the decays) can be expected in the energy interval up to about 820 keV. Peacock and Jones were aware of this possibility but asserted that the effect did not cause appreciable distortion in their measurements. Later, Stirling and Goldberg[3] remeasured the Y^{88} positron spectrum using a double-focusing spectrometer. They reported that their gross experimental positron distribution was not a pure positron group, and concluded that it could be reasonably interpreted as a superposition of a positron spectrum having an end-point energy around 580 keV and a positron distribution from the internal-pair de-excitation of the 1840-keV level in Sr^{88}. More recently, Ramaswamy and Jastram[4] have measured the Y^{88} positron spectrum using a 4π scintillation spectrometer, gating on the an-

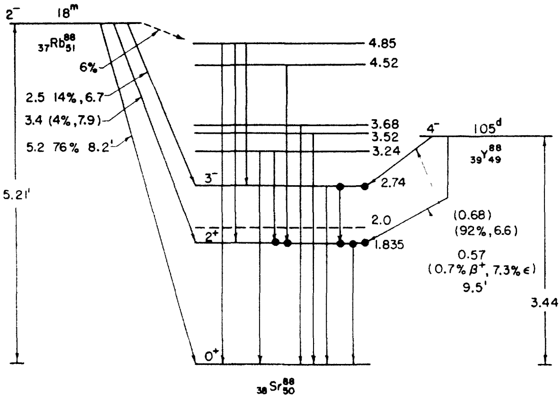

FIG. 1. Y^{88} decay scheme as given in the Nuclear Data Sheets, 1960. The values for the log f_1t and branching percentage of the first-excited-state transition are inconsistent.

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[*] This report is based on a portion of a thesis submitted by J. I. Rhode to the faculty of Purdue University in partial fulfillment of the requirements for the degree of Ph.D. in physics.

[‡] National Science Foundation Cooperative Fellow, September 1959 to September 1961. Present address: Physics Department, Indiana University, Bloomington, Indiana.

[1] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C., 1958–1962).

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nihilation quanta and the 1840-keV nuclear gamma radiation. This last requirement serves to eliminate problems associated with internal and external pairs. They reported that the positron spectrum exhibits the unique once-forbidden shape above about 200 keV and has an end-point energy of 560±30 keV, in good agreement with the results of Stirling and Goldberg. Very recently, results have been reported for threshold measurements in the [5,6] $Sr^{88}(p,n)Y^{88}$ and[6] $Sr^{88}(p,n)Y^{88*}(\gamma)Y^{88}$ reactions, which bear upon the question of the Y^{88} positron spectrum end-point energy. Nelson *et al.*[5] report a ground-state Q value for the $Sr^{88}(p,n)Y^{88}$ reaction of 4406±10 keV, which implies that the $Y^{88}-Sr^{88}$ mass difference is 3623±10 keV. Shafroth[6] gives a ground-state threshold value for the $Sr^{88}(p,n)Y^{88}$ reaction of 4452±6 keV. This latter number is an average of the values obtained from two different experiments. One was a direct $Sr^{88}(p,n)Y^{88}$ threshold measurement and the other a $Sr^{88}(p,n)Y^{88*}(\gamma)Y^{88}$ gamma-ray threshold measurement. He derived an $Y^{88}-Sr^{88}$ mass difference of 3619±6 keV.

Taking 1840±4 keV (a weighted average of all measurements since 1948 for which errors are given[2,7–12]) for the energy of the first excited state in Sr^{88}, one obtains either 761±10 keV or 757±7 keV for the expected end-point energy of the positron group, according as Nelson's or Shafroth's $Y^{88}-Sr^{88}$ mass differences, respectively, are used. While the positron spectrum end-point energies derived from these (p,n) measurements are in very good agreement, they differ considerably from the values obtained by direct beta measurements.

The spin and parity assignments for the ground, first, and second excited states of Sr^{88}, namely, 0^+, 2^+, and 3^-, respectively, have been well established through directional correlation[13–16] and polarization-directional correlation measurements.[17,18] The 0^+ assignment to the Sr^{88} ground state is expected on the basis of general theoretical arguments and nuclear systematics. The $E2$ character of the gamma transition from the first excited state to the ground state in Sr^{88} has been established from lifetime measurements,[19,20] pair angular correlation,[18] and the internal conversion coefficient.[2,10]

The Y^{88} ground-state spin and parity assignments can be made with some degree of confidence apart from consideration of the results of the shape measurements for the positron transition to the first excited state of Sr^{88}. The log ft value for the strong electron-capture transition to the 2740-keV state of Sr^{88} is around 6.6 according to the accepted decay scheme.[1] This log ft value is insensitive to minor variations in the branching percentage of the weak positron transition to the first excited state. On the basis of the log ft value the second excited state transition could be either allowed or once-forbidden nonunique. If one assumes the latter, then the Y^{88} ground state must have positive parity and a spin of 2, 3, or 4. The 2^+ and 3^+ assignments would not be consistent with the extremely small branching to the first excited state of Sr^{88}, since this transition should then be much more intense, being allowed and having a much greater decay energy than the second excited state group. A 4^+ assignment for the Y^{88} ground state would imply that the first excited state transition is twice forbidden. The experimental log ft value for this transition is about 9.5, which is low for a twice forbidden transition. Another objection to a 4^+ assignment for the Y^{88} ground state is the problem of obtaining a positive parity for a reasonable shell-model configuration. The systematics of the measured or assigned spins of nearby odd-even nuclei suggest that the ${}_{39}Y_{49}{}^{88}$ ground-state configuration is a $g_{9/2}$ neutron hole and a $p_{1/2}$ proton, for which the parity is negative. If the second excited state transition is assumed to be allowed, then the Y^{88} ground state would be 2^-, 3^-, or 4^-. The 2^- assignment can be reasonably excluded due to the absence of the ground-state positron group. The 3^- assignment is unlikely, since the expected shell-model configuration can not give a spin lower than 4. A direct application of the rule of Brennan and Bernstein[21] yields a spin of 4 for the Y^{88} ground state.

On the basis of these arguments it is very likely that the Y^{88} ground state is 4^-. This, of course, implies that the first excited state positron transition is unique once-forbidden and should, therefore, exhibit the characteristic shape.

The measurements to be described in this report were undertaken in order to investigate the positron mode of decay of Y^{88}. A direct measurement of the shape of the positron spectrum could serve to reduce, if not completely remove, the ambiguity in spin and parity assignments for the Y^{88} ground state. In addition, the determination of the end-point energy for this positron group would, together with the known excitation energy for the Sr^{88} first excited state, provide a determination of the Y^{88}–Sr^{88} mass difference.

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II. SOURCE PREPARATION

The Y^{88} activity used in this investigation was produced by the bombardment of natural strontium nitrate with 9.5-MeV deuterons in the external beam of the Purdue University Cyclotron. The shorter-lived yttrium activities were allowed to decay before the chemical separation was performed.

The target material was dissolved in dilute HCl, 1 mg La^{3+} carrier was added, and the solution was diluted to 10 ml. Three ml 6*M* NH_4Cl and 1 ml glacial acetic acid were added; the pH, measured with pH paper, was adjusted to 8–9 with conc. NH_4OH. This precipitates $La(OH)_3$, which carries the yttrium activity, and the large mass of strontium remains in solution. The $La(OH)_3$ precipitate was dissolved in conc. HNO_3 plus saturated H_3BO_3. $La(OH)_3$ was precipitated by adding NH_4OH. The hydroxide was dissolved in dilute HCl. The fluoride and hydroxide precipitations were repeated. The latter was dissolved in HCl and evaporated to dryness under a heat lamp. The $LaCl_3$ was dissolved in 0.05*M* HCl; the La^{3+} and Y^{88} were separated by eluting from a heated cation exchange column with lactic acid. The latter was removed by absorbing the Y^{88} on a cold cation column at a low HCl concentration, washing the lactic acid through, and eluting the Y^{88} with 6*M* HCl; or by destruction of the lactic acid by repeated evaporations with HNO_3.

The sources were prepared by the evaporation on thin Zaponite backings (areal density $<30\mu$ g/cm^2) of a dilute HCl solution containing the activity. The sources were then covered with a similar Zaponite film.

III. INSTRUMENTATION AND EXPERIMENTAL PROCEDURES

The spectrometer system used in these measurements of the positron spectrum of Y^{88} has been described in considerable detail elsewhere.[22] For convenience, however, a diagram of the experimental configuration is shown in Fig. 2, and a short description of the system is presented here.

It is a 4π scintillation spectrometer operated in conjunction with auxiliary gamma detectors and associated gating and coincidence circuitry. The beta detector is composed of two $1\frac{3}{8}$-in. diameter by $\frac{3}{16}$ in. thick cylindrical Pilot-*B* plastic scintillators, each of which is optically coupled to a separate photomultiplier tube. The mounted source is placed between the parallel and slightly separated faces of the plastic scintillator detectors. The outputs of the individual scintillation-phototube assemblies are amplified and added. The added pulse is further amplified and passed to a multichannel differential pulse-height analyzer. The system is calibrated using the electron internal conversion lines of Bi^{207} (974 keV), Cs^{137} (630 keV), Sn^{113} (368 keV), and In^{114} (175 keV). The energies assigned to these various lines are determined by locating the central position at half-maximum (in the case of Bi^{207} the maximum point) of the resultant distribution obtained by adding two Gaussian curves corresponding in energy, resolution, and magnitude, to the *K* and *L* conversion lines for the transition in question. These energy assignments are referred to as the E', or primed, energy assignments in reference 22, to distinguish them from other assignments based on different criteria. It is for this reason that the end-point energies for the Y^{88} positron spectra are indicated here with a prime, i.e., W_0'.

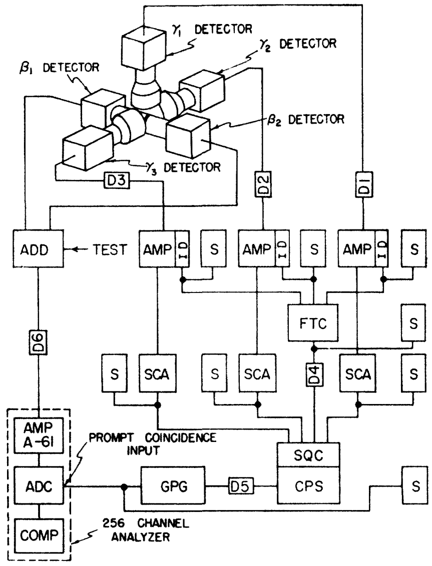

FIG. 2. Detector configuration and block diagram for positron-scintillation-spectrometer system with functional component designations as follows: γ_2, γ_3,=annihilation quanta detectors; γ_1=nuclear gamma-ray detector; *D*1,. . .,*D*6=variable lengths of delay cable (RG 65/*U*); AMP=linear amplifier; ID=integral discriminator contained in chassis of linear amplifier; S=scaler; FTC=fast triple coincidence circuit; SCA=single-channel analyzer; SQC=slow quadruple coincidence circuit; CPS=coincidence pulse shaper; GPG=gate pulse generator; ADD=linear addition circuit and cathode follower.

It is necessary to eliminate the distortion of the positron spectrum arising from Compton-scattered electrons due to the annihilation radiation and the coincident 1840-keV nuclear gamma radiation. Also, a means must be provided for discriminating against the detection of positrons from internal-pair de-excitation of the 1840-keV state in Sr^{88} and from external-pair production due to the 1840-keV gamma radiation. This is accomplished by gating the analyzer to accept and store pulses from the beta detector only when the two 511-keV annihilation quanta and the 1840-keV nuclear gamma radiation are simultaneously detected. A 2-μsec gate is obtained from the output of a conventional three-channel fast-slow coincidence system (resolving time 0.10 μsec). The pulses driving the coincidence circuit are derived from the gamma detector channels, each of which consists of a 3 in.×3 in. NaI(Tl) gamma detector, photomultiplier, preamplifier, amplifier, and single-channel

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differential discriminator. The windows of the differential discriminators associated with the annihilation-radiation-detector channels are set to span a 120-keV interval centered at 511 keV, while that in the nuclear gamma channel spans a 380-keV interval centered at 1840 keV.

Three measurements of the Y^{88} positron spectrum have been made using sources prepared from each of three different cyclotron bombardments. The earliest measurement is designated *A*, the second measurement *B*, and the last *C*. In all cases the general performance of the system was tested and evaluated using the results from measurements of the positron spectra of Zn^{65} and Na^{22} before each series of Y^{88} runs. In measurements *B* and *C* the performance was monitored by means of similar tests during the runs, and a final comprehensive test and evaluation was made at the completion of the measurements. The measuring period required to obtain an adequate number of counts in the distribution (about 8000 counts) was nominally 350 h. Each spectral measurement consisted of about 18 separate runs with each run extending over a period of nominally 20 h. At the end of a run the data accumulated and stored in the memory of the 256-channel pulse-height analyzer were printed out, and the memory was cleared. At this time the total "singles" and "in-channel" counts in the gamma channels, as well as the total gate and triple-coincidence counts were recorded. The stability of the gamma channels and the coincidence circuitry was monitored in part by checking the various counting rates for each day's run. The gamma channels were calibrated and realigned periodically (every four of five days) using the 900- and 1840-keV gamma lines from the Y^{88} positron source in exactly the same configuration that was used in the positron measurements proper. Between the various runs, the locations of only the 900-keV line in the annihilation-quanta channels and only the 1840-keV line in the nuclear-gamma channel were checked, and the positions of the windows were adjusted to compensate for any small variations. The timing alignment in the fast-slow triple coincidence circuit was checked by arranging it successively to operate as a double coincidence circuit in each of the three pairs of input channels and then noting the variation in double coincidence rate as the delay in each of the two contributing channels was varied. This procedure was required because the very low triple coincidence rate, 0.4 count per min., precluded a direct threefold coincidence alignment.

The calibration of the beta channel was checked every four or five days using the four internal conversion lines mentioned above. Between the complete calibrations the gain was monitored by observing the Compton edge of the 900-keV gamma line of Y^{88}, which is the most prominent feature in the ungated spectrum from the 4π detector. Small variations in gain that occurred between complete calibrations were compensated for by adjusting the high voltage on the photomultiplier tubes associated with the beta detectors. In general, it is possible to maintain the gain so that the maximum spread in the channel position of any given calibration line in all the separate calibration runs over a period of twenty days was no more than 3%. The final calibration to be used in analysis was obtained by taking an average of the channel positions for each of the various lines over all of the calibrations associated with a given measurement of the Y^{88} positron spectrum.

The Fermi-Kurie and shape-factor plots for these measurements were constructed utilizing graphs of $\eta^2F(Z,\eta)$ prepared from published tables.[23] Outer screening corrections[24] have been applied in all cases. A correction for finite resolution[25] has been applied to the body of the spectrum, but not to the data near the end point. The end-point correction given in reference 25 assumes a statistical spectral shape near the end point and, therefore, is not applicable to a spectrum which, as in *B* and *C*, is interpreted as having a nonstatistical shape. The end-point correction significantly affects only the two highest energy points of the spectrum in the present measurements. Furthermore, these points are statistically unreliable and therefore do not play any significant role in the determination of the spectrum shape. For this reason the matter of the end-point correction is not critical.

The source intensities were adjusted so that the ungated, analyzed pulse rate from the 4π detector was less than 2000 counts/sec. This rate produced an analyzer dead time of nominally 17% at the amplifier gain used in these measurements. The proper operation of the system at these counting rates was established through measurements of test spectra using Na^{22} and Zn^{65}. On the basis of the ungated, analyzed pulse rate, the gate rate, and the gate pulse width, the chance-coincidence rate was calculated to be less than 0.5% of the coincidence count rate in the analyzer. This was confirmed experimentally by observing the chance-coincidence rate when operating with time-displaced gate pulses. The coincidence background with the Y^{88} source removed was checked and found to be negligible.

IV. EXPERIMENTAL RESULTS AND CONCLUSIONS

The results of measurement *A* have been reported elsewhere.[26,27] The experimental positron spectrum yielded a Fermi-Kurie plot (F–K plot) that was linear within statistics above approximately 280 keV. A straight line fitted to the linear portion of the data gave an end-point energy of 770±10 keV. Below 280 keV the F–K plot turned upward, suggesting the possible

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existence of one or more weak lower energy positron groups. In attempting to understand this latter feature a careful re-examination of the data and experimental procedures was made. An intercomparison of data from the various runs which were added to obtain the final spectrum revealed evidence for a small secular change in the shape of the experimental distribution. No definitive evidence could be found to support the conclusion that the effect had a phsycial rather than instrumental origin. Consequently, in measurements *B* and *C*, experimental procedures were modified in such a way as to permit a better monitoring of the performance of the system. In addition, certain minor modifications in instrumentation were made in an effort to increase the over-all reliabliity of the spectrometer.

The F–K plot and shape-factor plot for measurement *B* are shown in Fig. 3. The F–K plot for $a=1$ shows the curvature which is characteristic of a unique once-forbidden transition. The experimental shape-factor plot for $W_0'=2.45$ (maximum kinetic energy 741 keV) is resonably well fit above $W=1.5$ by the curve *C* proportional to the theoretical unique once-forbidden shape factor, $(W_0'-W)^2L_0+9L_1$.[28] Below $W=1.5$ the experimental shape factor exhibits a deviation above the theoretical curve. The error in the end-point energy is estimated to be ±12 keV on the basis of the behavior of the experimental shape factor as the end-point energy is adjusted and on estimated random errors in calibration. No evidence was found for any secular variation in the shape of the distribution throughout this series of runs.

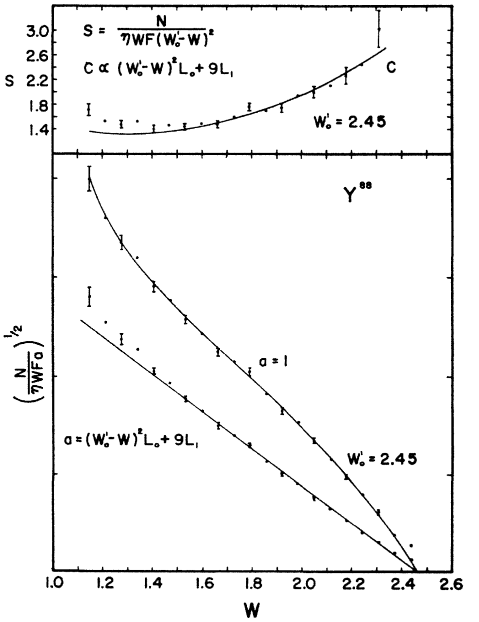

FIG. 3. Fermi-Kurie and shape-factor plot for measurement *B* of the Y^{88} positron spectrum.

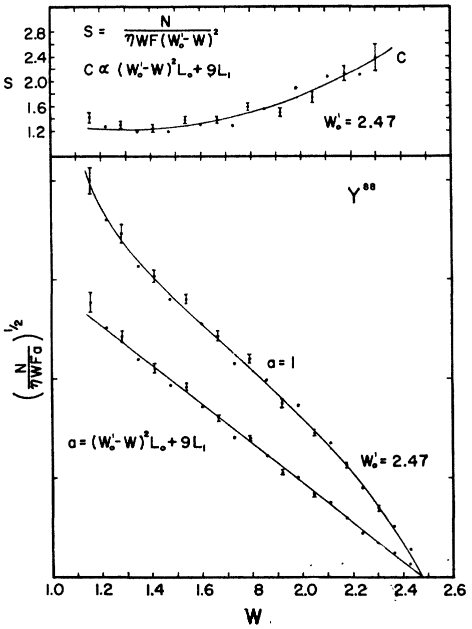

FIG. 4. Fermi-Kurie and shape-factor plot for measurement *C* of the Y^{88} positron spectrum.

The F–K and shape-factor plots for measurement *C* are shown in Fig. 4. Here again the F–K plot indicates a unique once-forbidden spectrum. The experimental shape factor for $W_0'=2.47$ (maximum kinetic energy 751 keV) is well fit above $W=1.2$ by the theoretical unique once-forbidden shape factor. There is a small upward deviation of the experimental shape factor below $W=1.2$, but it is smaller than in the preceding measurement. The error in the end-point energy here is again estimated to be ±12 keV. There was no indication of any secular variation in the shape of the spectrum during this measurement.

The average end-point energy for these two measurements is 746±9 keV. It has been observed in measurements of the Na^{22} and Zn^{65} positron spectra with this system that the experimental end-point energies are consistently about 2% below accepted values.[22] On this basis, then, an empirical increase of 2% is made in the Y^{88} positron spectrum end-point energy, which brings it to 761±9 keV. This is in excellent agreement with the values calculated on the basis of the (*p*,*n*) results discussed in Sec. I. A more detailed discussion of this systematic error in end-point energies is presented in reference 22.

Within the last several years experimental results have been reported which indicate that small deviations from theoretically predicted shapes may occur in unique once-forbidden transitions.[29–31] The limited sta-

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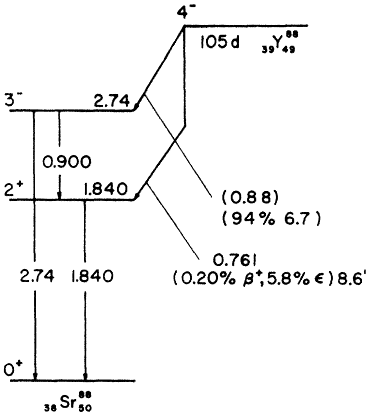

FIG. 5. Y^{88} decay scheme proposed on the basis of the present measurements.

tistical accuracy of the data presented here, together with the small discrepancy between the results of measurements *B* and *C*, precludes making any assertions about such effects for this transition.

In addition to making determinations of the spectrum shape and end-point energy, it is also possible to extract from these measurements values for the positron branching to the 1840-keV first excited state in Sr^{88}. This was accomplished by calibrating the efficiency of the spectrometer with data from the Na^{22} and Zn^{65} positron spectrum measurements. The positron branching percentages obtained for the three spectrum measurements discussed here are $0.23\pm0.01\%$ for measurement *A* and $0.20\pm0.01\%$ for measurements *B* and *C*.

If it is assumed that the positron decay to other levels in Sr^{88} is completely negligible in comparison to that to the 1840-keV level, then the experimental end-point energy and positron branching determined in this work, together with the half-life, can be used to determine the log *ft* value for the transition. For $W_0=2.49$ and $t_{1/2}=105d^1$, the log *ft* values[32,33] from measurements *B* and *C* are both 9.4 (that from measurement *A* is essentially the same). Using an expression and curves given by Davidson,[34] one obtains from this log *ft* value a log f_1t, appropriate for a unique once-forbidden transition, of 8.7. It is of interest to note that this value is very near the center of the range of log f_1t values obtained for various other known unique once-forbidden transitions.

Recently, Peelle and Love[35] have reported very accurate values for the relative intensities of the gamma transitions associated with the decay of Y^{88}, which may be combined with the positron branching percentage determined here to yield a value for the electron capture to positron ratio for this transition. These investigators reported that the ratio of the 1840- to the 900-keV gamma transition is 1.064 ± 0.008, and the ratio of the weak 2740-keV cross-over transition to the 1840-keV transition is $(5.97\pm0.25)\times10^{-3}$. On the basis of these relative intensity values and a positron branching of $0.20\pm0.01\%$, the electron-capture branching to the first excited state is $5.8\pm0.7\%$, and the electron capture to positron ratio is 29 ± 4. From the tables of Zweifel[36] and an expression by Rose,[37] the theoretical value of this ratio for a unique once-forbidden transition with end-point energy of 761 ± 9 keV is calculated to be 25 ± 2. The electron-capture branching to the 2740-keV state, which can also be determined, is $94.0\pm0.7\%$, and the log *ft* is 6.7. In Fig. 5 is presented the decay scheme for Y^{88} proposed on the basis of the present measurements.

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