assumption of pure $M1$ radiation and the second to pure $E2$ radiation for the gamma rays.

The half-life for the decay of the second excited state of Tc^{99} has been measured[11] to be $(3.57\pm0.05)\times10^{-9}$ sec. By means of the equation

$$(\tau_{1/2})^{-1}=1.4T_\gamma(E2)(1+\alpha),$$

it is possible to relate the observed lifetime to the transition probability for gamma-ray emission $T_\gamma(E2)$. For the conversion coefficient α, an experimental value of 0.13 ± 0.03 has been found.[8] The transition probability thus obtained may be converted to a reduced transition probability by a simple calculation.[1] The cross section for Coulomb excitation and the corresponding radiative lifetime thus provide two independent measurements of $B(E2)$. From the radiative lifetime, a value of 0.045×10^{-48} cm^4 is obtained for $B(E2)/e^2$, while the Coulomb excitation data reported here result in a value of 0.021×10^{-48} cm^4. The Coulomb excitation reduced transition probability is smaller by a factor of 2 which reflects the limited accuracy of the yield determination for the radiation from the second excited state.

The Weisskopf single-particle estimate[12] for the reduced transition probability is given by

$$B_{\rm sp}(E\lambda)/e^2=\frac{S}{4\pi}\left(\frac{3}{3+\lambda}\right)^2R_0^{2\lambda},$$

with $R_0=1.2A^{1/3}$ F, and S a statistical factor which depends on the spins of the initial and final states involved and the multipole order λ. In the present work S has been somewhat arbitrarily taken[1] to be $(2\lambda+1)$.

The nucleus Ta^{181} is typical of strongly deformed nuclei for which one finds reduced transition probabilities of 10–100 times the Weisskopf single-particle estimate. The reduced transition probabilities from Sm^{147} and Tc^{99} are comparable in magnitude to the single-particle estimate.

The authors wish to thank Dr. E. Merzbacher for helpful comments

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Positron Decay of Co^{58}[†][*]

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The allowed positron transition from the Co^{58} ground state (2+) to the Fe^{58} first excited state (2+, 810 keV) was studied using a 4π positron-scintillation spectrometer. The experimental shape factor exhibits a small systematic deviation from that theoretically predicted for an allowed transition and corresponds to an excess of low-energy positrons. The experimental shape factor can be fit by a curve proportional to $(1+b/W)$ with $b=0.3$. The Fermi-Kurie plot is linearized by this correction factor and yields an end-point energy of 474 ± 5 keV. Similar discrepancies between the experimental and theoretically predicted shapes of Gamow-Teller beta transitions for negatrons (In^{114}, P^{32}, and Y^{90}) and positrons (Na^{22}) have been reported. In these cases it was found that this same shape factor with $0.2<b<0.4$ would linearize the theoretically-corrected Fermi-Kurie plots. No satisfactory explanation for this effect has been offered. As previously suggested by other investigators, the shape factor $(1+b/W)$ must, for the present, be regarded as a purely empirical correction. The end-point energy from the present investigation combined with the recent high-precision measurement of the gamma-ray transition energy from the first excited state to the ground state of Fe^{58} yields a Co^{58}-Fe^{58} mass difference of 2306 ± 5 keV.

INTRODUCTION

SMALL discrepancies between the experimental and theoretical shapes of certain beta spectra have been reported by various investigators.[1] Johnson, Johnson, and Langer[2] have reported small systematic deviations from linearity in the theoretically-corrected Fermi-Kurie (F-K) plots for the Gamow-Teller (G-T) electron transitions in In^{114}, P^{32}, and Y^{90}. In each case, the F-K plot deviated from linearity in a manner corresponding to an excess of low-energy electrons, and it could be linearized

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[*] This report is based in part on 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. See also, O. E. Johnson and J. I. Rhode, Bull. Am. Phys. Soc. **8**, 74 (1962).

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[1] For a comprehensive review and discussion of the measurement of beta spectra, in general, and these deviations, in particular, see L. M. Langer, in *Proceedings of Rehovoth Conference on Nuclear Structure*, (North-Holland Publishing Company, Amsterdam, 1958), p. 437.

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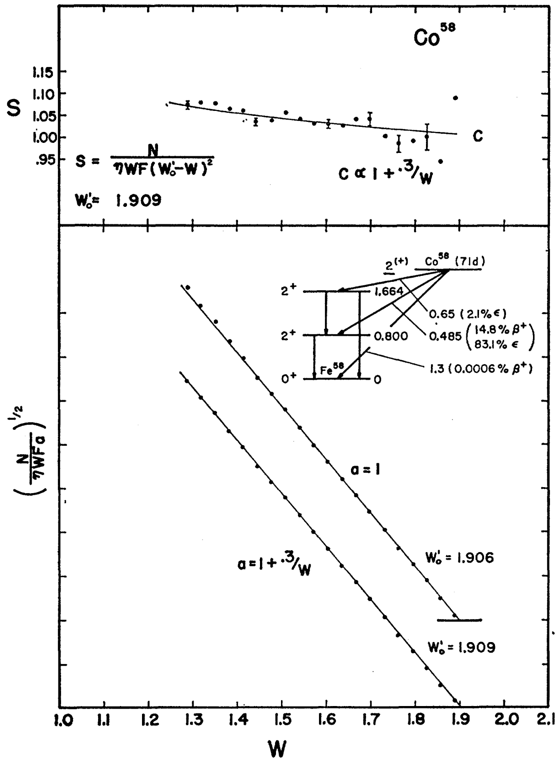

FIG. 1. The decay scheme for Co^{58} is taken directly from the *Nuclear Data Sheets* (see Ref. 16). The upper plot is the experimental shape factor corresponding to a W_0' value of 1.909 for the dominant positron group in the decay of Co^{58}. The curve, $C \propto (1+0.3/W)$, is normalized to the data point at $W' \approx 1.6$. The lower plots are the "corrected" Fermi-Kurie plots for two forms of the shape factor, a. The straight lines are fitted to the experimental points, and the end-point energies are obtained from their intercepts. See the text and Ref. 30 and 34 for an explanation of the energy calibration and end-point energies.

by an empirical shape factor of the form $(1+b/W)$, where the "best" value of b is in the range $0.2<b<0.4$. Yuasa, Laberrique-Frolow, and Feuvaris[3] observed a similar deviation in the Y^{90} spectrum. Porter, Wagner, and Freedman[4] found a similar deviation in the P^{32} spectrum, but it was smaller in magnitude than that reported by Johnson *et al.*[2] The results for the P^{32} spectrum reported by Graham, Geiger, and Eastwood[5] are in closer agreement with those of Johnson *et al.*[2] than those of Porter *et al.*[4]

The empirical shape factor suggested by Johnson *et al.*[2] has the same form as that associated with Fierz interference.[6] For a G-T transition the quantity b, the Fierz parameter, which appears in the Fierz term, is a combination of the tensor and axial vector coupling constants and the G-T matrix elements.[7] Experimental evidence derived from the measurement of the electron-capture to positron ratios, K/β^+ ratios, of various isotopes,[8–11] and the polarization of beta particles[12] has been interpreted in support of the conclusion that Fierz interference is either nonexistent or at most extremely small. The results of statistical analyses of selected, published beta spectra have also been interpreted to support this conclusion.[13,14] Hamilton, Langer, and Smith[15] measured the positron spectrum of Na^{22}, an allowed G-T transition, and reported that a shape factor of the form $(1+b/W)$ with $b \approx 0.3$ would linearize the resulting F-K plot. It should be pointed out that if the source of the nonlinearity were Fierz interference, then a change in the sign of b would be expected for positron spectra. These investigators suggest that the abnormally high log ft value of 7.4 for Na^{22} might make it less than an ideal case for comparison with negatron spectra. (A similar reservation might be made in the case of the P^{32} negatron spectrum, log $ft \approx 7.9$.)

The decay of Co^{58} to Fe^{58} has been studied by many investigators. In Fig. 1 is a reproduction from the *Nuclear Data Sheets*[16] of the decay scheme based on an interpretation of experimental information available before about December, 1960. The experimental results reported since that time have not indicated a need for major revision. Of particular interest is the principal mode of decay, the positron transition between the ground state (2+) of Co^{58} and the first excited state (2+) of Fe^{58}. On the basis of the selection rule ($\Delta I=0$, no), this transition would be classified as an allowed, mixed Fermi, and Gamow-Teller transition. It has been shown through nuclear alignment experiments that this transition is almost pure Gamow-Teller. Dagley, Grace, Hill, and Sowter[17] reported a Fermi admixture of 0.003 ± 0.005 and concluded that this measurement is "consistent with the complete absence of a Fermi admixture and makes it unlikely that it exceeds 0.005." Chapman, Gregory, Hill, and Johns[18] make the follow-

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ing summarizing statement: "Analysis shows that the limit of $\lambda=0.003\pm0.005$ for the intensity of the Fermi contribution set by Dagley *et al.*[17] is inconsistent both with their experiments and ours, and must be replaced by the less stringent limit of $\lambda=0.01\pm0.01$." This statement was based on the analysis of data from additional alignment experiments extending to much lower temperatures than used by Dagley *et al.*[17] Recently, MacArthur, Goodman, Artna, and Johns[19] reported the results of a reanalysis of the Oxford data on the alignment of Co^{58} using an improved experimental value for the branching ratio of the 865-keV gamma-ray transition. The Fermi admixture was determined to be 0.008 ± 0.004 which is consistent with the results of Chapman *et al.*[18] and indicates that a small Fermi admixture does exist in the decay. A number of experimental K/β^+ ratios for Co^{58} have been reported.[11,20–23] A weighted average of these values is 5.11 ± 0.02 which is higher than the theoretical values of 5.0 and 4.87 calculated by Zweifel[24] and Depommier *et al.*,[25] respectively. The most recent and most accurate, also the lowest, experimental value of the K/β^+ ratio was reported by Joshi and Lewis,[11] 4.92 ± 0.09. These investigators combined this result with the theoretical K/β^+ ratio of Depommier *et al.*[25] and determined the Fierz parameter for Co^{58} to be $+0.006\pm0.023$. The results of four investigations of the Co^{58} positron spectrum have been reported. Deutsch and Elliot,[26] and Cheng, Dick, and Kurbatov[27] obtained end-point energies of 470 ± 15 and 472 ± 6 keV, respectively, but made no specific assertions concerning the shape of the spectrum. Strauch[28] reported an end-point energy of 485 keV and a linear F-K plot above 150 keV. The investigations of Cork, Brice, and Schmid[29] yielded an end-point energy of 485 ± 10 keV and a F-K plot which was linear above 75 keV.

The Co^{58} decay provides an experimentally favorable case for the study of an interesting positron spectrum. The transition of interest is strong, and the general features of the decay scheme permit the effective use of coincidence and scintillation techniques. Furthermore, the positron group has been shown to be an almost pure G-T transition, and the log *ft*, which is 6.6, is well within the expected range for an allowed transition.

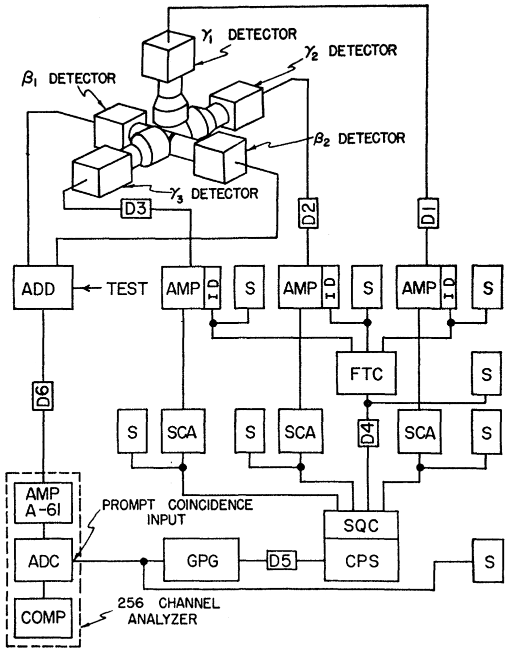

FIG. 2. Block diagram of the 4π scintillation spectrometer system for positrons. The functional component designations are: γ_1, nuclear gamma-ray detector; γ_2, γ_3, annihilation quanta detectors; $D_1\cdots D_6$, variable lengths of delay cable (RG 65/U); AMP, linear amplifier; ID, integral discriminators in linear amplifier chassis; S, scaler; FTC, fast triple coincidence circuits; SCA, single channel pulse-height analyzer; SQC, slow quadruple coincidence circuit; CPS, coincidence-pulse shaper; GPG, gate-pulse generator; and ADD, addition circuit.

EXPERIMENTAL

The source material was obtained from Oak Ridge National Laboratory. It was represented as being carrier-free with total solids less than 10 mg/mCi and was assayed to have a Co^{60} contaminant of less than 5%. The Co^{60} percentage at the time of the measurements was less than 10%. No further chemical processing was performed. The source material in the form of CoCl_2 was deposited from an aqueous solution on a thin, transparent Zaponite-lacquer film (area density <30 μg/cm^2). The region of source deposition was a circular area with a nominal diameter of 0.125 in. A similar covering film was applied over the source.

The positron spectrum was measured using a 4π positron-scintillation spectrometer system. A functional block-diagram of the circuit configuration and a schematic representation of the relative orientation of the five detectors are presented in Fig. 2. The reliability of this spectrometer system for the measurement of spectral shapes and end-point energies has been extensively investigated. The experimental results of these investigations are presented, discussed, and evaluated in detail elsewhere.[30]

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The spectrometer system consists of a 4π beta detector (β_1 and β_2), auxiliary gamma detectors (γ_1, γ_2, and γ_3), and associated coincidence and pulse-height analysis circuitry. The 4π beta detector is composed of two identical assemblies each of which consists of a right cylindrical (1.375-in. diam and 0.188-in. height) Pilot-B plastic phosphor optically coupled to a 2-in. photomultiplier tube (DuMont 6292). The source, mounted as described above, is placed between the parallel and slightly separated faces of the phosphors of the beta detectors. The outputs from the individual phosphor-phototube assemblies are amplified and added. The added-output is analyzed in a multichannel differential pulse-height analyzer when an appropriate gating pulse is provided. It is necessary to eliminate the distortion of the positron spectrum caused by Compton-scattered electrons due to the annihilation radiation and any coincident nuclear gamma radiation. This is accomplished by gating the analyzer to process only those added-pulses from the 4π beta detector for which a threefold gamma coincidence (two 511-keV annihilation quanta and the 800-keV nuclear gamma ray) has been registered. The gate pulse (2 μsec wide) is obtained from a three-channel fast-slow coincidence system (resolving time $\approx 0.10\ \mu$sec). The pulses which drive the coincidence system are derived from the gamma channels each of which consists of a 3×3-in. NaI(Tl) scintillation crystal, a 3-in. photomultiplier tube (DuMont 6363), preamplifier, linear amplifier, and single-channel differential discriminator. The discriminators associated with the two gamma detectors which are 180° apart (γ_2 and γ_3) are set to span the photoelectric peak of the annihilation quanta (a 120-keV interval centered at 511 keV), and the discriminator associated with the nuclear gamma detector (γ_1) spans a 180-keV interval at 800 keV.

The energy calibration of the 4π beta detector was accomplished using the internal conversion electrons associated with the decay of In^{114}, Sn^{113}, and Cs^{137}, and Bi^{207}. The nominal beta energy resolution for the Ba^{137m} internal conversion line was 11%. The energy calibration of the gamma channels was accomplished using gamma rays from various radioisotopes. The nominal resolution of these detectors in this spectrometer geometry was 9% for the 662-keV gamma ray from Ba^{137m}.

RESULTS AND DISCUSSION

The shape factor and Fermi-Kurie plots were constructed from the experimental data using published tables of Fermi functions.[31] Corrections were made for outer screening[32] and finite resolution[33] effects. In the lower portion of Fig. 1, two F-K plots are presented. The upper set of points is obtained in an analysis for which the correction factor, a, is taken to be constant, i.e., a conventional F-K plot. The positron spectrum would be said to have a "statistical shape" if the points fell on a straight line. A straight line fitted to those points for $W'>1.4$ yields an end-point energy of[34] $W_0'=1.906$ in units of the electron rest mass. The experimental points appear to be well fit by this line for $W'>1.4$; however, there is a tendency for the points to fall slightly above the line in the lower energy region. In the upper portion of Fig. 1 an experimental shape factor plot is shown. In this type of analysis, the behavior of the experimental points in the vicinity of the end point is very sensitive to the value of W_0' selected. The limits on the end-point energy were determined from a detailed study of the behavior of the experimental shape factor using W_0' as an adjustable parameter. The behavior of the last three experimental points should not be weighted too heavily due to their relatively poor statistical accuracy and to the approximations involved in the finite resolution end-point correction.[33] Using this procedure, the limits for W_0' were determined to be 1.906 and 1.912 with a "best" value of 1.909. The shape-factor plot for $W_0'=1.909$ is well fit by a curve which is proportional to $(1+0.3/W)$ and normalized to the experimental point at $W'\approx 1.6$. In the lower portion of Fig. 1 the data is analyzed using $a=(1+0.3/W)$. A straight line fitted to these points yields an end-point energy $W_0'=1.909$, which is consistent with the value obtained from the shape-factor analysis. It is interesting to note that while there is little apparent difference between the linearity of the two F-K plots, the experimental shape factor displays a definite departure from the energy independence which would be expected for an allowed transition with a statistical shape.

Instrumental and experimental effects, particularly those associated with this scintillation spectrometer configuration, have been extensively investigated, and are reported in detail elsewhere.[30] It has been demonstrated generally that the experimental shapes of beta spectra measured with this spectrometer system are consistent with the results of other investigations in which magnetic analysis was employed. On this basis it is concluded that the experimental shape observed for the 474-keV positron group of Co^{58} in this investigation represents the undistorted positron energy spectrum.

It should be re-emphasized that there are discrepancies among the reported experimental shape factors which have been determined from direct measurements of the beta-ray energy distributions. However, if only those cases in which a shape factor of the form $(1+b/W)$ with $0.2<b<0.3$ are considered, then it may be con-

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[31] *Tables for the Analysis of Beta Spectra*, National Bureau of Standards, Applied Mathematics Series No. 13 (U. S. Government Printing Office, Washington, D. C., 1952).

[32] J. R. Reitz, Phys. Rev. **77**, 10 (1950).

[33] J. P. Palmer and L. J. Laslett, Iowa State College Report ISC-175, 1950 (unpublished).

[34] Unless otherwise stated it may be assumed that the values quoted for the end-point energies are based on an energy calibration which assumes the following energy assignments for the conversion lines In^{114} (175 keV), Sn^{113} (368 keV), and Cs^{137} (630 keV). These are the "primed energy assignments" of Ref. 30 in which a detailed discussion of the problem of energy calibration is presented.

cluded that Fierz interference does not occur, since the algebraic sign of b for these measurements is the same for both positron and negatron spectra. The results of the present investigation represent another case in which b has been found to be a positive quantity with an experimental value in this same range. The present study has not provided any further insight into the origin of this effect; consequently, this shape factor must be regarded as a purely empirical correction as has been previously suggested.[15]

Several theoretical attempts[35,36] to find a satisfactory explanation of this anomalous beta-shape factor have not been completely successful and/or completely free of assumptions to which there are serious objections. Recently, Bhalla has presented an analysis[37] of the experimental shape factor of the allowed negatron decay of In^{114}, a pure G-T transition, which was reported to have the $(1+b/W)$-form: $0.2<b<0.3$, by Johnson *et al.*[2], and $0.03\leq b\leq 0.07$, by Daniel *et al.*[38] He claims that a reasonable fit for either range of b values may be obtained within the framework of the V-A theory by including the contributions of certain second-order effects. In particular, accurate electronic radial functions are used, and second forbidden matrix elements are included in the analysis. As given by Bhalla, the analysis involves the adjustment of two of three available parameters which are the ratios of various nuclear matrix elements. With two adjustable parameters and possibly a third at one's disposal, there would appear to be no difficulty in fitting the experimental Co^{58} shape.

As stated previously, Fierz analyses based on K/β^+ ratios[8–11] yield results which are interpreted in support of the conclusion that Fierz interference is either nonexistent or at most an extremely small effect. This type of analysis requires a theoretical calculation of the K/β^+ ratio assuming no Fierz interference. In essence, what is involved in this case is a determination of a theoretical allowed K-capture transition probability and a corresponding positron transition probability. If certain possible "second-order" effects are present and are responsible for at least a portion of the observed deviation in shapes of allowed spectra, then it is clear that the positron transition probability will be altered to some extent. Such second-order effects, however, may also affect the K-capture transition probability as well. To date, no adequate theoretical treatment of this latter effect has been given, therefore, one cannot say with complete confidence whether the calculated K/β^+ ratio will be larger, smaller, or essentially no different than the value calculated neglecting such higher order effects. It appears, then, that the full significance of a Fierz analysis on the basis of K/β^+ ratios cannot be understood unless this other question is settled first.

The observed anomalies in experimental beta shapes certainly do not support the existence of Fierz interference. If the Fierz parameter is zero or small, as it appears to be, then any deviations of experimental K/β^+ ratios from the theoretical values must be attributed to other effects. The comparison of experimental and theoretical K/β^+ ratios for various allowed transitions given by Depommier *et al.*[25] indicates that discrepancies may be present in certain cases, although the large experimental errors and considerable spread in experimental values for the same transition prevent definitive judgement. The case of Co^{58} is one in which a fairly significant difference is found between the measured and calculated K/β^+ ratios, and it is here also that an anomalous shape has been found. In contrast, the experimental values of the K/β^+ ratio for the Na^{22} positron transition exhibit no over-all discrepancy with the theoretical value even though a $(1+b/W)$-shape factor has been reported for the positron spectrum.[15]

Problems associated with the energy calibration of this spectrometer system have been discussed fully elsewhere.[30] In brief, it was found that if the primed energy assignments given in Ref. 34 are used for the calibration line energies, then an empirical increase (2% for positrons and 1% for negatrons) in the experimental value of the maximum beta-ray kinetic energy must be consistent with magnetic spectrometer measurements. Consequently, the energy of this positron transition is given as 474±5 keV. If this value is combined with the recent high-precision measurement by MacArthur *et al.*[19] of the gamma-ray transition energy from the first excited state to the ground state of Fe^{58}, a Co^{58}-Fe^{58} mass difference of 2306±5 keV is obtained.

ACKNOWLEDGMENTS

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