# Energy Levels of $^{56}$Fe†

K. W. Dolan, D. K. McDaniels, and D. O. Wells
*Department of Physics, University of Oregon, Eugene, Oregon*
(Received 28 February 1966)

The energies and relative intensities of the gamma radiations following the decay of $^{56}$Co to $^{56}$Fe have been measured using a 3-mm depletion-depth lithium-drifted germanium detector. Gamma rays of the following energies were observed (relative intensities in parentheses): 846.5(100.0), 1038.1(12.4), 1238.6(71.2), 1359.9(3.8), 1770.8(15.6), 2015.6(3.8), 2034.7(7.8), 2598.9(16.0), 3009.5(1.9), 3202.3(2.9), 3254.0(5.8), 3273.6(1.2), 3452.6(0.7), and 3548.3(0.2) keV. A decay scheme was constructed with levels at 846.5($2^+$), 2085.1($4^+$), 3123.2($4^+$), 3445.2($3^+$), 3856.0($3^+$), 4048.8, 4100.6, 4120.0, 4299.1, and 4394.8 keV. No evidence was found for doublet energy levels at 3123.2 and 3445.2 keV as indicated in recent particle-scattering experiments, thus supporting spin assignments of $1^+$ for the unobserved members. The energies of several new gamma-ray standards were established. Energies and relative intensities of gamma-ray transitions following the decay of $^{58}$Co to $^{58}$Fe were also measured and found to be 810.2(100.0), 863.8(0.64), and 1674.9(0.46) keV.

## 1. INTRODUCTION

THE gamma rays from the decay of $^{56}$Co to $^{56}$Fe (77.3 days[1]) have been studied extensively with the use of scintillation spectrometers.[2–11] The results of these experiments are summarized in Table I. The most complete information on the gamma-ray spectrum and the $^{56}$Fe level scheme is contained in the article by Kienle and Segel.[2] These authors studied the levels of $^{56}$Fe populated in the decay of both $^{56}$Mn and $^{56}$Co, and their measurements included beta-gamma and gamma-gamma coincidence studies. Most of the knowledge of the spins of the excited states comes from the extensive angular-distribution and linear-polarization measurements of gamma rays emitted by oriented $^{56}$Co nuclei by Diddens *et al.*[3] Their results established spin assignments for levels populated in $^{56}$Co decay at 845($2^+$), 2080($4^+$), 3450($3^+$), 3840($3^+$), and 4100($4^+$) keV.

We have restudied the $^{56}$Fe gamma-ray spectrum using a lithium-drifted germanium detector[12] for several reasons. In the first place it is apparent from Table I that considerable disagreement exists among previous investigators as to the gamma ray transitions coming from the $^{56}$Co decay. Furthermore, the very high Compton background made extremely difficult the investigation of possible low-energy gamma rays when using NaI(Tl) crystals. Finally, with the exception of the first excited state, different levels are populated in the decays of $^{56}$Co and $^{56}$Mn to $^{56}$Fe,[2] although transitions to the 3370- and 3450-keV levels would be expected to be equally allowed based on the spin assignments. The high resolution of lithium-drifted germanium detectors permitted further clarification of these questions and establishment of a very precise level scheme.

Table I. Summary of prior knowledge of the gamma rays from $^{56}$Co decay.

| Results previous to 1958[a] Established | Uncertain | J. W. Talley (1958)[b] | P. Kienle and R. E. Segel (1959)[c] |
|---|---|---|---|
| 845 (100%) | | 845 | 850 (100%) |
| | 975 (2%) | | |
| 1028 (16%) | | | 1040 (16%) |
| 1238 (70%) | | 1240 | 1240 (63%) |
| | | 1300 | |
| | 1330 (6%) | 1340 | 1370 (5%) |
| | 1500 ($\lesssim$1%) | | (1520) |
| 1750 (17%) | | 1740 | 1760 (23%) |
| | 1750 | 1770 | |
| 2020 (12%) | | | 2020 (12%) |
| | 2100 | | |
| | | | 2240 (0.3%) |
| | | 2540 | |
| 2609 (16%) | | 2600 | 2600 (16%) |
| | 2674 | 2660 | |
| | 2730 | | |
| 2990 (2%) | | | 2990 (0.7%) |
| 3250 (12%) | | 3200 | 3260 (8%) |
| | 3470 (1%) | | 3480 (0.3%) |

[a] A. N. Diddens, W. J. Huiskamp, J. C. Severiens, A. R. Miedema, and M. J. Steenland, Nucl. Phys. 5, 58 (1958).
[b] J. W. Talley, dissertation, Ohio State University, 1958 (unpublished).
[c] P. Kienle and R. E. Segel, Phys. Rev. 114, 1554 (1959).

In the production of $^{56}$Co by the bombardment of natural iron with alpha particles some $^{58}$Co was produced. New values for the energies and intensities of the transitions between levels in $^{58}$Fe are therefore included.

† Work supported in part by the U. S. Atomic Energy Commission.
[1] H. W. Wright, E. I. Wyatt, S. A. Reynolds, W. S. Lyon, and T. H. Handley, Nucl. Sci. Eng. 2, 427 (1957).
[2] P. Kienle and R. E. Segel, Phys. Rev. 114, 1554 (1959).
[3] A. N. Diddens, W. J. Huiskamp, J. C. Severiens, A. R. Miedema, and M. J. Steenland, Nucl. Phys. 5, 58 (1958).
[4] J. W. Talley, dissertation, Ohio State University, 1958 (unpublished).
[5] T. Azuma, F. T. Kokoszka, D. R. Cartwright, and J. D. Kurbatov, Bull. Am. Phys. Soc. 3, 103 (1958).
[6] C. S. Cook and F. M. Tomnovec, Phys. Rev. 104, 1407 (1956).
[7] O. J. Poppema, J. G. Siekman, R. van Wageningen, and H. A. Tolhoek, Physica 21, 223 (1955).
[8] K. P. Howard, T. A. Pond, and P. S. Jastram (private communication) quoted in *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C.), NRC 59-4-61.
[9] M. Sakai, J. Phys. Soc. Japan 10, 729 (1955).
[10] M. Sakai, J. L. Dick, W. S. Anderson, and J. D. Kurbatov, Phys. Rev. 95, 101 (1954).
[11] L. G. Elliott and M. Deutsch, Phys. Rev. 64, 321 (1943).
[12] K. W. Dolan, D. K. McDaniels, and D. O. Wells, Bull. Am. Phys. Soc. 10, 1204 (1965).

## 2. EXPERIMENTAL PROCEDURE

Radioactive $^{56}$Co was produced by bombarding pure iron foils with the 30-MeV degraded alpha-particle beam from the University of Washington cyclotron. The cobalt was extracted chemically from the targets and deposited on cellophane backings.[13,14] In addition to $^{56}$Co other radioactive isotopes present included $^{57}$Co, $^{58}$Co, and $^{60}$Co.

Singles spectra were obtained with a lithium-drifted germanium detector of 3-mm depletion depth and 160-mm$^2$ sensitive area. The low-noise electronics was provided by an ORTEC 101XL-201 preamplifier and amplifier system. Details of the detector mount and cooling have been discussed elsewhere.[13,15] The system resolution was 3.8 keV for the $^{60}$Co gamma rays for runs of a few hours length and varied from 4.0 to 5.0 keV for runs of 48 h or longer.

Energies of the strong gamma rays were obtained by recording appropriate standard gamma-ray sources simultaneously with the $^{56}$Co spectrum. Because of the lack of suitable calibration gamma rays of precisely known energy, it became necessary to establish a number of secondary standards. These measurements and the calibration sources used are discussed in the Appendix. The relationship between pulse height and energy was obtained by a least-squares fitting of the calibration peaks to a quadratic equation. The energy of each of the intense $^{56}$Co gamma rays was then determined from the calibration curves of five to eight independent runs and the results were averaged. Energies of weaker gamma rays were then determined in a similar manner using the strong $^{56}$Co lines as standards. For gamma rays with an energy greater than 2000 keV the energy determinations were made using the double-escape peaks. Since each double-escape peak has associated with it a full-energy peak with 1022.0-keV higher energy, we were then able to use the corresponding full-energy peaks as calibration standards for double-escape peaks of higher energy transitions.

The photopeak efficiency of the germanium detector was determined as a function of incident gamma-ray energy by comparing the photopeak areas for a large number of sources of known absolute source strength. These absolute source strengths were determined from photopeak areas measured using a 3-in.×3-in. NaI(Tl) scintillation spectrometer making use of tabulated NaI(Tl) efficiencies,[16] NaI(Tl) photopeak-to-total ratios,[17] and gamma-ray attenuation coefficients.[18] The germanium detector efficiency established from these data includes the effect of absorption in the Dewar window. The resultant photopeak-efficiency curve is presented in Fig. 1. The energy dependence of the efficiency agrees closely with that of the photoelectric cross section from 100 to 1000 keV. A reduction is noted below 100 keV due to attenuation in the Dewar window.

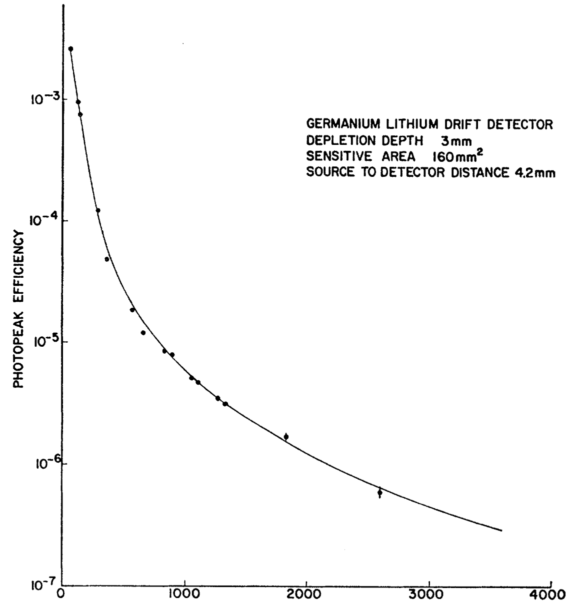


FIG. 1. Efficiency curve for the 3-mm depletion-depth lithium-drifted germanium detector.

For gamma-ray energies greater than 2000 keV positive identification of the gamma rays was made only after correlating the positions of the full-energy and double-escape peaks. For our detector, the number of counts in the double-escape peak was greater than that in the full-energy peak for this energy region. A few gamma-ray transitions were intense enough to exhibit single-escape peaks, thus providing another check for the positive identification of these gamma rays.

## 3. RESULTS

Typical pulse-height spectra observed with the 3-mm germanium detector are presented in Figs. 2 to 4. The gamma-ray spectrum below 900 keV is shown in Fig. 2. The strong peaks at 122.05 and 136.40 keV[19] were due to a $^{57}$Co contaminant in the source. The small peaks at 84, 170 and 194 keV were caused by higher energy gamma rays backscattering into the detector. The annihilation-radiation peak (511.006 keV[20]) was due to both $^{56}$Co and $^{58}$Co. The relative contributions from

[13] C. J. Piluso, D. O. Wells, and D. K. McDaniels, Nucl. Phys. **77**, 193 (1966).
[14] D. O. Wells, Ph.D. dissertation, Stanford University, 1962, pp. 127–130 (unpublished).
[15] P. Venugopala Rao, D. K. McDaniels, and B. Crasemann, Nucl. Phys. **81**, 296 (1966).
[16] E. A. Wolicki, R. Jastrow, and F. Brooks, U. S. Naval Research Laboratory Report No. 4833, 1956 (unpublished).
[17] S. H. Vegors, L. L. Marsden, and R. L. Heath, U. S. Atomic Energy Commission Report No. IDO-16370, 1958 (unpublished).
[18] G. White Grodstein, Natl. Bur. Std. (U. S.) Circ. No. 583 (1957).
[19] E. L. Chupp, J. W. M. DuMond, F. J. Gordon, R. C. Jopson, and Hans Mark, Phys. Rev. **109**, 2036 (1958).
[20] E. R. Cohen and J. W. M. Dumond, Rev. Mod. Phys. **37**, 537 (1965).

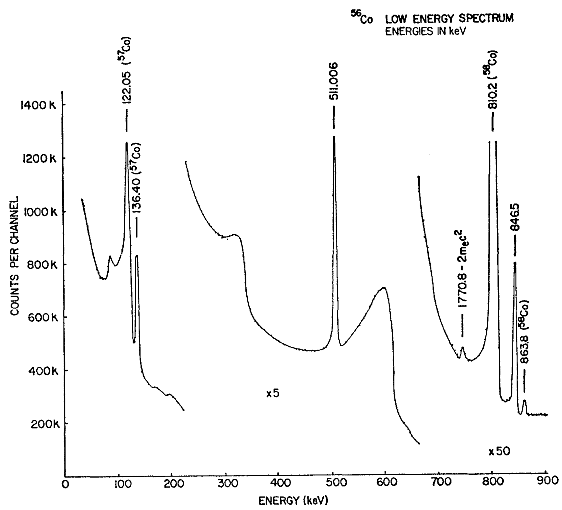


FIG. 2. $^{56}$Co gamma-ray spectrum obtained with a lithium-drifted germanium detector: 0–900 keV.

these two isotopes could not be separated because of their similar half-lives of 77.3 [1] and 71.3 [21] days. Both the 748.8-keV double-escape peak from the intense 1770.8-keV gamma ray and the 846.5-keV peak belong to $^{56}$Co. Those at 810.2 and 863.8 keV belong to $^{58}$Co. The double-escape peak for the 1674.9-keV gamma ray from $^{58}$Co was obscured by the Compton edge of the strong 810.2-keV gamma ray. A careful search was made for any weak transitions in this energy range and none was found with an intensity greater than 1% relative to the intensity of the 846.5-keV gamma ray.

In Fig. 3, $^{56}$Co gamma-ray photopeaks are apparent at 1038.1, 1238.6, 1359.9, and 1770.8 keV. The gamma ray at 1359.9 keV, seen previously only in coincidence experiments or after unfolding singles spectra, is firmly established. Double-escape peaks for gamma rays at 2015.6, 2034.7, and 2589.9 keV also appear in this portion of the spectrum. No evidence was found for

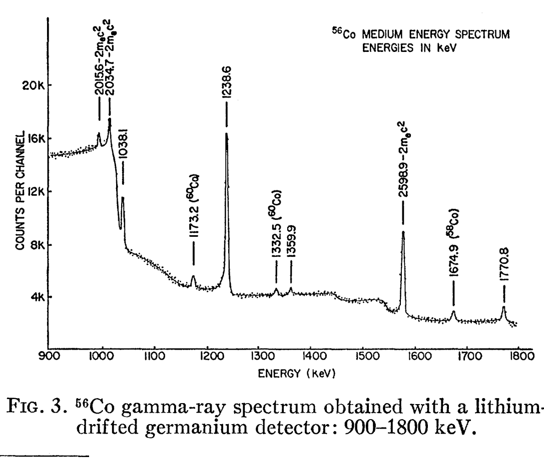


FIG. 3. $^{56}$Co gamma-ray spectrum obtained with a lithium-drifted germanium detector: 900–1800 keV.

[21] R. P. Schuman, M. E. Jones, and A. C. Mewherter, J. Inorg. Nucl. Chem. **3**, 160 (1956).

gamma rays at 975,[6] 1300,[4] and 1500 keV[2,4,8] as reported in earlier work. Upper limits of 0.5% were placed on gamma rays of these energies. The known peak at 1750 keV was found not to be double as reported by Howard *et al.*[8] and Talley[4] but rather to correspond to a single gamma ray at 1770.8 keV. The peaks at 1173.2 and 1332.5 keV[22] were identified as belonging to $^{60}$Co. The peak at 1674.9 keV was due to $^{58}$Co.

Figure 4 summarizes the spectra obtained between 1800 and 3600 keV. The well-established gamma ray at 2020 keV was resolved into a 2015.6- and 2034.7-keV doublet. Similarly the well-known 3250-keV peak actually consisted of gamma rays corresponding to transition energies of 3202.3, 3254.0, and 3273.6 keV. Weak transitions at 3009.5 and 3452.6 keV were confirmed and a new gamma ray was found at 3548.3 keV. The presence of all of these gamma rays was confirmed by their double-escape peaks and, in the case of the stronger transitions, by their single-escape peaks. A

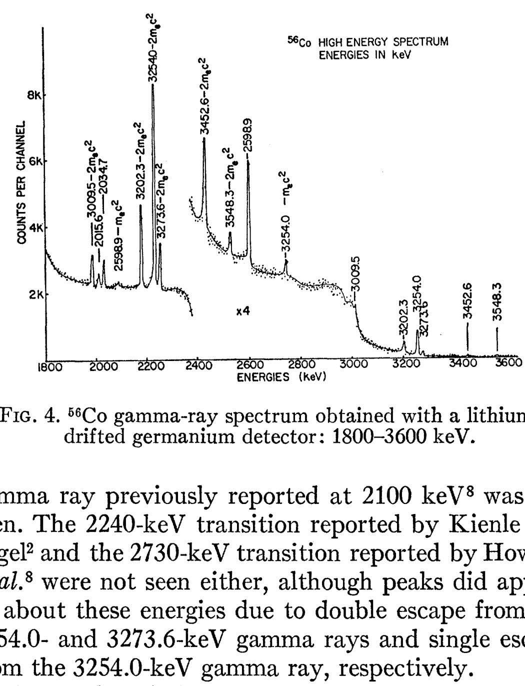


FIG. 4. $^{56}$Co gamma-ray spectrum obtained with a lithium-drifted germanium detector: 1800–3600 keV.

gamma ray previously reported at 2100 keV[8] was not seen. The 2240-keV transition reported by Kienle and Segel[2] and the 2730-keV transition reported by Howard *et al.*[8] were not seen either, although peaks did appear at about these energies due to double escape from the 3254.0- and 3273.6-keV gamma rays and single escape from the 3254.0-keV gamma ray, respectively.

The results of the present measurements are summarized in Table II and interpreted in the decay scheme of Fig. 5. The errors quoted on the energy values are standard deviations. All intensities are relative to 100 for the 846.5-keV gamma ray. The intensities of the beta-decay branches presented in the decay scheme were obtained from the relative intensities of the gamma rays depopulating the levels of $^{56}$Fe. The ratios of $K$-capture to positron emission were obtained by averaging previous results.[6,10,23]

[22] G. J. Nijgh, A. H. Wapstra, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (Interscience Publishers, Inc., New York, 1959), p. 126.

[23] J. H. Hamilton, L. M. Langer, and D. R. Smith, Phys. Rev. **123**, 189 (1961).

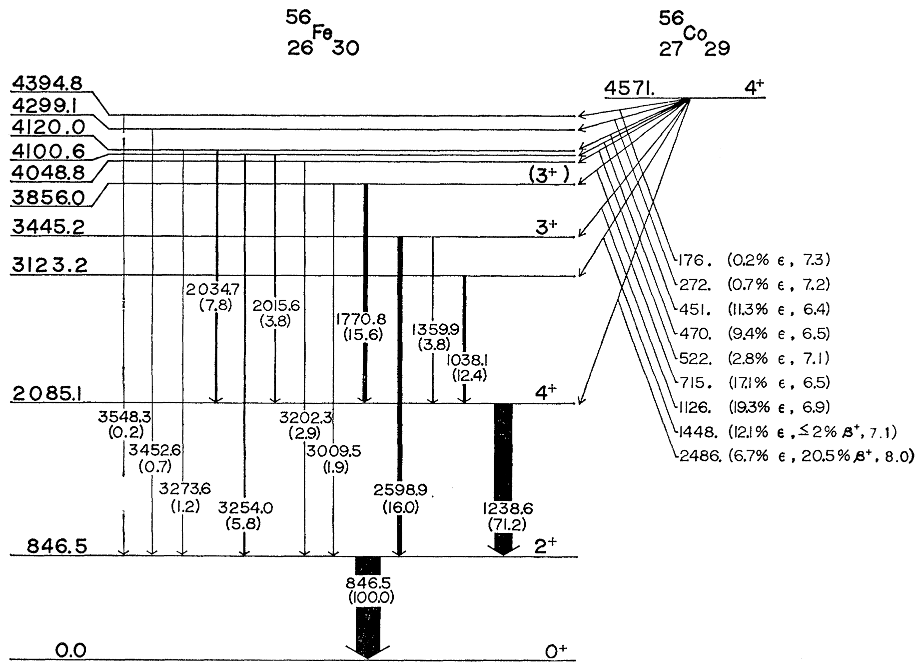


FIG. 5. Decay scheme for $^{56}$Co. Transition energies are given in keV; numbers in parentheses are transition intensities relative to 100 for the 846.5-keV gamma ray. The energies of the positron branches are from Ref. 23.

The energy and intensity measurements of the gamma-ray transitions in $^{58}$Fe are in good agreement with previous investigations[6,24–26] which indicated that

TABLE II. $^{56}$Co gamma-ray energies and relative intensities.

| Gamma-ray energy (keV) | Intensity |
|---|---|
| 846.5±0.2 | 100.0 |
| 1038.1±0.2 | 12.4±0.5 |
| 1238.6±0.2 | 71.2±2.6 |
| 1359.9±0.3 | 3.8±0.3 |
| 1770.8±0.4 | 15.6±1.3 |
| 2015.6±0.7 | 3.8±0.7 |
| 2034.7±0.3 | 7.8±1.0 |
| 2598.9±0.3 | 16.0±2.7 |
| 3009.5±0.4 | 1.9±0.8 |
| 3202.3±0.5 | 2.9±1.1 |
| 3254.0±0.5 | 5.8±2.2 |
| 3273.6±0.4 | 1.2±0.5 |
| 3452.6±0.5 | 0.7±0.3 |
| 3548.3±0.6 | 0.2±0.1 |

only two levels are populated in the beta-decay of $^{58}$Co. Gamma rays of 810.2±0.4(100.0), 863.8±0.2(0.64), and 1674.9±0.3(0.46) keV were found. MacArthur *et al.*[24] measured the transitions using a magnetic spectrometer, and their values of 810.48±0.1, 865±1, and 1673±10 keV agree within error with the present measurements.

## 4. DISCUSSION

A good measure of the accuracy of the energy determinations in the present study of the levels of $^{56}$Fe can be obtained by comparing the sums of the energies of cascaded gamma rays with the energies of the corresponding cross-over transitions. The four cases in which this comparison is possible are presented in Table III.

TABLE III. Comparison of the cascade- with the crossover-transition energies.

| Cascade-transition energies (keV) | Crossover-transition energies (keV) |
|---|---|
| (1359.9±0.3)+(1238.6±0.2)=2598.5±0.4 | 2598.9±0.3 |
| (1770.8±0.4)+(1238.6±0.2)=3009.4±0.4 | 3009.5±0.4 |
| (2015.6±0.7)+(1238.6±0.2)=3254.2±0.7 | 3254.0±0.5 |
| (2034.7±0.3)+(1238.6±0.2)=3273.3±0.4 | 3273.6±0.4 |

In every case the energies agree to within a few tenths of one keV.

Three levels not previously observed in the decay of $^{56}$Co are shown in the decay scheme of Fig. 5. The level formerly reported at 4100 keV is seen to consist of three levels at 4048.8, 4100.6, and 4120.0 keV. These levels were identified by resolving the gamma rays of 3202.3, 3254.0, and 3273.6 keV and of 2015.6 and 2034.7 keV. The other new level proposed in this work is at 4394.8 keV.

A careful search was made for additional gamma rays that would fit into the proposed decay scheme. The most likely possibilities are the 977-keV (4100.6 → 3123.2) and 1176-keV (4299.1 → 3123.2) transitions. If a 977-keV gamma ray exists it is too weak (<0.5%)

[24] D. MacArthur, R. Goodman, A. Artna, and M. W. Johns, Nucl. Phys. **38**, 106 (1962).
[25] H. Frauenfelder, N. Levine, A. Rossi, and S. Singer, Phys. Rev. **103**, 352 (1956).
[26] B. L. Robinson and R. W. Fink, Bull. Am. Phys. Soc. **1**, 40 (1956).

to be confirmed. The 1176-keV transition is also too weak to be definitely established, although the impurity $^{60}$Co gamma ray at 1173 keV appeared to be broadened toward higher energy in all of the data. A 2600-keV gamma ray reported in the work of Talley[4] and attributed to a ground-state transition from the 2657.8-keV level populated in the $^{56}$Mn decay was also not observed.

All of the $^{56}$Fe levels observed in this experiment have also been observed in charged particle reactions. The comprehensive results of Sperduto and Buechner[27] on the $^{56}$Fe$(p,p')^{56}$Fe reaction are presented in Fig. 6 where they are compared with the levels observed in the present work and in the $^{56}$Mn decay.[2,28]

Recent inelastic-scattering experiments with protons,[29,30] neutrons,[31] and alpha particles[32] have yielded evidence for doublet levels at 3120 ($3^-$ or $4^+$:$1^+$),[30,32] 3450($1^+$:$3^+$),[30–32] and 3600[$0^+$: (2)][30,32] keV with spacings of 3, 3, and 6 keV, respectively. Neither of the levels at 3600 keV was observed in this work. Population of both of the levels of the first two doublets would have resulted in a broadening of the observed transitions or in the presence of ground-state transitions. No evidence was found for these doublets. This is to be expected if the proposed assignment of $1^+$ for one member of each doublet is correct because of the large spin differences with the $^{56}$Co ground state ($4^+$). A gamma ray was seen at 3452.6 keV, an appropriate energy for a ground-state transition from the second level at about 3450 keV. However, this gamma ray is assumed to depopulate the established[27] level at 4299.1 keV because of the $1^+$ assignment to the doublet level.

Measurements by Diddens *et al.*[3] on the linear polarization of gamma rays from oriented $^{56}$Co nuclei established the spins of several of the excited states of $^{56}$Fe. The results of this group indicated assignments of $2^+$ for the 846.5-keV level, $4^+$ for the 2085.1-keV level, $3^+$ for the 3445.2- and 3856.0-keV levels, and $4^+$ for the 4100-keV level which was resolved into three levels in this experiment. The assignment of $3^+$ to the 3856.0-keV level may be questioned because of the relative intensities of the two gamma rays depopulating it.[2] An assignment of ($5^+$) has also been suggested for this level from inelastic neutron-scattering studies,[33] but this seems highly incompatible with the presence of a gamma transition to the $2^+$ level at 846.5 keV. The recent alpha-particle scattering experiments of Hendrie *et al.*[32] convincingly indicated a spin of $4^+$ for the 3123.2-keV level. Other investigators have suggested

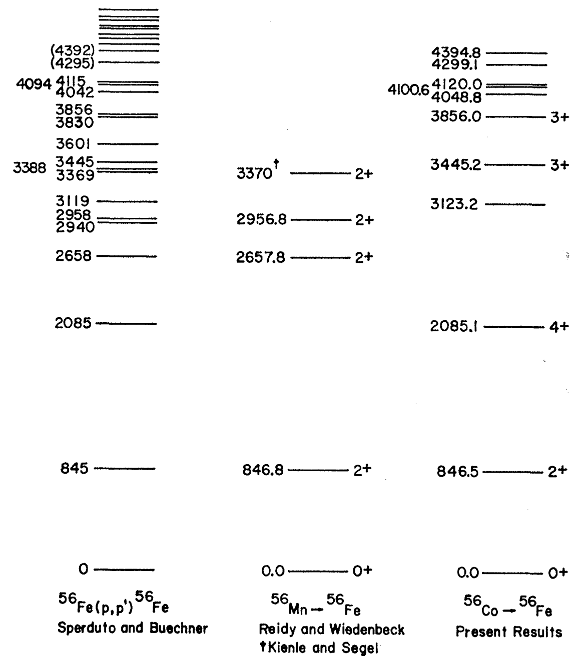


FIG. 6. Comparison of the present results with those from the $^{56}$Mn to $^{56}$Fe decay (Refs. 2, 28) and the inelastic proton scattering measurements of Sperduto and Buechner (Ref. 27).

spin assignments of $3^-$ from electron-scattering measurements,[34,35] $3^+$ from proton scattering,[36] $2^\pm$ or $3^\pm$ from neutron scattering,[33] and either ($3^-$:$1^+$)[30] or ($3^-$:1 or 2)[31] for the doublet found in particle-scattering experiments. A spin of $4^+$ seems most consistent with the absence of a transition to the level at 846.5($2^+$) keV.

The spin of the ground state of $^{56}$Co has been measured using magnetic resonance techniques and found to be $4^+$.[37] Thus the beta-decay to the levels at 2085.1, 3123.2, 3445.2, and 3856.0 keV are expected to be allowed transitions. However, as first reported by Kienle and Segel,[2] the observed log *ft* values are quite high for allowed transitions. These values can be understood within the framework of a simple shell-model picture. The $3^+$ and $4^+$ levels of $^{56}$Fe are most likely thorough mixtures of several shell-model configurations, including the configurations $(1f_{7/2}^{-2}, J_p=0; 2p_{3/2}\, 1f_{5/2}, J_n=3 \text{ or } 4)_{J=3 \text{ or } 4}$, $(1f_{7/2}^{-3}(7/2 \text{ or } 5/2), 2p_{3/2}, J_p=3 \text{ or } 4; 2p_{3/2}^2, J_n=0)_{J=3 \text{ or } 4}$, $(1f_{7/2}^{-2}, J_p=4; 2p_{3/2}^2, J_n=0)_{J=4}$, and $(1f_{7/2}^{-2}, J_p=2; 2p_{3/2}^2, J_n=2)_{J=3 \text{ or } 4}$. Since the ground state of $^{56}$Co is described by the $(1f_{7/2}^{-1}; 2p_{3/2})_{J=4}$ configuration, transitions to all but the first of these are $l$ forbidden. Furthermore, some of these transitions are also forbidden because they are two-particle transitions. It is thus reasonable that the

[27] A. Sperduto and W. W. Buechner, Phys. Rev. **134**, B142 (1964).
[28] J. J. Reidy and M. L. Wiedenbeck, Nucl. Phys. **70**, 518 (1965).
[29] P. F. Hinrichsen, M. H. Shapiro, and D. M. Van Patter, Bull. Am. Phys. Soc. **10**, 427 (1965).
[30] M. H. Shapiro, P. F. Hinrichsen, R. Middleton, and R. K. Mohindra (to be published and private communication).
[31] R. W. Benjamin, P. S. Buchanan, and I. L. Morgan, Nucl. Phys. **79**, 241 (1966).
[32] D. L. Hendrie (private communication).
[33] W. B. Gilboy and J. H. Towle, Nucl. Phys. **64**, 130 (1965).
[34] J. Bellicard and P. Barreau, Nucl. Phys. **36**, 476 (1962).
[35] J. C. Jacmart, M. Liu, R. A. Ricci, M. Riou, and C. Ruhla, Phys. Letters **8**, 273 (1964).
[36] K. Matsuca, Nucl. Phys. **33**, 536 (1962).
[37] R. V. Jones, W. Dobrowolski, and C. D. Jeffries, Phys. Rev. **102**, 738 (1956).

decays should be hindered and that the log $ft$ values should be high.

The $K$-capture transitions to the levels at 4048.8, 4100.6, 4120.0, 4299.1, and 4394.8 keV have log $ft$ values similar to those discussed above. It seems reasonable to assume that these transitions are also allowed and of a similar nature with possible spin assignments of $3^+$, $4^+$, or $5^+$. Assignments other than these are unlikely since the higher energy transitions are all to states with spins close to the $4^+$ $^{56}Co$ ground state.

These levels all decay to the $2^+$ first-excited state which probably excludes the $5^+$ assignments. The 4100.6-keV level decays to the 846.5- and 2085.1-keV levels with an intensity ratio of about 2:1, which is about what one gets assuming both are single-particle $M1$ transitions. Thus a spin of $3^+$ is favored since a $4^+$ assignment would require an enhancement factor of 70 for the resulting $E2$ transition to the 846.5-keV level. The 4120.0-keV level also decays to both the first and second excited states, but with the intensity ratio 1:6. In this case little can be said from comparison with the single-particle predictions and the assignments of $3^+$ and $4^+$ are probably equally likely. The remaining three levels decay only to the $2^+$ state at 846.5 keV. Barring an abnormally high $E2$ enhancement these transitions are probably all $M1$ transitions and spin assignments of $3^+$ are favored.

## APPENDIX

The improved resolution of lithium-drifted germanium detectors makes it possible to determine easily the energies of gamma rays with an accuracy of a few tenths of a keV out of 3000 keV. When this work was begun there was a definite need to establish precisely the energy of a number of gamma rays from readily available sources for use as secondary standards. To do this we have followed the same procedure for energy calibration that is outlined in Sec. 2. The gamma-ray transitions used as primary standards are listed in Table IV. All measurements were made utilizing at least 5 calibration points to determine the constants in the least-squares fitting of a quadratic equation relating peak position with energy. The secondary standards determined in this manner are summarized in Table V and compared with other recent measurements which appeared during the course of this work. The energies measured here are the averages of six to ten runs and the errors quoted are standard deviations. All measurements were made on photopeaks except for the 1836.1-keV line of $^{88}Y$ where the corresponding double-escape peak was measured.

TABLE IV. Gamma rays used as primary standards in establishing other useful standards.

| Source | Energy (keV) | Source | Energy (keV) |
|---|---|---|---|
| $^{131}I$ | 80.164±0.009[a] | $^{137}Cs$ | 661.595±0.076[d] |
| $^{131}I$ | 284.307±0.049[a] | $^{207}Bi$ | 1063.44 ±0.09[c] |
| $^{131}I$ | 364.467±0.050[a] | $^{60}Co$ | 1173.23 ±0.04[e] |
| $^{22}Na$ | 511.006±0.002[b] | $^{60}Co$ | 1332.48 ±0.05 |
| $^{207}Bi$ | 569.62 ±0.06[c] | | |

[a] H. C. Hoyt and J. W. M. DuMond, Phys. Rev. **91**, 1027 (1953).
[b] E. R. Cohen and J. W. M. DuMond, Rev. Mod. Phys. **37**, 537 (1965).
[c] F. P. Brady, N. F. Peek, and R. A. Warner, Nucl. Phys. **66**, 365 (1965).
[d] R. L. Graham, G. T. Ewan, and J. S. Geiger, Nucl. Instr. Methods **9**, 245 (1960).
[e] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **63**, 353 (1965).

TABLE V. Secondary calibration standards. Comparison is made with other recent measurements.

| Source | Present work Energy (keV) | Other recent measurements Energy (keV) | Method |
|---|---|---|---|
| $^{51}Cr$ | 320.3±0.3 | 320.3 ±0.3[a] | Ge(Li) det. |
| | | 319.8 ±0.3[b] | Ge(Li) det. |
| | | 320.18±0.21[c] | mag. spect. |
| | | 320.28±0.66[d] | NaI(Tl) det. |
| $^{54}Mn$ | 834.6±0.3 | 835.0 ±0.3[b] | Ge(Li) det. |
| $^{88}Y$ | 898.0±0.3 | 897.5 ±0.5[b] | Ge(Li) det. |
| $^{65}Zn$ | 1115.3±0.2 | 1115.6 ±0.4[b] | Ge(Li) det. |
| $^{22}Na$ | 1274.7±0.2 | 1274.6 ±0.3[b] | Ge(Li) det. |
| $Y^{88}$ | 1836.1±0.2 | 1836.2 ±0.3[b] | Ge(Li) det. |

[a] G. T. Ewan and A. J. Tavendale, Can. J. Phys. **42**, 2286 (1965).
[b] R. L. Robinson and P. H. Stelson, Nucl. Phys. **74**, 283 (1965).
[c] D. H. White, W. John, B. G. Saunders, and R. W. Jewell, Nucl. Phys. **72**, 241 (1965).
[d] W. R. Pierson, Phys. Rev. **140**, B1516 (1965).