One other possible argument against the 1.94-MeV level should be mentioned. In the $Mg^{25}(t, p)Mg^{27}$ reaction at 12 MeV, the 1.94-MeV level is twice as strongly populated as the 1.69-MeV level.[11] Since in the (t, p) reaction a pair of neutrons are captured, this would more likely occur to a state with configuration $(d_{5/2}{}^5 s_{1/2}{}^2)$, which is that proposed for the core excited $\frac{5}{2}^+$ $K=\frac{5}{2}$ state.

Attempts to interpret the levels of Mg^{27} in terms of the strong-coupling rotation model with a positive deformation are therefore confronted with conflicting evidence in the choice of the members of the $K=\frac{1}{2}$ ground-state band. This could simply mean that the model is not good for this nucleus; however, a consistent picture could possibly be made using a negative deformation as suggested by Glover.[11]

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Intensities of Gamma Rays from the Calibration Source ^{56}Co†

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The intensities and energies of γ rays from 77.3-day ^{56}Co are especially useful for calibration of Ge(Li) detectors in the range 0.8–3.5 MeV. We have reexamined the ^{56}Co γ-ray spectrum using a Ge(Li)-NaI(Tl) coincidence-anticoincidence spectrometer. This study revealed five previously unreported γ rays with energies of 896, 1140.2, 1336, 1443.2, and 1461.9 keV, all of which could be assigned to transitions from levels already established in the ^{56}Co decay. Other weak γ rays with energies of 2276.1, 2374.2, 2522.6, 3599.2, and 3612.5 keV have been confirmed and their intensities have been determined more accurately. A summary of the latest available data for the ^{56}Co decay is presented in the form of weighted averages for γ-ray energies and intensities and an improved decay scheme.

INTRODUCTION

RECENT high-resolution measurements[1–3] have advanced considerably our knowledge of the detailed level structure of ^{56}Fe. The existing knowledge concerning J^π values and γ-ray decay modes of levels up to 4-MeV excitation was summarized by Hinrichsen *et al.*[2] in connection with their $^{56}Fe(p, p')$ and $(p, p'\gamma)$ measurements. More recently, Daehnick[3] has discussed J^π assignments for levels up to 5.06 MeV including the results of his new study of the $^{57}Fe(d, t)^{56}Fe$ reaction. An intriguing feature of these experiments is the establishment of a surprisingly large number of closely spaced doublets whose occurrence is unexplained from a theoretical viewpoint.

An important contribution to the experimental spin-parity assignments[2–4] for some of the members of close doublets in ^{56}Fe has come from investigations of the decay schemes of ^{56}Mn and ^{56}Co. There have been several recent high-resolution studies of the γ-ray spectrum of ^{56}Co using a magnetic spectrometer[5] and Ge(Li) detector,[6–11] including γ-γ coincidence measurements.[11] There has been one investigation by Huguet *et al.*[6] using a three-crystal pair spectrometer. However, none of these experiments made use of a Ge(Li)-NaI(Tl) system to obtain suppression of Compton events, which will generally reveal new γ-ray components in a complex decay scheme, as illustrated by a recent study of the ^{60}Cu spectrum carried out at our laboratory.[12]

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1 B. L. Cohen and R. Middleton, Phys. Rev. **146**, 748 (1966).
2 P. F. Hinrichsen, M. H. Shapiro, and D. M. Van Patter, Nucl. Phys. **A101**, 81 (1967).
3 W. W. Daehnick, Phys. Rev. **177**, 1763 (1969).
4 *Nuclear Data Sheets*, compiled by K. Way *et al.* (U.S. Government Printing Office, National Academy of Sciences–National Research Council, Washington, D.C., 1959).
5 H. Pettersson, O. Bergman, and C. Bergman, Arkiv Fysik **29**, 423 (1965).
6 M. Huguet, H. Forest, and C. Ythier, Compt. Rend. **263B**, 1342 (1966).
7 R. Schöneberg, M. Schumacher, and A. Flammersfeld, Z. Physik **192**, 305 (1966).
8 R. L. Auble, W. C. McHarris, and W. H. Kelly, Nucl. Phys. **A91**, 225 (1967).
9 C. Chasman and R. A. Ristinen, Phys. Rev. **159**, 915 (1967).
10 P. H. Barker and R. D. Connor, Nucl. Instr. Methods **57**, 147 (1967).
11 A. H. Sher and B. D. Pate, Nucl. Phys. **A112**, 85 (1968).
12 F. Rauch, D. M. Van Patter, and P. F. Hinrichsen, Nucl. Phys. **A124**, 145 (1969).

TABLE I. γ-ray energy and intensity measurements on ^{56}Co. Intensities I_γ are given in % per disintegration.

Transition[a]	E_γ (keV)[b]	Ref.	I_γ	Ref.	Adopted value[b]
8→5	733.6±0.4	c, d	0.10±0.05	e	0.11±0.04
			0.13±0.06	d	
7→3	787.97±0.14	c, d	0.2±0.1	d	0.36±0.03
			0.4±0.2	e	
			0.36±0.2	f	
			0.37±0.04	g	
1→0	846.78±0.06	c, d, h	100	c	100
8→4	895.7±1.2	g	0.14±0.04	g	0.14±0.04
10→5	977.48±0.13	c, d, h	1.55±0.08	c, d, i	1.55±0.08
5→2	1037.90±0.05	c, d, h	12.8±0.3	c, d	12.8±0.3
10→4	1140.2±0.8	g	0.17±0.03	g	0.17±0.03
12→5	1175.13±0.06	c, d, h	2.04±0.13	c, d	2.04±0.13
2→1	1238.30±0.04	c, d, h	69.5±1.3	c, d	69.5±1.3
12→4	1336.1±3.0	g	0.12±0.02	g	0.12±0.02
7→2	1360.24±0.05	c, d, h	4.30±0.13	c, d	4.30±0.13
10→3	1443.2±0.8	g	0.23±0.03	g	0.23±0.03
11→3	1461.9±0.8	g	0.12±0.03	g	0.12±0.03
8→2	1771.42±0.07	c, d, h	15.5±0.5	c, d	15.5±0.5
3→1	1810.6±0.2	d	0.5±0.3	d	0.62±0.06[j]
			0.4±0.2	e	
			0.65±0.06	g	
9→2	1964.22±0.38	c, d, h	0.75±0.27	k	0.64±0.04
			0.80±0.15	l	
			0.59±0.09	e	
			0.68±0.10	f	
			0.63±0.20	d	
			0.63±0.05	g	
10→2	2015.35±0.06	c, d, h	2.93±0.14	c, d	2.93±0.14
11→2	2034.92±0.05	c, d, h	7.42±0.26	c, d	7.42±0.26
4→1	2112.99±0.11	c, d	0.32±0.15	d	0.35±0.04
			0.4±0.09	l	
			0.29±0.05	e	
			0.56±0.08	f	
			0.4±0.1	i	
			0.32±0.04	g	
12→2	2213.7±0.3	c, d	0.43±0.09	l	0.44±0.04
			0.4±0.1	i	
			0.46±0.05	g	
5→1	2276.1±0.8	g	0.12±0.03	l	0.13±0.02
			0.14±0.02	g	
15→2	2374.2±0.8	g	0.15±0.03	l	0.12±0.02
			0.11±0.02	g	

TABLE I (*Continued*)

Transition[a]	E_γ (keV)[b]	Ref.	I_γ	Ref.	Adopted value[b]
6→1	2522.6±0.8	g	<0.03	l	0.09±0.03
			0.09±0.03	g	
7→1	2598.57±0.06	c, d, h	17.0±0.4	c, d	17.0±0.4
8→1	3009.96±0.21	c, d	0.89±0.11	c, d	0.89±0.11
9→1	3202.19±0.06	c, d, h	3.22±0.12	c, d	3.22±0.12
10→1	3253.64±0.06	c, d, h	7.71±0.27	c, d	7.71±0.27
11→1	3273.19±0.06	c, d, h	1.56±0.10	c, d	1.56±0.10
12→1	3451.43±0.14	c, d, h	0.90±0.09	c, d	0.90±0.09
13→1	3548.12±0.21	c, d	0.17±0.01	c, d	0.17±0.01
14→1	3599.2±0.8	g, d	0.02±0.01	d	0.019±0.005
			0.01±0.005	l	
			0.024±0.004	g	
15→1	3612.5±0.8	g	<0.005	l	0.007±0.003
			0.007±0.003	g	

[a] See Table II for level numbers and excitation energies.
[b] Weighted average of measurements.
[c] Marion (Ref. 14).
[d] Sher and Pate (Ref. 11).
[e] Auble *et al.* (Ref. 8).
[f] Chasman and Ristinen (Ref. 9).
[g] Present work.
[h] Gunnink *et al.* (Ref. 15).
[i] Barker and Connor (Ref. 10).
[j] The values given by Refs. 7 and 10 have been omitted.
[k] Pettersson *et al.* (Ref. 5).
[l] Huguet *et al.* (Ref. 6).

The present measurements were undertaken using a coincidence-anticoincidence Ge(Li)-NaI(Tl) system[13] to look for previously undetected γ rays in the decay of ^{56}Co.

A ^{56}Co source is especially useful for the calibration of the efficiency of Ge(Li) detectors since it contains several prominent components in the range of $E_\gamma=0.8$ to 3.5 MeV with accurately established intensities which have been tabulated.[10,14] The new precise determinations of Gunnink *et al.*[15] make this radioisotope equally valuable as a standard for γ-ray energy measurements. A second objective of the present investigation was to obtain more accurate energies and intensities for several of the weaker γ-ray components, and at the same time to provide an improved decay scheme for ^{56}Co.

EXPERIMENTAL METHOD

The ^{56}Co source was produced by the ^{56}Fe(p, n)^{56}Co reaction, using a beam of 6.5-MeV protons from the University of Pennsylvania tandem accelerator to bombard a 0.5 mg/cm^2 foil of 99.0%-enriched ^{56}Fe. Although no radiochemical analysis was carried out, the only contaminant activities detected during five months of observations were due to 267-day ^{57}Co and 71-day ^{58}Co, produced by the (p, n) reaction from small contaminants of ^{57}Fe(0.36%) and ^{58}Fe(0.03%) present in the enriched material. Within the statistical accuracy of the measurements, all the other γ rays observed had a decay period consistent with that of 77.3-day ^{56}Co.

γ-ray spectra were obtained using a Ge(Li)-NaI(Tl) coincidence-anticoincidence spectrometer[12,13] which consists of a 20-cm^3 Ge(Li) detector placed at the center of a large split NaI(Tl) annulus. This spectrometer permits both Compton-suppressed and three-crystal pair spectra to be recorded simultaneously.

The relative efficiency of the spectrometer for various γ-ray energies was determined for this experiment by adopting the averaged intensities given by Marion[14] for the strong ^{56}Co γ rays. This calibration agreed very well (within 4%) with the relative efficiency curves which had been previously established[12] up to 5 MeV using a source of ^{66}Ga and the γ-ray intensities reported by Camp.[16] The intensities of the weaker ^{56}Co γ rays were obtained from peak areas in both the Compton suppressed and three-crystal pair spectra whenever possible.

RESULTS AND DISCUSSION

The energies and relative intensities of the γ rays from the decay of ^{56}Co obtained from the present experiment and previous studies[5–11,14,15] are listed in

[13] P. F. Hinrichsen and T. Bardin, Bull. Am. Phys. Soc. **12**, 462 (1967); D. M. Van Patter, *Nuclear Research with Low Energy Accelerators* (Academic Press Inc., New York, 1967), p. 99.
[14] J. B. Marion, Nucl. Data **A4**, 301 (1968).
[15] R. Gunnink, R. A. Meyer, J. B. Niday, and R. P. Anderson, Nucl. Instr. Methods **65**, 26 (1968).
[16] D. C. Camp, Lawrence Radiation Laboratory Report No. UCRL-50156 (1967) TID-4500 UC-4 (unpublished).

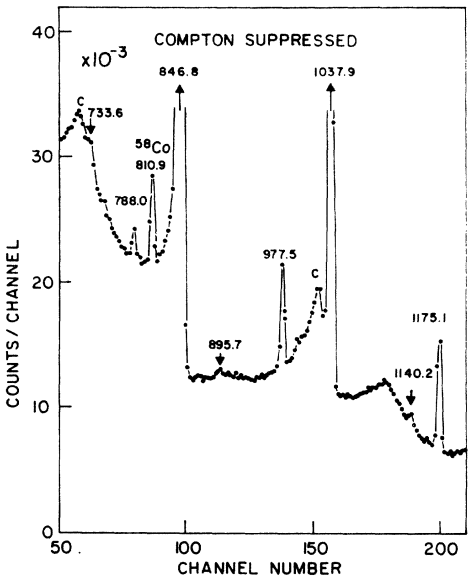

FIG. 1. Compton suppressed γ-ray spectrum showing the energy region from 0.7 to 1.2 MeV. The regions noted with the letter C are Compton back-scattering peaks due to incomplete suppression of Compton events for scattering at angles near 180° with respect to the spectrometer axis.

Table I. The values adopted for the γ ray energies and intensities represent the average of all measurements weighted inversely as the squares of the uncertainties. The quoted errors are the larger of the internal or external errors. In a few cases, intensities reported for certain transitions which clearly differ considerably from other measurements have been omitted, especially when it appears likely that the authors did not make a sufficient correction for the contribution of the two-escape peak of a higher-energy transition. It should be noted that for 14 prominent ^{56}Co γ rays, the new energy determinations of Gunnink *et al.*[15] are sufficiently precise ($\pm$0.05–0.1 keV) to provide the major contribution to the weighted averages. These were used as calibration points to determine the energies of weaker transitions investigated in the present experiment.

The Ge(Li)-NaI(Tl) spectrometer used in this investigation suppresses Compton scattering events by a factor of about 4. Thus the detection of weak transitions in the presence of strong higher-energy γ rays is greatly improved. Figure 1 shows the evidence for two previously unreported transitions with energies of 895.7$\pm$1.2 and 1140.2$\pm$0.8 keV, and intensities of 0.14 and 0.17% per disintegration. Primarily on the basis of energy matches, we assign these γ rays to transitions from the 3856.6- and 4100.4-keV levels to the 2959.8-keV level.

Daehnick[3] has proposed an assignment of $2^+(3^+)$ for the 4100.4-keV level from his observed $l=3$ angular pattern and suggested $f_{5/2}$ transfer in the ^{57}Fe(d, t) reaction. This level is directly populated in the decay of ^{56}Co with $\log ft=6.3$. Since a $J^\pi=2^+$ assignment would require a second forbidden transition, which should have a $\log ft>10.6$ according to Gove,[17] this possibility can be eliminated. Thus $J^\pi=3^+$ remains the best choice for this level.

Figure 2 shows a portion of the Compton suppressed spectrum which includes three new γ rays of energies 1336.1$\pm$3.0, 1443.2$\pm$0.8, and 1461.9$\pm$0.8 keV, with intensities of 0.12, 0.23, and 0.12% per disintegration. These have been assigned the following transitions: 4298.2$\rightarrow$2959.8, 4100.4$\rightarrow$2657.4 and 4120.0$\rightarrow$2657.4 keV. In each case, the new γ rays correspond to new weak branches of levels which were already known to be populated in the ^{56}Co decay.

Figure 3 represents a partial three-crystal pair spectrum showing peaks corresponding to γ rays with energies of 2213.7, 2276.1, 2374.2, and 2522.6 keV. The two higher transitions are only barely evident in the Compton suppressed spectrum, and thus the triple coincidence spectrum for two-escape events[6] is by far the best means of observing them. The 2522.6-keV γ ray is assigned to the 3369.4$\rightarrow$846.8 transition which accounts for 84% of the decays of this level.[2] The $J^\pi=2^+$ assignment of the 3369.4-keV level is well established[2,3]; therefore, the yield of the 2522.6-keV γ ray (0.09) is much too large for direct feeding in the ^{56}Co decay, and it must arise following a cascade transition from a higher level. One possibility would be a 4110.4$\rightarrow$3369.4-keV transition of 731.0 keV which would be unresolved in the Ge(Li) measurements from the 733.6-keV γ ray. Unfortunately, Pettersson *et al.*[5] did not present their higher resolution (0.22%) data for the internal-conversion line of their 733.8-keV radiation. The remaining three γ rays are assigned to the

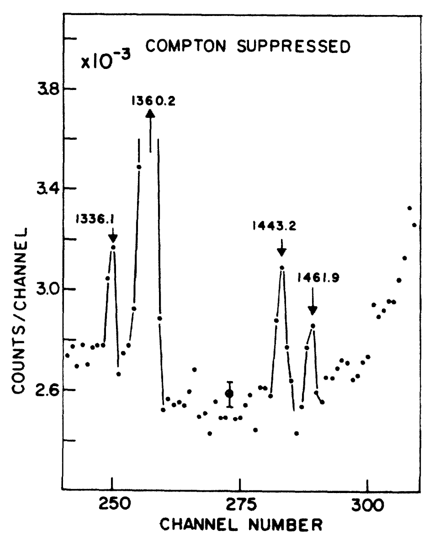

FIG. 2. Partial ^{56}Co γ-ray spectrum showing new γ-ray transitions at 1336.1, 1443.2, and 1461.9 keV.

[17] N. B. Gove, in *Nuclear Spin-Parity Assignments*, edited by N. B. Gove (Academic Press Inc., New York, 1966), p. 83.

4298.2→2085.1-, 3123.0→846.8-, and 4459.3→2085.1-keV transitions.

Evidence for two very weak γ rays at 3600±4 and 3611±4 keV was reported by Huguet *et al.*[6] using a three-crystal pair spectrometer, while Sher and Pate[11] observed a weak two-escape peak assigned to a 3598.7±0.5-keV γ ray. The present data for these radiations are shown in Fig. 4, and indicate γ rays with energies of 3600.5±0.8 and 3612.5±0.8 keV and intensities of 0.024 and 0.007%. The 3612.5-keV γ ray had been previously assigned to a 4459.3→846.8-keV transition.[6,11]

The identification of the 3599.2±0.8-keV transition requires some discussion. Huguet *et al.*[6] tentatively assigned this to a ground-state transition from a 2^+ level near 3604 keV reported by Hinrichsen *et al.*[2] We

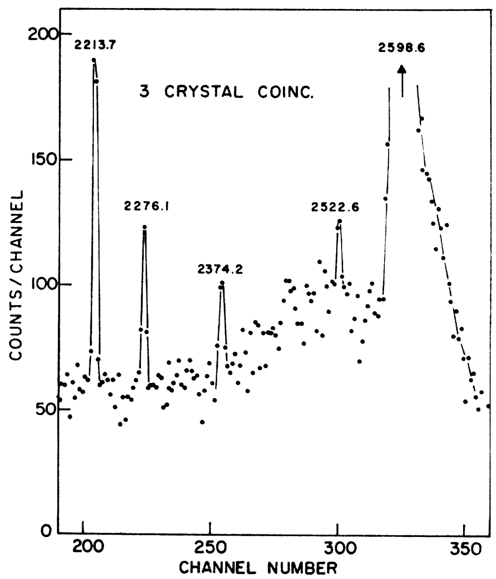

FIG. 3. Three-crystal pair spectrum of ^{56}Co γ rays for the energy region between 2200 and 2600 keV.

note that there is an energy mismatch of about 6 keV on the basis of the relative (p, p') spacing observed for this level from states whose energies are well established in studies of the ^{56}Mn and ^{56}Co decays.[2] In a preliminary report of lifetime measurements for states up to 3.86 MeV, Benczer-Koller *et al.*[18] list the energy of this level as 3605 keV. From ^{56}Fe$(p, p'\gamma)$ studies,[2] it is known that at least half of the decays of this level proceed via a 2757-keV cascade to the 846.8-keV 2_1^+ level. We were unable to detect this cascade γ ray, and can place an upper limit of $<1.2\times10^{-4}$ per disintegration on its intensity, which is about one-half that of the observed yield of the 3599-keV transition. Daehnick[3] noted that the ^{57}Fe$(d, t)^{56}$Fe triton group corresponding to a level at 4459 keV appeared to be

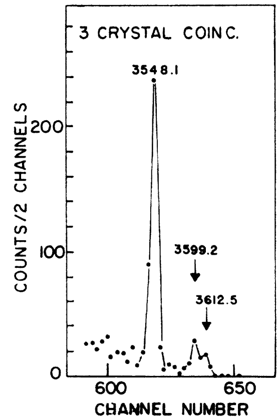

FIG. 4. Three-crystal pair spectrum showing the weak 3599.2- and 3612.5-keV ^{56}Co γ rays. For this plot, the counts in two adjacent channels have been summed.

broadened, indicating the possibility of a very narrow doublet. An anomalous angular distribution was seen in the ^{54}Fe(t, p) reaction[1] for the 4.46-MeV level; this observation also supports the possibility of a doublet near this energy. Therefore, we have assigned the 3599-keV γ ray to a 4446.0→846.8-keV transition in agreement with Sher and Pate.[11]

A decay scheme consistent with the available evidence for energies and intensities of γ rays from ^{56}Co is shown in Fig. 5. The J^π assignments are based on information which includes the latest nuclear data such as those from the ^{57}Fe$(d, t)^{56}$Fe reaction.[3] After taking account of the contributions of cascades from higher

TABLE II. ^{56}Fe levels populated in the decay of ^{56}Co.

Level[a]	E_x (keV)	Direct feeding % total decays	log*ft*	J^π
1	846.78±0.06	−2.1±1.4	>11	2^+
2	2085.08±0.07	25.3±1.4	8.5	4^+
3	2657.36±0.15	−0.1±0.1	>10.8	2^+
4	2959.77±0.12	−0.1±0.1	>10.7	2^+
5	3122.98±0.09	9.3±0.4	7.5	4^+
6	3369.4±0.8	<0.11	>9.3	2^+
7	3445.33±0.06	21.7±0.4	6.8	3^+
8	3856.62±0.12	16.7±0.5	6.6	3^+
9	4048.99±0.09	3.9±0.2	6.9	$3^+(4^+)$
10	4100.43±0.07	12.7±0.4	6.3	3^+
11	4119.97±0.09	9.1±0.3	6.5	4^+
12	4298.16±0.09	3.5±0.3	6.4	4^+
13	4394.90±0.22	0.17±0.01	7.3	$3^+(4^+)$
14	4446.0±0.8	0.019±0.005	8.0	
15	4459.3±0.4	0.127±0.020	7.0	$3^+(4^+)$

[a] Note that only levels seen in the decay of ^{56}Co are listed.

[18] N. Benczer-Koller, G. G. Seaman, M. C. Bertin, and J. R. MacDonald, Bull. Am. Phys. Soc. **14**, 125 (1969).

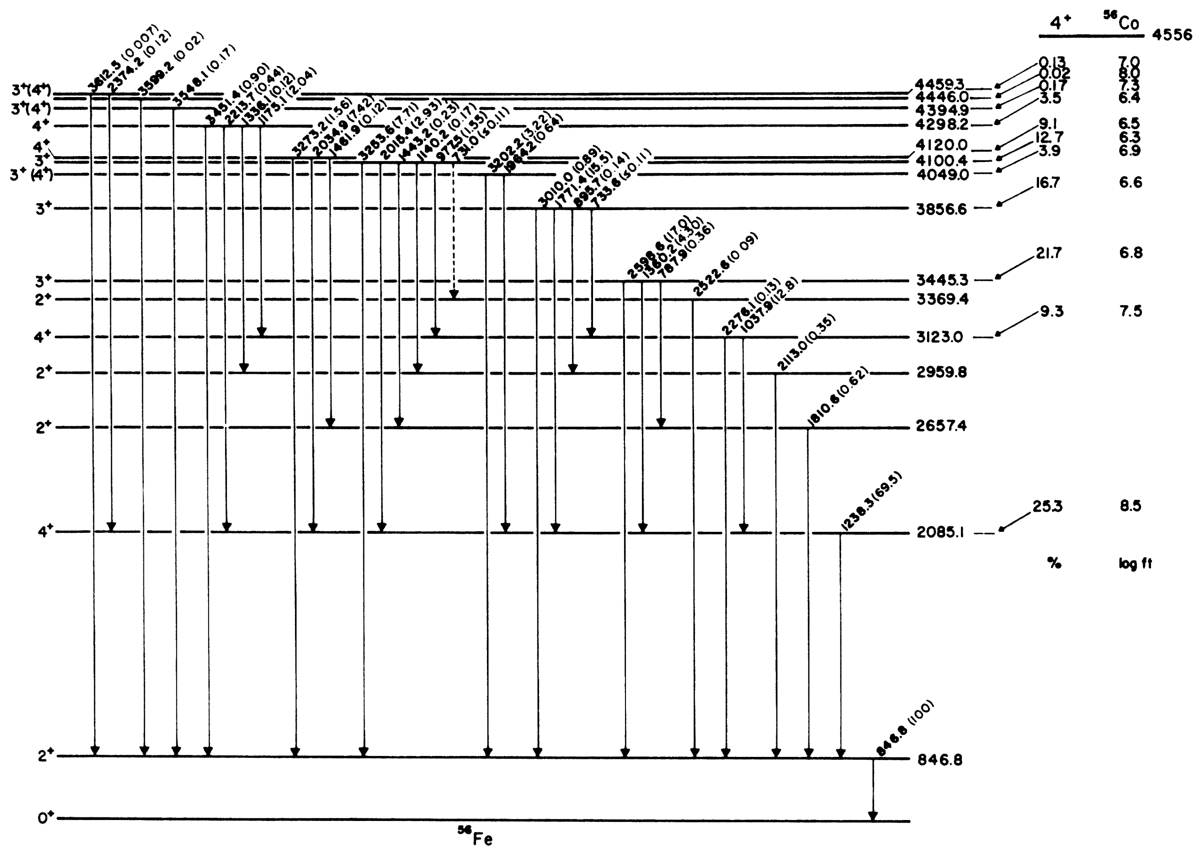

FIG. 5. Proposed decay scheme for ^{56}Co. Intensities are per 100 decays of ^{56}Co.

levels, the amount of direct feeding for each level has been calculated and listed in Table II together with the log*ft* value and best level energy. We note that there is no evidence for direct feeding of the 2^+ states at 846.8, 2657.4, and 2959.8 keV, and the limits for log*ft* values ($\gtrsim 11$) are consistent with those expected[17] for second forbidden β transitions.

In the present investigation of the ^{56}Co γ-ray spectrum, five new transitions were observed and identified. The existence of several other weak transitions was confirmed and improved values of their intensities were determined. A list of recommended values for energies and intensities of the 32 known ^{56}Co γ rays is presented in Table I. This represents an improvement and extension of the values previously tabulated,[10,14,15] and thus should be useful for any measurements in which ^{56}Co is used as a calibration source.

Note added in proof. Recent accurate measurements of the intensities of 12 prominent γ rays in the ^{56}Co decay by G. Aubin *et al.* [Laboratoire de Physique Nucleaire, Université de Montreal, Report No. LPN-UM-34, 1969 (unpublished)] have just come to our attention. These intensity values are not included in the present weighted averages.