

Beta Decay of Mn⁵⁶ and Co⁵⁶†

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γ -ray transitions following the decay of Mn⁵⁶ to Fe⁵⁶ have been investigated with particular attention given to weak transitions following hindered β decays. Two such transitions were found, one to the 2.085-MeV state in Fe⁵⁶ ($\log ft=8.7\pm 0.2$) and the other to the 3.445-MeV state ($\log ft=6.0\pm 0.2$). Precision γ -ray measurements have been made both to corroborate the decay scheme and to provide γ -ray calibration energies. The decay of Co⁵⁶ to Fe⁵⁶ was similarly investigated; several new transitions were found, and precision γ -ray energies are reported.

I. INTRODUCTION

THE β decays of Mn⁵⁶ and Co⁵⁶ to Fe⁵⁶ have been examined by several investigators who have established the energies, spins, and parities of many of the low-lying levels of Fe⁵⁶.¹⁻⁹ Many of the levels of Fe⁵⁶ have also been established by charged-particle reactions and inelastic neutron scattering.^{8,10} The spin of the ground state of Mn⁵⁶ is measured¹¹ as 3 and the parity can be taken as positive from both the allowed β decay to the states of positive parity in Fe⁵⁶ and from shell-model considerations. Mn⁵⁶ β decays to the Fe⁵⁶ states at 2.66 (2+), 2.96 (2+), and 3.37 (2+) MeV with allowed $\log ft$ values between 5 and 6 (Fig. 1). However, the $\log ft$ to the first excited 2+ state in Fe⁵⁶ is 7.2 and to the second excited state has been reported² as >9 and more recently >10 ,^{3,12} although the 2+ and 4+ assignments to these states would indicate an allowed decay. No states in Fe⁵⁶ (not even the 3.445-MeV level) had been observed as populated from both the Mn⁵⁶ and Co⁵⁶ sides. As has been pointed out fre-

quently in the literature the collective nature of the first two excited states¹³ together with the l -forbiddenness of the β transitions to these states should result in a retardation of the β transitions. Although it is recognized that the β decays to higher vibrational states are often increasingly hindered,^{14,15} it is difficult to explain the large differences in transition rates between the decay to the 0.8466- and 2.085-MeV states and especially a $\log ft > 10$. A search was made therefore for the 1.238-MeV transition from the second excited state of Fe⁵⁶ as a signature of the β decay to this state. This transition has been difficult to observe in the past for two reasons: (1) the one escape peak ($E_\gamma - m_0c^2$) of the very strong 1.811-MeV transition lies within 65 keV of the transition and dominates the spectrum taken with a NaI crystal and (2) the full energy peak of a strong transition in Ar⁴¹, a common background source near reactors, is also within 65 keV. In the course of searching for the 1.238-MeV transition an examination of the decay schemes of Mn⁵⁶ and Co⁵⁶ was made, revealing some new transitions. Accurate energy measurements were made of the γ -ray transitions in Fe⁵⁶.

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¹ P. Dagley, M. A. Grace, J. M. Gregory, and J. S. Hill, Proc. Roy. Soc. (London) **250A**, 550 (1959).

² P. Kienle and R. E. Segel, Phys. Rev. **114**, 1554 (1959).

³ J. K. Bienlein and H. Dinter, Nucl. Phys. **55**, 113 (1964).

⁴ H. Pettersson, O. Bergman, and C. Bergman, Arkiv Fysik **29**, 423 (1964).

⁵ K. W. Dolan, D. K. McDaniels, and D. O. Wells, Phys. Rev. **148**, 1151 (1966).

⁶ M. Huguet, H. Forest, and C. Ythier, Compt. Rend. **263**, 1342 (1966).

⁷ R. Schöneberg, M. Schumacher, and A. Flammersfeld, Z. Physik **192**, 305 (1966).

⁸ A. A. Katsanos, J. R. Huizenga, and H. K. Vonack, Phys. Rev. **141**, 1053 (1966). Other recent work is summarized in this paper.

⁹ R. L. Auble, W. C. McHarris, and W. H. Kelly, Nucl. Phys. **A91**, 465 (1967). This paper was received while the present work was in the final stages of preparation. The energy measurements are in generally good agreement with the reported errors somewhat smaller in this work. Auble, McHarris, and Kelly do not report observation of the two weakest transitions in Mn⁵⁶. Transitions in Co⁵⁶ reported in this reference not observed in our work are at 732.2 and 1811 keV. Transitions not observed in this reference but observed in our work are at 1141.2 and 2213.0 keV.

¹⁰ R. W. Benjamin, P. S. Buchanan, and I. L. Morgan, Nucl. Phys. **79**, 241 (1966).

¹¹ W. J. Childs, L. S. Goodman, and L. J. Kiefer, Phys. Rev. **122**, 891 (1961).

¹² H. J. Fischbeck, W. M. Greenberg, and E. B. Arnold, Bull. Am. Phys. Soc. **10**, 931 (1965).

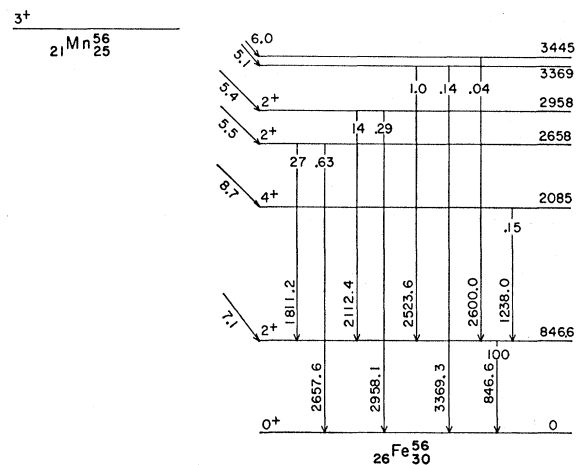


FIG. 1. Energy-level diagram of Fe⁵⁶ from the decay of Mn⁵⁶. Energies are in keV. $\log ft$ values obtained from the γ -ray intensities are given alongside the different β branches.

¹³ J. Bellicard and P. Barreau, Nucl. Phys. **36**, 476 (1962).

¹⁴ L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).

¹⁵ M. Sakai, Nucl. Phys. **33**, 96 (1962).

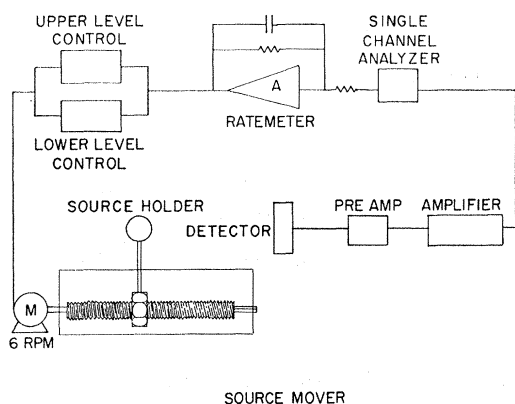


FIG. 2. The source holder is advanced by the lead screw by a 6-rpm motor driven from a ratemeter. In this fashion the counting rate can be maintained constant to within 5%.

II. METHOD

Mn^{56} was made by neutron capture in monoisotopic Mn^{55} in the Brookhaven Graphite Reactor. Samples of MnO_2 and of Mn (99.9% purity) were used of about 10–20 mg irradiated in polyethylene capsules. Gamma-ray spectra were then taken with a 4-cm³ lithium-drifted germanium detector and a conventional pulse-height-analysis system. Since the intensity of the transition sought was very small the counting rate was increased to about 8000 counts/sec at the cost of pulse-height resolution (about 5 keV full width at half-maximum, FWHM). The amplifier clipping and integrating times were also adjusted to compromise for faster counting rather than high resolution.

Because the source has a comparatively short half-life (2.6 h) and the electronics were counting at a moderately high rate, the resolution was seriously degraded by rate-dependent pulse-height changes. To overcome this difficulty a source mover advanced by a rate meter was employed. In this arrangement the source capsule is placed on an arm extending perpendicularly from the axis of a 30-in. threaded shaft (13 threads/in.). This shaft is driven by a 6-rpm motor controlled by a rate meter so that if the rate drops below a preset value the motor is turned on and then turned off again when the rate exceeds a different preset value. The input to the rate meter is the output of a single-channel analyzer

TABLE I. Mn^{56} γ -ray energies (MeV) and intensities.

This work		Bienlein and Dinter ^a		Reidy and Wiedenbeck ^b
Energy	Intensity	Energy	Intensity	Energy
0.84664 ± 0.0001	100	0.845 ± 0.005	100	0.84679 ± 0.00010
1.8112 ± 0.001	27	1.80 ± 0.001	34	1.81098 ± 0.00063
1.238 ± 0.002	0.15			
2.1124 ± 0.001	14	2.11 ± 0.01	18.0	2.110 ± 0.0016
2.523 ± 0.001	1.0	2.52 ± 0.02	0.87	
2.600 ± 0.002	0.04			
2.6576 ± 0.001	0.63	2.67 ± 0.01	0.69	
2.9581 ± 0.001	0.29	3.00 ± 0.02	0.55	
3.3693 ± 0.001	0.14	3.38 ± 0.02	0.15	

^a Reference 3.

^b J. J. Reidy and M. L. Wiedenbeck, Nucl. Phys. **70**, 518 (1965).

whose window is adjusted to maintain the counting rate desired. A block diagram of the source mover is shown in Fig. 2. By this method the counting rate could be kept constant to about 5% until the source was too weak to be of value. An average source would last about 24 h. In some of the later experiments the analyzer was digitally stabilized from external pulsers at two points: one at the high-energy end and one at the low-energy end of the multichannel analyzer. Since the electronic line shape is a function of the counting rate, digital stabilization is only satisfactory for high resolution when the counting rate is unchanging. Stability was maintained better than 1/10 000 per day.

Measurements were made with more than fifteen different samples of Mn and MnO_2 . To check for contaminants irradiation times were changed from 30 sec to 150 sec and the spectra obtained were stored before using from 15 min to 2½ h with no significant change in the spectra obtained. Measurements were also made under different background conditions. The line at 1.238 MeV appeared in every run. Figure 3 is the sum of three runs in the energy region of interest. For comparison the intensity of the 1.811-MeV transition is also shown. The intensity of the 1.238-MeV line was compared to that of the 1.811-MeV transition which was measured as a 27% transition. Since the 1.238-MeV transition could also appear if Mn^{56} could decay to the 3.445- or 3.123-MeV level in Fe^{56} it was decided to search for a 2.600-MeV and a 1.038-MeV γ -ray transition. The 2.600-MeV transition was found and its intensity is measured as 0.04% of the 0.846-MeV line. A search for the 1.038-MeV transition was negative and an upper limit of 0.02% decays to the 3.123-MeV state is established. Figures 4 and 5 show the γ -ray spectrum from the Mn^{56} decay covering the total decay energy. Table I lists γ -ray intensities and energies from the Mn^{56} decay. Gamma-ray intensities have an uncertainty of about 15%.

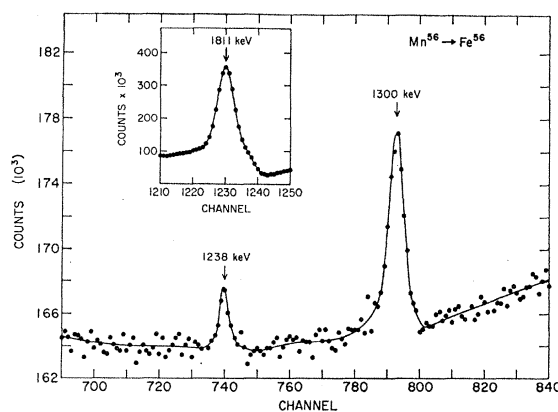


FIG. 3. The γ -ray spectrum from the decay of Mn^{56} in the region of 1250 keV, showing the 1238-keV transition and the one-escape peak of the 1811-keV transition. The insert shows the 1811-keV full-energy peak. Note suppressed zero. These data represent the sum of three runs.

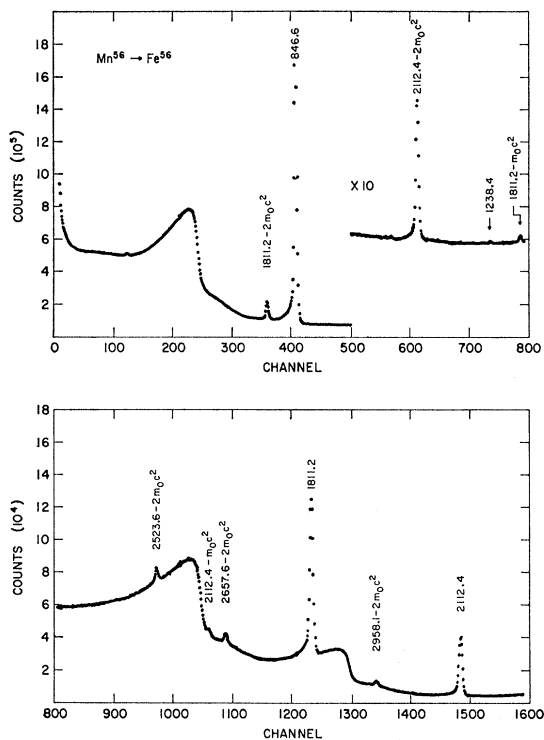


FIG. 4. The γ -ray spectrum from the decay of Mn^{56} from 0 to 2.2 MeV.

Because the 2.600-MeV transition was found it was necessary to measure the branching ratio of the 2.600- and 1.360-MeV transitions to find the feeding of the 2.085-MeV level from the 3.445-MeV level. To do this a Co^{56} source was prepared since the 3.445-MeV level is strongly populated in the Co^{56} positron decay.

The Co^{56} source was made at the Brookhaven Cyclotron by irradiating natural iron (99.9% purity) with 9.5-MeV protons. Co^{57} and Co^{58} are the only long-lived contaminants expected. Co^{57} has a decay energy of about 0.850 MeV with the highest-energy γ -ray transition¹⁶ of 0.7064 MeV and is consequently not troublesome. Co^{58} comes from the (p,n) reaction on Fe^{58} which is only 1/3% abundant. The three lines which are known in the beta decay of Co^{58} are at 0.81, 0.86, and 1.67 MeV, and do not interfere with the measurements made.

Besides measuring the ratio of intensities of the 2.599- and 1.360-MeV transitions the whole decay of Co^{56} was examined (Fig. 6). Most of the transitions found are in essential agreement with those of Petterson *et al.*⁴ and Dolan *et al.*⁵ Table II is a summary of these results comparing the energies and intensities found in the three experiments. Intensities have an uncertainty of about 15%. Gamma-ray transitions of 788.6, 977.51, 1141.2, 1175.5, 1964.6, 2113.0, and 2213.0 keV were not reported seen by Dolan *et al.* Transitions of 1141.2, 2213.0, and 3548.1 keV were not observed by Petterson

et al. (See also Ref. 17.) Figures 7 and 8 show γ -ray spectra from the decay of Co^{56} . An upper limit on the γ -ray intensity of the 734-keV transition observed only in the conversion electron spectrum by Petterson was measured as a 0.08% relative to the intensity of the 846-keV transition.

Calibration of the γ -ray energies from both the Mn^{56} and Co^{56} decays was done using the standard γ -ray energies given in Table III and calibrating the electronics with a high-precision mercury pulser. Our method has assumed that two-escape peaks and one-escape peaks fall $2m_0c^2$ and m_0c^2 , respectively, below the full-energy peak linearly in the number of hole-electron pairs per keV energy loss. Because of the very stable electronics and in particular the digital stabilization it was possible to use very large pulse-height suppression in a biased amplifier followed by a large amount of gain. This resulted in multichannel-analyzer dispersions of about 300 eV/channel. Since the high-energy end of the Co^{56} spectrum is considerably above convenient calibration γ rays with the listed sources the two-escape peak of the 3253.7-keV transition was standardized against the $n-p$ capture γ ray measured as 2223.39 ± 0.100 keV by comparison of its two escape peaks with the Co^{60} standards given in Table III. This value is in good agreement with that of 2223.29 ± 0.07 keV given by Greenwood and Black.¹⁷ This γ ray thus established the calibration for the high-energy Co^{56} γ rays without need for a large extrapolation with the pulser.

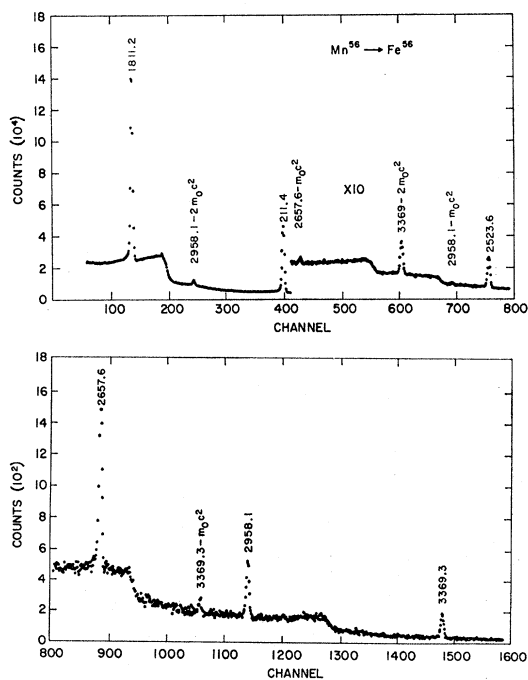


FIG. 5. The γ -ray spectrum from the decay of Mn^{56} from 1.7 to 3.5 MeV.

¹⁷ R. C. Greenwood and W. W. Black, Phys. Letters 21, 702 (1966).

¹⁶ O. C. Kistner and A. W. Sunyar, Phys. Rev. 139, B295 (1965).

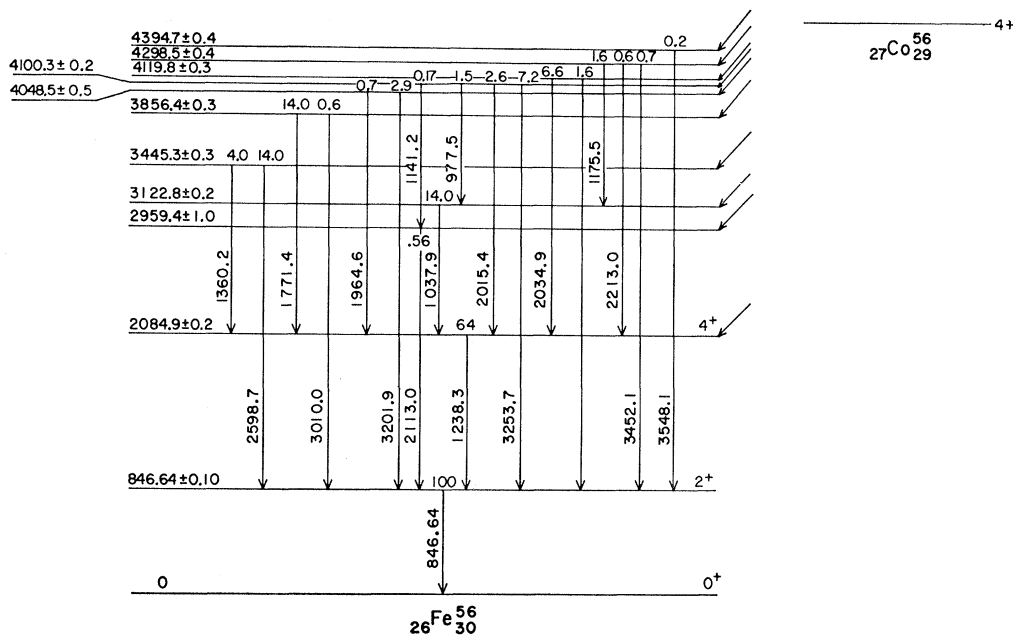


FIG. 6. Energy-level diagram of Fe⁵⁶ from the decay of Co⁵⁶. Energies are in keV.

III. DISCUSSION

A. Co⁵⁶

The energies and intensities of the Co⁵⁶ measurements are in good agreement with the results of Pettersson

et al. and Dolan *et al.* as shown in Table II. Unlike Ref. 6, no transitions were found to correspond to the doublets found by Hinrichsen *et al.* in their particle-gamma coincidence reaction studies nor evidence for levels at 4459.4, 3600, and 2658 keV.¹⁸ Attention here is given only to the transitions found in this experiment that were not observed by both Pettersson *et al.* and Dolan *et al.*

The transition at 788.6 keV seen by Pettersson *et al.* but not Dolan *et al.* is confirmed but remains unassigned. A transition of 3548.1 keV is assigned to the decay of a level at 4394.7 keV and is the only evidence for such a state. This transition was also seen and similarly as-

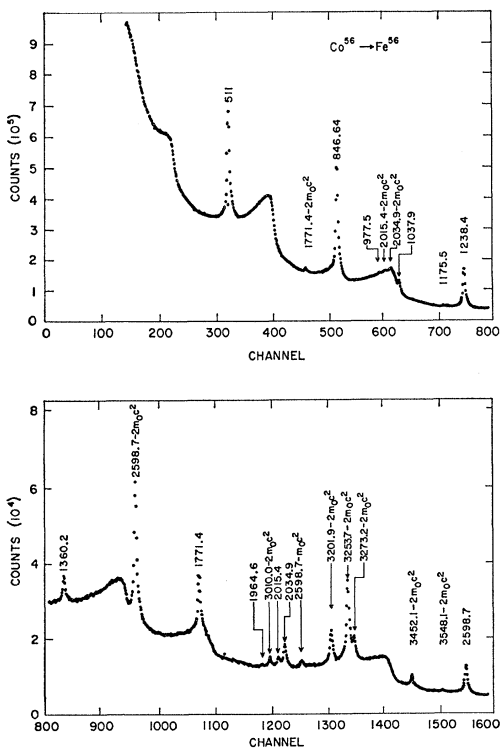


FIG. 7. γ -ray spectrum from the decay of Co⁵⁶ from 0 to 2.6 MeV. Spectra used for calibration of γ -ray energies were taken at more than twice this dispersion.

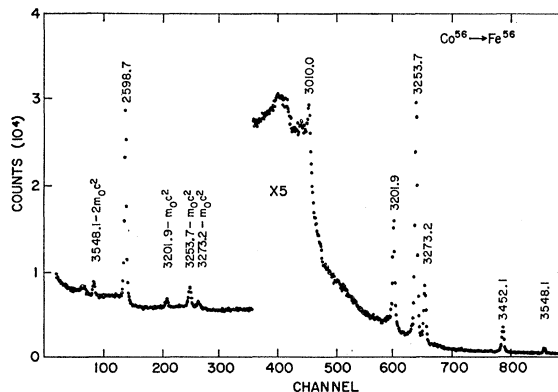


FIG. 8. The γ -ray spectrum from the decay of Co⁵⁶ from 2.5 to 3.6 MeV. Spectra used for calibration of γ -ray energies were taken at more than twice this dispersion.

¹⁸ P. F. Hinrichsen, M. H. Shapiro, and D. M. Van Patter, *Bull. Am. Phys. Soc.* **10**, 427 (1965); M. H. Shapiro, P. F. H. Hinrichsen, R. Middleton, and R. K. Mohindra, *Phys. Letters* **19**, 573 (1965).

TABLE II. Co^{56} γ -ray energies (keV) and intensities.

This work		Pettersson <i>et al.</i> ^a		Dolan <i>et al.</i> ^b	
Energy	Intensity	Energy	Intensity	Energy	Intensity
788.6 \pm 1.5	0.36	787.91	1.04 \pm 0.21		
846.64 \pm 0.10	100	846.82	100	846.5 \pm 0.1	100
977.5 \pm 0.5	1.5	977.46	1.73 \pm 0.35		
1037.87 \pm 0.20	14.0	1038.02	14.1 \pm 1.5	1038.1 \pm 0.1	12.4 \pm 0.5
1141.2 \pm 1.0	0.17				
1175.5 \pm 0.5	1.6	1175.25	2.1 \pm 0.6		
1238.4 \pm 0.2	64	1238.56	66.8 \pm 4.0	1238.6 \pm 0.1	71.2 \pm 2.6
1360.2 \pm 0.15	4.0	1360.58	4.0 \pm 0.8	1359.9 \pm 0.2	3.8 \pm 0.3
1771.4 \pm 0.15	14.0	1771.90	16.2 \pm 1.4	1770.8 \pm 0.2	15.6 \pm 1.3
1964.6 \pm 1.2	0.68	1964.8	0.75 \pm 0.27		
2015.4 \pm 0.3	2.6	2015.60	4.1 \pm 1.2	2015.6 \pm 0.3	3.8 \pm 0.7
2034.9 \pm 0.3	6.6	2035.50	9.2 \pm 1.7	2034.7 \pm 0.2	7.8 \pm 1.0
2113.0 \pm 0.1	0.56				
2213.0 \pm 1.5	0.60				
2598.70 \pm 0.15	14.0	2599.7	17.4 \pm 1.5	2598.9 \pm 0.2	16.0 \pm 2.7
3010.0 \pm 0.4	0.60	3010.4	1.3 \pm 0.4	3009.5 \pm 0.2	1.9 \pm 0.8
3201.9 \pm 0.3	2.9	3202.3	3.2 \pm 0.5	3202.3 \pm 0.3	2.9 \pm 1.1
3253.7 \pm 0.2	7.2	3254.0	8.5 \pm 0.6	3254.0 \pm 0.3	5.8 \pm 2.7
3273.2 \pm 0.3	1.6	3272.8	1.5 \pm 0.4	3273.6 \pm 0.2	1.2 \pm 0.5
3452.1 \pm 0.3	0.72	3452.5	0.95 \pm 0.15	3452.6 \pm 0.3	0.7 \pm 0.3
3548.1 \pm 0.3	0.2			3548.3 \pm 0.3	0.2 \pm 0.1

^a Reference 4.^b Reference 5.

signed by Dolan *et al.* With the exception of this state all levels above and including 3445.3-keV decay to the levels at 2085 and 846 keV. However the branching ratios of these transitions are such that it is impossible to definitely say whether the spins and parities of these states are the same. States of 4298.3 and 4100.3 keV have, in addition, a decay mode to the 3122.8-keV level but does not allow spin or parity assignments either. The new transitions of 1141.2 and 2113.0 keV sum to within 0.5 keV of the energy difference between the 4100.3- and 846.6-keV levels. This suggests a level of 2938 keV. Such a level is known from the Mn^{56} decay to decay by a transition to the ground state. However, the intensity of this γ ray precluded its observation in the Co^{56} decay. The γ ray of 1175.5 keV is not a Co^{60} contaminant because the 1332.-keV transition is not observed. This γ ray is satisfactorily placed depopulating the level at 4298.5 keV.

It is very difficult to assign spins and parities of the higher states on the basis of branching ratios. These states are presumably 3^+ , 4^+ , 5^+ because of the allowed β decay from the 4^+ Co^{56} ground state.

TABLE III. Energies of calibration γ rays.

Source	Energy (keV) ^a
Cs^{137}	661.595 \pm 0.076
Co^{60}	1173.226 \pm 0.040
Co^{60}	1332.48 \pm 0.05
ThC''	2614.47 \pm 0.10

^a G. T. Ewan and A. J. Tavendale, Canadian Atomic Energy Commission Report No. AECL 2079, 1964 (unpublished).

B. Mn^{56}

The β decay of Mn^{56} to the 2085-keV state in Fe^{56} has been found. The transition rate measured by comparing the intensity of the 1238-keV transition to that of 1811-keV transition corrected for feeding from the 3445-keV state yields $\log ft = 8.7 \pm 0.2$ for the decay to the 2.085-MeV state. This is in distinct contrast to the recently reported^{3,12} value of $\log ft > 10$. A β transition to the 3.445-MeV state in Fe^{56} has been found with an allowed $\log ft = 6.0 \pm 0.1$. The lower $\log ft$ value is anticipated because at this excitation energy the transition need not be l forbidden. The absence of a 1038-keV transition implies a $\log ft > 7.9 \pm 0.2$ for populating the 3112-keV state. The states at 3445, 2085, and 2958 keV appear to be the only ones fed in the β decay of both Mn^{56} and Co^{56} . The $\log ft$ values for the Mn^{56} and Co^{56} decays to the 2085-keV state are very similar although both very large for allowed decays. It is reasonable to interpret this as indicative of the l forbiddenness of the decays together with the collective nature of the 2085-keV state. The lower $\log ft$ values for the 3445-keV level from the Mn^{56} side might be interpreted as the transition of a $f_{7/2}$ proton to a $p_{3/2}$ neutron. It is not surprising then that the β transition from the Co^{56} ground state is retarded to this level.

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