Proc. Indian natn. Sci. Acad., **46**, A, No. 2, 1980, pp. 181–190.

Physics

DECAY OF ^{56}Co TO LEVELS IN ^{56}Fe

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(*Received 20 April 1979; after revision 14 January 1980*)

The properties of the gamma transitions and excited energy levels in ^{56}Fe, following the beta decay of 77.3 day ^{56}Co have been investigated. The precise energies and intensities of 44 gamma rays emitted in the decay of ^{56}Co have been measured. In addition, γ-γ angular correlation measurements on 16 cascades have been done. It has been possible to assign spins 3^+, 4^+ and 3^+ to the levels at 4048.92, 4100.39 and 4120.13 keV in ^{56}Fe respectively. The mixing ratios for the 977.48, 1037.91, 1175.22, 1360.50, 1771.31, 1810.74, 1963.69, 2015.16, 2034.76, 2598.61, 3202.26 and 3253.63 keV transitions have been measured. Two gamma-ray transitions in ^{56}Fe of energies 675.50 and 2657.56 keV have been confirmed. The energy level of 3601.38 keV has been confirmed, whereas the 4448.1 keV level has been discarded.

INTRODUCTION

A considerable interest has been focused on the decay properties of ^{56}Co by many research workers (Rao, 1970; Phelps *et al.*, 1970; Taylor & Singh, 1971; Agarwal *et al.*, 1971; Hofmann, 1974; Katou, 1975; and Auble, 1977) using a variety of techniques. Even then, controversy exists in the spin assignment to the various energy levels (Auble, 1977). The placement of a transition of energy 3601.38 keV in the decay scheme is also uncertain. Phelps *et al.* (1970) placed the 3601.38 keV transition between 4448.1 and 846.78 keV levels but this transition was suggested to be a ground state transition from an energy level at 3601.38 keV by Hofmann (1974). Two new gamma transitions of energies 674.7 and 2657.4 keV have been shown by Hofmann (1974) which need confirmation.

The gamma-gamma angular correlation studies have been done extensively by Hofmann (1974) using a Ge(Li)-NaI(Tl) detectors set-up. It appears that the errors shown by these workers in their angular correlation coefficients are not very realistic, as even the statistical errors are normally expected to be more than their quoted errors. The mixing ratios for some transitions show considerable disagreement as far as the results of earlier workers are concerned (Taylor & Singh, 1971; Agarwal *et al.*, 1971; and Hofmann, 1974).

Keeping in view the above mentioned discrepancies and uncertainties, it was thought worthwhile to re-investigate the decay characteristic of ^{56}Co with better precision and to provide more reliable experimental data. In the present work, the gamma-ray energy and intensity measurements together with an extensive series of γ-γ angular correlation and coincidence measurements have been made to establish the role of 44 γ-transitions in the ^{56}Fe level scheme.

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Experimental Set-up and Data Analysis

The radioisotope ^{56}Co was prepared by bombarding pure iron strip (99.9 per cent) with 11 MeV proton beam of the AERE, Harwell, U. K. tandem generator. For single spectrum measurements, the source was placed at a distance of 25 cm from a 64.1 cc Ge(Li) detector coupled to a 4096 channel analyser. The strength of the source was adjusted so as to provide around 1000 counts per sec and consequently sum coincidence effects were avoided. Several singles gamma-ray spectra were recorded, each after an interval of one half life. The energy resolution of the Ge(Li) spectrometer was $\leqslant$ 2.2 keV for the 1.33 MeV gamma ray of ^{60}Co. In order to reduce the effect of room background, the detector was shielded with a lead cylinder and a lead cone having an anti-Compton lining on the inside. At the same experimental settings, a spectrum for the room background was also taken to confirm the presence of genuine gamma-ray peaks of ^{56}Co and also to correct for the room background.

A set-up involving 64.1 cc Ge(Li) and 3″ × 3″ NaI(Tl) detectors alongwith a fast coincidence circuit (2τ = 9 nsec) was used for γ-γ angular correlation and coincidence measurements. The source was placed at a distance of 10 cm from both the detectors, at the point of intersection of the axes of the two detectors. The NaI(Tl) detector was used to gate one energy peak of interest, whereas the Ge(Li) detector was used as an analog detector. The coincidence peaks related to the gated peak at the NaI(Tl) detector side were recorded on a 4096 channel analyser. The present angular correlation measurements have been carried out by fixing the position of the Ge(Li) detector whereas, the NaI(Tl) detector was moved from 180° to 90° in 15° steps at seven angles. The chance coincidences were collected by shifting the gate of the timing single channel analyser connected with time-to-pulse height converter from coincidence peak region to the chance region of the time spectrum.

The gamma-gamma angular correlation studies have been performed on 16 cascades, by selecting two energy gates at 846.86 and 1238.24 keV on NaI(Tl) detector side and the corresponding coincidence spectrum for each gate was recorded on the multichannel analyser for seven different angular positions of the NaI(Tl) detector. The least square fitting method of Rose (1953) was used to obtain the angular correlation coefficients for various cascades. Solid angle corrections were made by using the correction factors calculated by Yates (1965) for the NaI(Tl) detector, and for the Ge(Li) detector, the method of Camp and Vanlehn (1969) was used. The mixing ratio analysis was done by using the methods of Arns and Wiedenbeck (1958) and Taylor *et al.* (1971).

Measurements and Results

Singles Spectrum Measurements

A sample pulse height spectrum of ^{56}Fe as recorded by the 64.1 cc Ge(Li) detector is shown in Fig. 1. In order to confirm the weak transitions, the data were recorded for a long time until good statistics was collected for each peak. The energy calibration of the spectrometer was done by the method of Gehrke *et al.* (1971) and

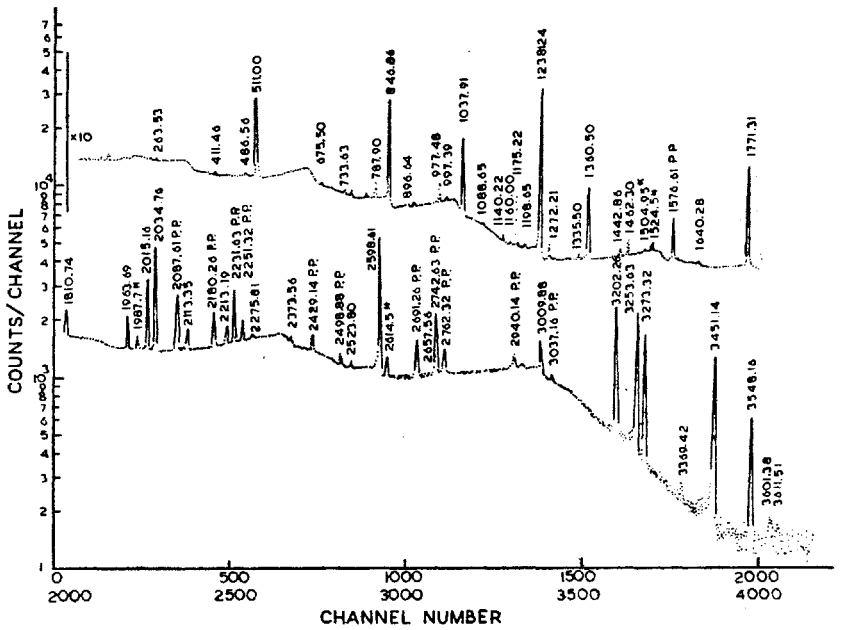

FIG. 1. Gamma ray singles spectrum of ^{56}Co observed with a 64.1 cc Ge (Li) detector. The source-to-detector distance was 25cm. Numbers above the peaks indicate energies in keV and stars indicate background peaks. P. P. means pair peak i.e., either single escape or double escape peaks.

the strong peaks of ^{56}Fe of well defined energies (846.752, 1238.26, 1771.40 and 2598.55 keV) given by Auble (1977) have been used as reference peaks.

For the measurements of relative intensities of various gamma rays in ^{56}Fe, the efficiency calibration of the Ge(Li) spectrometer was done by using NBS standard calibrated sources (^{109}Cd, ^{137}Cs, ^{75}Se, ^{60}Co and ^{88}Y) and liquid source of ^{110m}Ag. The areas of various peaks under study in ^{56}Fe were evaluated from the singles spectrum after applying suitable corrections for the Compton contributions of higher energy gamma rays. These areas were then corrected for the efficiency of the detector to get the values of intensities of various gamma transitions observed in the decay of ^{56}Co. The results of these energy and intensity measurements have been summarised in Table I alongwith the earlier results (Auble, 1977). The accuracy in the intensity measurements is $\sim$ 2 per cent for the most prominent gamma rays.

Coincidence Measurements

Three coincidence spectra with Ge(Li)-NaI(Tl) coincidence set-up (2τ = 9 nsec) were recorded with energy gates set to observe 846.86, 1037.91 and 1238.24 keV gamma rays respectively on NaI(Tl) detector side. The angle between the two detectors was set at 90° to avoid crystal-to-crystal scattering. In order to correct for the Compton contributions appearing in the various energy gates, three more coincidence spectra were recorded by setting the window on higher energy side of 846.86, 1037.91 and 1238.24 keV peaks respectively.

TABLE I

Energies and relative intensities of γ-rays in ^{56}Fe *from the decay of* ^{56}Co.

Energy (keV)	Relative intensity	
	Present work	Auble (1977)
263.53	0.31 ± 0.009	0.21 ± 0.004
411.46	0.026 ± 0.008	0.025 ± 0.005
486.56	0.065 ± 0.011	0.05 ± 0.01
675.50	0.045 ± 0.020	0.03 ± 0.01
733.63	0.166 ± 0.012	0.192 ± 0.022
787.90	0.28 ± 0.01	0.307 ± 0.007
846.86	100	100
896.64	0.089 ± 0.013	0.075 ± 0.010
977.48	1.38 ± 0.03	1.40 ± 0.03
997.39	0.11 ± 0.01	0.14 ± 0.03
1037.91	14.06 ± 0.28	14.1 ± 0.2
1088.65	0.075 ± 0.009	0.05 ± 0.02
1140.22	0.11 ± 0.01	0.126 ± 0.015
1160.00	0.079 ± 0.009	0.091 ± 0.010
1175.22	2.22 ± 0.05	2.26 ± 0.06
1198.65	0.035 ± 0.01	0.043 ± 0.011
1238.24	67.59 ± 1.31	67.0 ± 0.7
1272.21	0.022 ± 0.008	0.020 ± 0.001
1335.50	0.124 ± 0.010	0.121 ± 0.002
1360.50	4.29 ± 0.08	4.29 ± 0.04
1442.86	0.182 ± 0.011	0.174 ± 0.004
1462.30	0.086 ± 0.003	0.072 ± 0.006
1640.28	0.055 ± 0.009	0.063 ± 0.003
1771.31	15.61 ± 0.30	15.52 ± 0.14
1810.74	0.62 ± 0.02	0.65 ± 0.02
1963.69	0.71 ± 0.02	0.702 ± 0.011
2015.16	2.95 ± 0.06	3.03 ± 0.05
2034.76	7.74 ± 0.02	7.78 ± 0.12
2113.35	0.35 ± 0.01	0.376 ± 0.007
2213.19	0.35 ± 0.01	0.376 ± 0.008
2275.81	0.115 ± 0.01	0.120 ± 0.018
2373.56	0.079 ± 0.010	0.061 ± 0.008
2523.80	0.14 ± 0.01	0.048 ± 0.009
2598.61	16.41 ± 0.33	16.75 ± 0.22
2657.56	0.015 ± 0.003	0.016 ± 0.005
3009.88	1.02 ± 0.02	1.03 ± 0.09
3202.26	3.04 ± 0.06	3.02 ± 0.21
3253.63	7.52 ± 0.15	7.4 ± 0.5
3273.32	1.77 ± 0.04	1.73 ± 0.12
3369.42	0.007 ± 0.002	0.0097±0.0009
3451.14	0.90 ± 0.02	0.89 ± 0.09
3548.16	0.19 ± 0.05	0.173 ± 0.017
3601.38	0.015 ± 0.003	0.015 ± 0.002
3611.51	0.007 ± 0.002	0.0078± 0.0010

These coincidence measurements were helpful to confirm and place some of the gamma transitions in the level scheme of ^{56}Fe. The coincidence spectrum taken with gate set at 846.86 keV confirms the direct feeding of the 846.86 keV level by the 1238.24, 1810.74, 2113.35, 2275.81, 2523.8, 2598.61, 3009.88, 3202.26, 3253.63, 3273.32, 3451.14, 3548.16 and 3611.51 keV gamma rays. The present authors could not observe the 3601.38 keV gamma ray in coincidence with the 846.86 keV transition. This implies that this gamma ray has to be assigned to a level at 3601.38 keV and not the level at 4448.1 keV as suggested by Phelps *et al.* (1970). This agrees with the results of Hofmann (1974).

The 2657.56 keV gamma ray was not found in coincidence with any of the 846.86, 1037.91, and 1238.24 keV transitions. Taking into account the energy of the parent state of ^{56}Co, the 2657.56 keV γ-ray can only be a ground state transition from a level at 2657.6 keV. The 675.50 keV transition proposed by Hofmann (1974), for the first time, was observed in coincidence with 846.86 and 1238.24 keV transitions (triple coincidences) but not in coincidence with 1037.91 keV transition. On the basis of coincidence results and various level energies, the 675.50 keV transition has been placed between 4120.13 and 3445.52 keV levels.

γ-γ *Angular Correlation Measurements*

The γ-γ angular correlation measurements on nine 1–2 and seven 1–3 cascades have been performed in the present study. All the results have been checked by repeating the measurements twice. The results of the present angular correlation studies are given in Table 2 and Table 3. In the succeeding sections, a discussion has been made only on those cascades which have resulted in the assignment of suitable spin values to the levels at 4048.92, 4100.39 and 4120.13 keV in ^{56}Fe.

Spin Assignment to the 4048.92 *keV Level* — The character of the 4048.92 keV level in ^{56}Fe was so far uncertain (Auble, 1977) and has been limited to 3^+ and 4^+ assignments. In the present work, the 3202–847 kcV and 1964–1238 keV cascades have been used to assign spin to the 4048.92 keV level.

The two possible spin sequences for the 3202–847 keV cascade are 3^+–2^+–0^+ and 4^+–2^+–0^+ (Auble, 1977). The 3202 keV transition is found to be M1 + E2 with δ (E2/M1) = —0.47 $\pm$ 0.05 (Auble, 1977). In the case of 4^+–2^+–0^+ spin sequence, the 3202 keV transition is generally expected to be pure E2 in character. This excludes the possibility of 4^+ spin assignment to the 4048.92 keV level. This is also supported by the angular correlation coefficient A_2 which should be 0.102 for the 4^+–2^+–0^+ spin sequence, whereas from the present measurements, the value of A_2 is found to be 0.203 $\pm$ 0.041 (Table II).

Taking δ (E2/M1) = —0.47 $\pm$ 0.05 (Auble, 1977) for the 3202 keV transition, the theoretical value of A_2 is found to be 0.202 $\pm$ 0.022 for the 3^+–2^+–0^+ spin sequence. This value agrees very well with our experimental correlation coefficient. Hence the 3^+–2^+–0^+ spin sequence is accepted for this cascade and a spin 3^+ is ascertained for the 4048.92 keV level in ^{56}Fe. Assuming the 847 keV transition (Hofmann, 1974) to be pure E2, the mixing ratio for the 3202 keV transition was found to be δ(E2/M1) = —0.46 $\pm$ 0.09 which is in good agreement with the earlier results (Table III).

TABLE II

Gamma-gamma angular correlation coefficients in ^{56}Fe

Cascade (keV)	Angular Correlation coefficients	Present work	Hofmann (1974)
977–(2276)–847	A_2	0.231 ± 0.089	0.21 ± 0.05
	A_4	—0.087 ± 0.045	—0.11 ± 0.08
1038–(1238)–847	A_2	0.198 ± 0.012	0.196 ± 0.005
	A_4	0.052 ± 0.019	0.16 ± 0.008
1175–(2276)–847	A_2	0.048 ± 0.035	0.082 ± 0.023
	A_4	0.076 ± 0.056	0.067 ± 0.036
1771–(1238)–847	A_2	—0.142 ± 0.011	—0.13 ± 0.004
	A_4	0.022 ± 0.015	—0.00 ± 0.006
2015–(1238)–847	A_2	—0.032 ± 0.024	—0.037 ± 0.009
	A_4	0.086 ± 0.038	0.07 ± 0.015
2035–(1238)–847	A_2	—0.051 ± 0.031	—0.07 ± 0.005
	A_4	0.009 ± 0.049	0.005 ± 0.008
2599–847	A_2	—0.275 ± 0.030	—0.277 ± 0.008
	A_4	—0.006 ± 0.040	—0.009 ± 0.011
3202–847	A_2	0.203 ± 0.040	0.193 ± 0.017
	A_4	0.008 ± 0.006	—0.017 ± 0.026
3254–847	A_2	0.151 ± 0.048	0.102 ± 0.008
	A_4	0.047 ± 0.077	0.011 ± 0.013
1038–1238	A_2	0.199 ± 0.012	—
	A_4	—0.025 ± 0.019	—
1175–(1038)–1238	A_2	0.067 ± 0.034	—
	A_4	0.073 ± 0.052	—
1360–1238	A_2	—0.058 ± 0.047	—
	A_4	—0.049 ± 0.077	—
1771–1238	A_2	—0.13 ± 0.01	—
	A_4	0.033 ± 0.015	—
1964–1238	A_2	—0.30 ± 0.01	—
	A_4	0.245 ± 0.151	—
2015–1238	A_2	—0.022 ± 0.029	—
	A_4	0.165 ± 0.043	—
2035–1238	A_2	—0.074 ± 0.021	—
	A_4	—0.001 ± 0.030	—

In order to confirm the 3^+ assignment to the 4048.92 keV level, the 1964–1238 keV cascade was also analysed. If 4^+ spin is taken for the 4048.92 keV level, the multipole character of the 1964 keV transition is found to be predominantly E2. This transition is quoted to be M1 in character by several workers (Agarwal *et al.*, 1971; Taylor & Singh, 1971; and Auble, 1977). Therefore, the 4^+ spin assignment to the level at 4048.92 keV is unacceptable. Thus the only possibility left is 3^+ spin assignment for this state. The mixing in the 1964 keV γ-ray transition was found to be E2+(95.5 ± 3.5 per cent) M1 when we assumed 3^+ spin assignment for the 4048.92 keV level. This is in agreement with the previous results (Hofmann, 1974). Hence the spin 3^+ for the 4048.92 keV level has been confirmed.

TABLE III

Mixing ratio results for various transitions in ^{56}Fe

Cascade (keV)	Gamma transition (keV)	Mixing ratio δ (E2/M1)			
		Present work	Hofmann (1974)	Agarwal *et al.* (1971)	Taylor and Singh (1971)
977–(2276)–847	977	0.12 ± 0.01	1.5 ± 0.11	−0.09 ± 0.18 or 1.17 ± 0.42	0.35 ± 0.05 or 6.5 ± 1.5
1038–(1238)–847	1038	0.0 ± 0.04	0.02 ± 0.02	0.01 ± 0.04	0.02 ± 0.02
1175–(2276)–847	1175	−0.41 + 0.07 − 0.08	−0.22 ± 0.075 or 1.70 + 0.26 − 0.33	−0.25 ± 0.10 or 1.6 ± 0.3	—
1771–(1238)–847	1771	0.0 ± 0.02	0.01 ± 0.01	0.023 ± 0.008	0.02 ± 0.01
2015–(1238)–847	2015	−0.65 ± 0.05	−0.639 ± 0.027	−0.62 ± 0.05	—
2035–(1238)–847	2035	0.25 ± 0.03	0.087 ± 0.012	0.065 ± 0.008	−0.09 ± 0.02 or 0.75 ± 0.10
2599–847	2599	0.27 + 0.04 − 0.05	0.266 ± 0.016	0.278 ± 0.011	0.28 ± 0.03
3202–847	3202	−0.46 ± 0.09	−0.43 ± 0.06 or 1.44 ± 0.12	−0.51 ± 0.06 or −1.34 ± 0.15	−0.50 ± 0.05
3254–847	3254	−0.12 ± 0.05	< 0.01	—	−0.27 ± 0.03
1038–1238	1038	0.0 ± 0.05	0.02 ± 0.02	0.01 ± 0.04	0.02 ± 0.02
1175–(1038)–1238	1175	−0.33 ± 0.09	−0.22 ± 0.075 or 1.70 + 0.26 − 0.33	−0.25 ± 0.10 or 1.6 ± 0.3	—
1360–1238	1360	0.12 ± 0.05	0.136 ± 0.013	0.11 ± 0.02	0.11 ± 0.02
1771–1238	1771	0.0 ± 0.03	0.01 ± 0.01	0.023 ± 0.008	−0.02 ± 0.01
1964–1238	1964	−0.22 ± 0.07	−0.163 ± 0.054 or −3.5 ± 0.6	−0.19 ± 0.06	—
2015–1238	2015	−0.62 ± 0.09	−0.639 ± 0.027	−0.62 ± 0.05	—
2035–1238	2035	0.11 + 0.01 − 0.02	0.087 ± 0.012	0.065 ± 0.008	−0.09 ± 0.02 or 0.75 ± 0.10

Spin Assignment to the 4100.39 *keV Level* — The spin for the 4100.39 keV level is so far uncertain (Auble, 1977). Taylor and Singh (1971) have assigned a 3^+ spin to this level but later on Hofmann (1974) has assigned a 4^+ spin to this level. Therefore, the present analysis considers both 3^+ and 4^+ spin assignments for the 4100.39 keV level. The 977–(2276)–847 and 3254–847 keV cascades have been used to assign the spin to the 4100.39 keV level in ^{56}Fe. Taking the two possible spin sequences 3^+–$(4^+$–$2^+)$–0^+ and 4^+–$(4^+$–$2^+)$–0^+ for the 977–(2276)–847 keV cascade and assuming the 2276 and 847 keV transitions as pure E2, the mixing ratio analysis has been carried out. Depending upon these two spin sequences, the quadrupole mixing for the 977.48 keV transition is found to be:

Spin sequence	*Quadrupole mixing*
	$Q_1 = 0.17 \pm 0.05$
3^+–$(4^+$–$2^+)$–0^+	$Q_2 = 0.95 \pm 0.03$
4^+–$(4^+$–$2^+)$–0^+	$Q_1 = 0.015 \pm 0.05$
	$Q_2 = 0.48 \pm 0.15$

The conversion coefficient measurements (Auble, 1977) show an almost M1 character for the 977.48 keV transition, which is possible only when $Q = 0.015 \pm 0.005$ is accepted. Therefore, the 4^+ spin has been assigned to the 4100.39 keV level.

In order to support the 4^+ spin assignment, the 3254–847 keV cascade has also been analysed. Taking 4^+–2^+–0^+ spin sequence, two values of quadrupole mixing in 3254 keV have been found viz., $Q = 0.015^{+0.025}_{0.015}$, $0.65^{+0.075}_{0.10}$. The experimental A_4 value as well as conversion coefficient results (Auble, 1977) reject the second value of Q. The first value of Q gives the multipole admixture in the 3253.63 keV transition to be M1+$(1.5^{+2.5}_{1.5})$ per cent E2. This is in good agreement with earlier measurements (Auble,1977). Hence, the 4^+ spin has been confirmed for the 4100.39 keV level in ^{56}Fe.

Spin Assignment to the 4120.13 *keV Level* — The spin to the 4120.13 keV level in ^{56}Fe is so far uncertain and is assumed to be 3^+ or 4^+ (Auble, 1977). The spin assignment to the 4120.13 keV level has been done on the basis of 2035–1238 keV cascade.

In the present analysis, the two possible spin sequences 3^+–4^+–2^+ and 4^+–4^+–2^+ for the 2035–1238 keV cascade have been taken (Auble, 1977). The mixing ratio analysis yields the following values of quadrupole mixing in the 2035 keV transition :

Spin sequence	*Quadrupole mixing*
	$Q_1 = 0.013\ ^{+0.003}_{-0.005}$
3^+–4^+–2^+	$Q_2 = 0.99 \pm 0.005$
4^+–4^+–2^+	$Q_1 = 0.40 \pm 0.05$
	$Q_2 = 0.975 \pm 0.015$

The experimental A_4 value as well as conversion coefficient results (Auble, 1977) show an almost M1 character of the 2035 keV transition. This is possible only when $Q = 0.013^{+0.003}_{-0.005}$ is accepted which yields M1 + $(1.3^{+0.3}_{-0.5})$ per cent

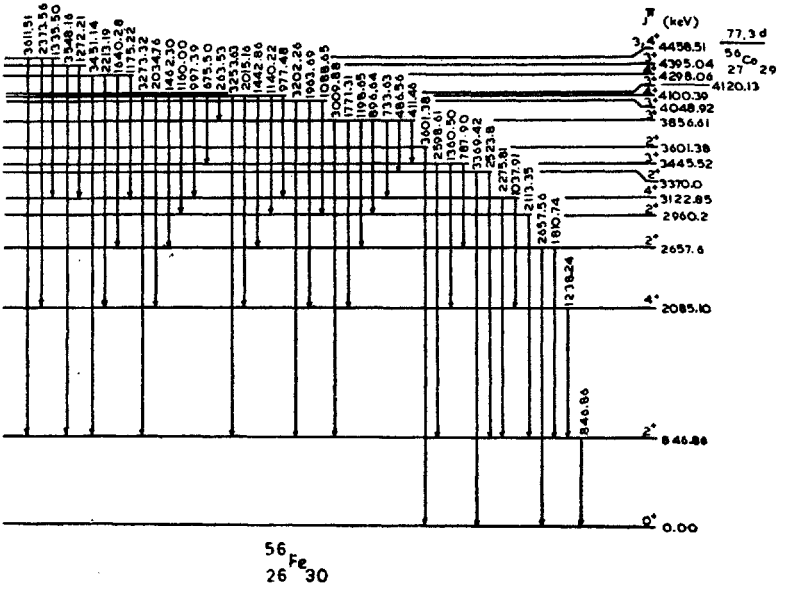

FIG. 2. Level scheme of ^{56}Fe resulting from the decay of ^{56}Co.

E2 character of the 2035 keV transition. Therefore, the spin 3^+ has been assigned to the 4120.13 keV level in ^{56}Fe.

DISCUSSION

The decay scheme of ^{56}Co consistent with the present measurements is shown in Fig. 2. The spins to the 4048.92, 4100.39 and 4120.13 keV level are unambiguously assigned to be 3^+, 4^+ and 3^+ respectively on the basis of the present angular correlation measurements. Two new gamma transitions of energies 675.50 and 2657.56 keV shown by Hofmann (1974) and also observed in the present study have been placed in the decay scheme of ^{56}Co. Also, the 3601.38 keV transition, has been confirmed to be a ground state transition from a level at 3601.38 keV.

The mixing ratio for the transitions of energy 1037.91, 1175.22, 1771.31, 2015.16 and 2034.76 keV in the present angular correlation measurements are supported by two or more cascade results. The multipole admixitures for these transitions are in good agreement with earlier results (Table III). The mixing ratio for the 977.48 keV transition is not in agreement with earlier measurements (Agarwal *et al.*, 1971; and Hofmann, 1974); this result is in agreement with that of Taylor *et al.* (1971) (Table III).

ACKNOWLEDGEMENTS

Two of the authors (AKS, RK) SRF, CSIR wish to acknowledge the financial assistance given by Council of Scientific and Industrial Research, Government of India. This work was sponsored by the National Bureau of Standards, Washington, D.C., U.S.A.

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