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Decay of ^{61}Fe to levels in ^{61}Co

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Single γ ray, $\gamma-\gamma$ coincidence, and level spectrometer studies have been performed on the decay of ^{61}Fe ($T_{1/2} = 5.98 \pm 0.06$ min). 48 γ transitions with energies up to 3365 keV are assigned to this decay and 22 levels are proposed in the ^{61}Fe decay scheme. Spins and parities of levels in ^{61}Co are given. The level structure of ^{61}Co is compared with neighboring odd Co nuclei.

[RADIOACTIVITY ^{61}Fe; measured $T_{1/2}$, E_γ, I_γ, γ-γ coin, γ-γ anticoin; deduced logft, J^π. ^{61}Co; deduced E_{levels}, J^π_{levels}; compared with odd Co nuclei.]

I. INTRODUCTION

The β decay of ^{61}Fe was investigated by several groups[1-7]; the data of most of these groups[1-6] as well as the data of Blair and Armstrong,[8] who investigated the ^{62}Ni(t, α)^{61}Co reaction, are summarized in Ref. 9. The conclusions drawn from these studies, for instance the ground-state spin of ^{61}Fe, are not very well argued. Since then more reaction data became available. Coop *et al.* investigated the ^{64}Ni(p, α)^{61}Co [10] and the ^{64}Ni(p, $\alpha\gamma$)-^{61}Co [11] reactions, and Hudson *et al.* studied the ^{62}Ni(t, α)^{61}Co and the ^{59}Co(t, p)^{61}Co [12] reactions. A comparison of the energy levels of ^{61}Co proposed by different groups who studied the β decay of ^{61}Fe reveals several problems. The level at 1410 keV proposed by Gujrathi *et al.*[3] was not found by others. Furthermore, it is not clear which members of the multiplets at 1650 and 2000 keV, found in reaction work, are populated in the decay of ^{61}Fe.

A theoretical calculation of Satpathy and Gujrathi describes[13] the low-lying levels in the odd Co nuclei as a proton hole coupled to a vibrating Ni core (cf. Sec. IV D). Recently Stewart, Castel, and Singh,[14] and Gómez[15] performed calculations based on the same model, but now including microscopic core excitations[14,15] and anharmonic terms in the vibrating Ni core.[14] Up to about 2000 keV the level schemes of ^{57}Co and ^{59}Co, calculated by Stewart *et al.* and Gómez, are in good agreement with the experimental data. For ^{61}Co the data about the spin and parity of the experimentally observed levels are rather scarce, so a comparison with the theory is hampered. The present investigation of the decay of ^{61}Fe was undertaken to resolve the discrepancies between the experimental data as mentioned above, to investigate if levels above 2000 keV are fed by β decay and to get more experimental information about the excited states of ^{61}Co.

Some of the results have been published before.[16]

II. SOURCES, EQUIPMENT AND METHODS

The ^{61}Fe sources were produced by the ^{64}Ni(n, α)^{61}Fe reaction on enriched ^{64}Ni (97.92% ^{64}Ni; 0.92% ^{58}Ni; 0.73% ^{60}Ni; 0.05% ^{61}Ni; and 0.38% ^{62}Ni), packed in polyethylene capsules. Two capsules with 20 mg Ni were available. We used 15 MeV neutrons produced by the 600 keV Cockroft-Walton generator, as well as neutrons produced by a 16 MeV deuteron beam of the AVF cyclotron of our institute on a thick Be target. The sources produced by the generator appeared to be very weak, but also very clean. Using the cyclotron we could produce three times as much ^{61}Fe, but the sources contained much more contamination, particularly ^{65}Ni arising from neutron capture on ^{64}Ni.

All experiments were performed with 75 cm^3 Ge(Li) detectors (Gamma Tech), standard Ortec electronics, and a ND 50/50 analyzing system. The PDP8/L computer, part of this system, controlled the experiments. The PDP8/L is interfaced with a CDC1700 computer, where the data were dumped on magnetic tapes.[16] The single γ ray spectra were measured, after ten minutes of irradiations, during eight consecutive periods of three minutes. Because the sources were weak they were placed against the cap of the detector. This made intensity corrections for coincident summation necessary (cf. Sec. III). A two-dimensional γ-γ coincidence experiment was performed with two 75 cm^3 Ge(Li) detectors in a face-to-face geometry, separated by a lead shield with a hole in which the source was placed. Coincidences were stored temporarily, event by event, in a part of the memory of the ND 50/50 system and then dumped on a magnetic tape. Afterwards digital gates were set and the tapes were searched in order to build up the coincident spectra. We used an anti-Compton system as a "level spectrometer".[17] The single and suppressed spectrum were measured simultaneously. Because of the almost 4π geometry of the NaJ(Tl) crystal, all peaks will be strongly suppressed, except ground-state transitions from levels directly fed by β decay. The suppression (= suppressed intensity/single intensity) of a ground-state transition from a level is a measure for the ratio of the total intensity of the direct β feeding to this level and the total γ feeding to this level.

III. RESULTS AND ANALYSIS

The γ ray spectrum of ^{61}Fe is shown in Fig. 1. The spectra were analyzed by a peak-search and peak-fit code POESPAS developed by Blok *et al.*[18] The energies were calibrated with ^{56}Co[19] and ^{133}Ba.[20] In order to calculate the corrections for coincident summation, not only the photopeak efficiency but also the Compton efficiency in the same geometry was determined. The photopeak efficiency plus Compton efficiency varied from 22% for 122 keV to 15% for 1115 keV. These corrections were calculated using the level scheme shown in Fig. 4 and assuming an isotropic angular distribution of the γ rays. For the strongest γ transitions the corrections were checked in a measurement with a larger source-detector distance. The energies and relative γ intensities of the transitions assigned to the decay in ^{61}Fe are listed in Table I. As far as they were known before, the intensities of the γ transitions are in agreement with the values adopted in Ref. 9; however, the γ transitions of 230, 400, and 2250 keV, reported by several authors,[1-3] are not found in the present investigation. The γ ray branching ratios obtained from this study are in agreement with the data from the ^{64}Ni(p, $\alpha\gamma$)^{61}Co reaction.[11] (See Table II.) From

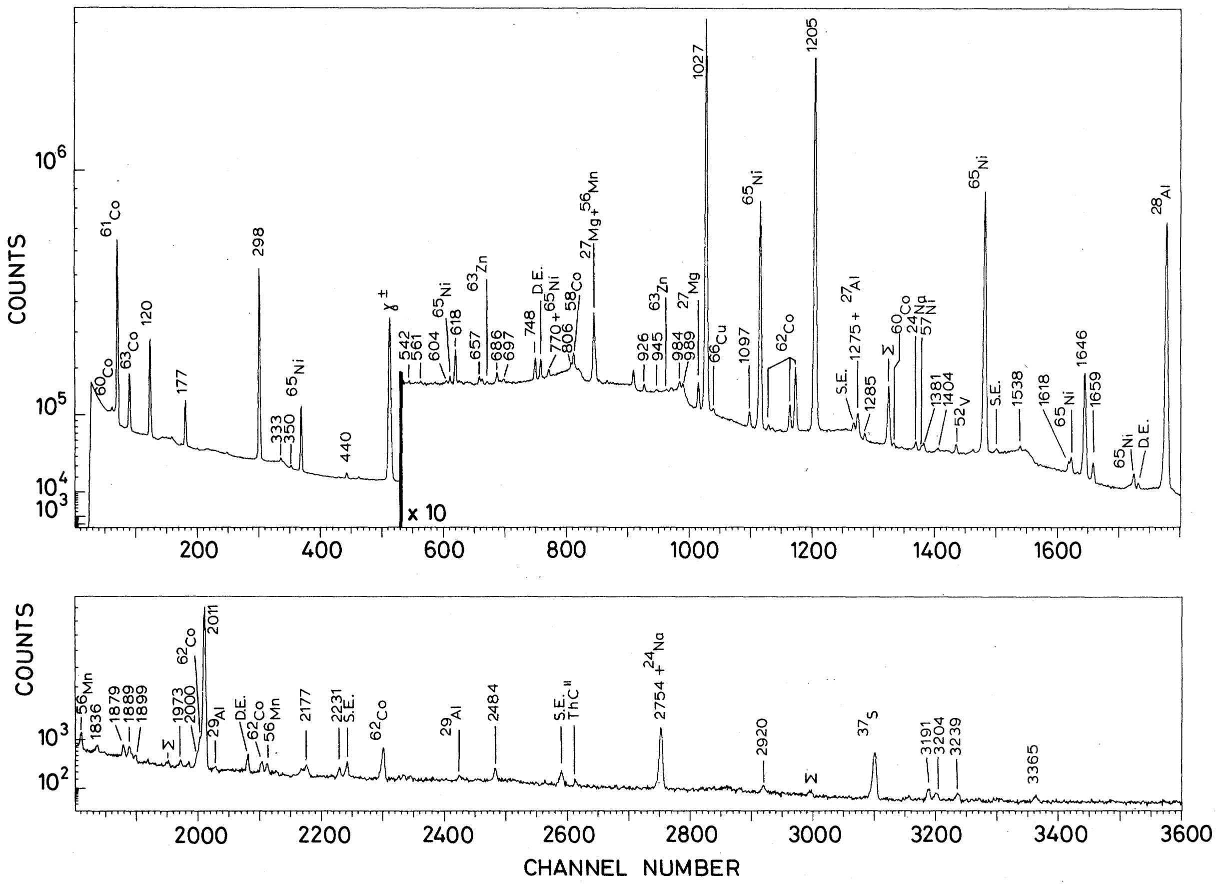

FIG. 1. The γ ray spectrum of ^{61}Fe, obtained by adding the spectra of 25 sources, produced by the AVF cyclotron. Each spectrum was measured during 6 min, starting 0.5 min after the end of irradiation. The γ transitions of ^{61}Fe are indicated with their energies in keV. Peaks due to coincident summation are indicated by a "Σ".

TABLE I. Energies and relative intensities of the γ transitions of ^{61}Fe.

	E_γ (keV)			I_γ	
Ref. 9	Ref. 5	This work	Ref. 9	Ref. 5	This work
120.0	121 ± 1	120.34 ± 0.12	12.0	11.9 ± 0.7	12.2 ± 0.9
177.1	177 ± 2	177.61 ± 0.12	4.5	5.0 ± 0.5	4.6 ± 0.4
230[a]			3		<0.07
297.3	298 ± 3	297.90 ± 0.07	49	54 ± 3	51 ± 4
		333.0 ± 0.4			0.51 ± 0.08
		349.7 ± 0.3			0.37 ± 0.09
400[a]			0.7		<0.07
		440.5 ± 0.4			0.50 ± 0.10
		542.6 ± 0.5[b]			0.15 ± 0.07
		561.4 ± 0.5[b]			0.13 ± 0.06
		603.3 ± 0.5			0.17 ± 0.07
		618.40 ± 0.16			2.14 ± 0.17
		657.3 ± 0.4			0.51 ± 0.22
		686.0 ± 0.3			0.92 ± 0.18
		696.9 ± 0.4			0.26 ± 0.07
		748.10 ± 0.18			1.85 ± 0.17
		769.4 ± 0.5			0.37 ± 0.09
		806.3 ± 0.4			0.44 ± 0.11
		925.6 ± 0.3			0.78 ± 0.09
		945.4 ± 0.5			0.25 ± 0.07
		978[c]			0.17 ± 0.09
		984.1 ± 0.4			1.4 ± 0.3
		989.2 ± 0.4			1.4 ± 0.3
1025	1025 ± 3	1027.42 ± 0.11	100	86 ± 7	98 ± 5
		1097.8 ± 0.2			1.60 ± 0.13
1204	1202 ± 3	1205.07 ± 0.12	100	100	100
		1275			1.4 ± 0.3[d]
		1285.7 ± 0.3			0.85 ± 0.13
		1381.4 ± 0.3			0.92 ± 0.11
		1403.9 ± 0.5			0.27 ± 0.12
		1538.8 ± 0.3			0.63 ± 0.11
		1618.9 ± 0.2			0.84 ± 0.10
1636[a]		1645.95 ± 0.16	19.1		16.0 ± 0.8
		1659.3 ± 0.2			1.78 ± 0.20
		1837.2 ± 0.6			0.32 ± 0.07
		1879.4 ± 0.4			0.60 ± 0.08
		1889.0 ± 0.4			0.41 ± 0.08
		1899.3 ± 0.5			0.17 ± 0.05
		1972.7 ± 0.5			0.14 ± 0.04
		1999.8 ± 0.8			0.30 ± 0.10
1973[a]		2011.6 ± 0.2	9.9		10.1 ± 0.7
		2177.1 ± 0.7			0.48 ± 0.10
		2230.8 ± 0.4			0.25 ± 0.04
2250[a]			2.6		<0.03
		2484.4 ± 0.4			0.28 ± 0.03
2720[a]		2754.4 ± 0.4	2.6		1.76 ± 0.20
		2920.0 ± 0.5			0.16 ± 0.03
		3191.0 ± 0.6			0.19 ± 0.03
		3204.2 ± 0.6			0.10 ± 0.02
		3239.1 ± 0.6			0.13 ± 0.03
		3364.9 ± 0.7			0.10 ± 0.02

[a] Only observed with scintillation detectors.

[b] Tentatively assigned.

[c] Tentatively assigned; evidence for this γ transition is found in the 298 keV coincidence spectrum (cf. Fig. 3).

[d] The intensity is deduced from the coincidence spectra, because the contribution of the 1275 keV transition of ^{29}Al ($T_{1/2} = 6.6$ min) could not be determined accurately.

its three strongest γ rays the half-life of ^{61}Fe is determined to be 5.98 ± 0.06 min, in agreement with previous results.

The results of the coincidence experiment are summarized in Fig. 2 and some of the coincident spectra are shown in Fig. 3.

The results from the energy level experiment show that the 1027, 1205, 1646, 2011, 2484, 2754, 2920, 3191, 3204, 3239, and 3365 keV γ rays and the 1325, 1953, and 3000 keV sum peaks are only partly (1027 keV) or very little suppressed, showing that there are levels in ^{61}Co at these energies which are directly fed by β decay. The suppressions for the 1286, 1619, 1889, and 2230 keV γ rays are <0.10, <0.15, 0.20 ± 0.10, and 0.15 ± 0.05, respectively, showing that the levels with these energies are not fed, or very weakly fed, by direct β decay.

IV. DISCUSSION

A. Decay of ^{61}Fe to ^{61}Co

The decay scheme of ^{61}Fe based on our data is given in Fig. 4. The parity of the ground state of ^{61}Fe is negative because of the allowed β transitions to the $L=2$ negative parity levels at 1205, 2754, and 3000 keV. [All L assignments refer to the ^{59}Co$(t,p)^{61}$Co reaction of Hudson and Glover.[12] All l_p assignments refer to the ^{62}Ni$(t,\alpha)^{61}$Co reaction of Blair and Armstrong.[8]] The level at 1027 keV has $J^\pi = \frac{3}{2}^-$, as can be concluded from a $L=2(J^\pi = \frac{3}{2}^- - \frac{11}{2})$ and a $l_p = 1$ $(J^\pi = \frac{1}{2}^-, \frac{3}{2}^-)$ transition. The β feeding to this level restricts the spin of the ground state of ^{61}Fe to $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$. The $\frac{1}{2}^-$ assignment can be ruled out, because β feeding to $l_p = 3$ $(J^\pi = \frac{5}{2}^-, \frac{7}{2}^-)$ levels should be at least second

TRANSITION GATE	120	178	298	333	350	440	603	618	657	686	697	748	770	806	926	945	984	989	1027	1098	1205	1275	1286	1381	1404	1539	1619	1646	1659	1837	1879	1899	1973	2000	2011	2177	2231
120		Y̲																			Y̲																
178	Y̲											?							Y̲																		
298										Y̲									Y̲							Y̲					Y̲						
333																							Y̲	Y̲													
350												Y̲			Y̲				Y̲		Y̲																
440		?																	?		Y̲																
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657																												Y̲									
686	Y		Y̲																Y̲																		
697																			Y	Y̲	Y̲	Y̲															
748		?			Y̲																Y̲																
770																Y							?														Y
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926					Y̲														Y̲																		
945													?										Y̲														
984																			Y̲																		
989																																			Y̲		
1027		Y̲	Y̲		Y̲			Y̲		Y̲	?̲				Y̲		Y̲					Y̲			?̲	Y̲				Y̲	Y̲		Y̲			Y̲	
1098		Y									Y̲										Y̲																
1205	Y̲				Y̲	Y̲					Y̲	Y̲		Y̲						Y̲									Y̲			Y̲		Y̲			
1275											Y								Y̲																		
1286				Y̲			Y̲						?			Y̲								Y̲													
1381				Y̲																			Y̲				Y̲										
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2231													?̲																								

FIG. 2. Coincidence matrix of the decay of ^{61}Fe. A "Y" indicates a coincidence relationship and a "?" indicates a coincidence relationship that is uncertain due to weak statistics. When the coincidence relationship (γ_1, γ_2) is observed, the symbol at (γ_2, γ_1) is underlined.

order forbidden; however, β feeding (logft< 5.5) was observed to the $l_p = 3$ levels at 2864 and 3000 keV. In the odd ^{57}Co and ^{59}Co nuclei we find a low lying $\frac{1}{2}^-$ level[22-24]; in ^{61}Co the only $\frac{1}{2}^-$ candidate is the 1325 keV level, which is fed by β decay (logft = 5.8). The spin and parity of the ground state of ^{61}Co is known to be $\frac{7}{2}^-$.[12,21] In previous decay work no direct β feeding to the ^{61}Co ground state was observed; in the present study no direct β feeding to the $\frac{7}{2}^-$ [12] level at 1619 keV is observed either, while the $\frac{7}{2}^-$ [12] level at 2348 keV is not found at all. So, a $J^\pi = \frac{3}{2}^-$ assignment for the ground state of ^{61}Fe is most probable; however, $J^\pi = \frac{5}{2}^-$ cannot be definitly excluded. Previous arguments for a $J^\pi = \frac{3}{2}^-$ assignment were also taken from systematics and shell model considerations. However, in ^{57}Fe, ^{61}Ni, and ^{63}Ni the $\frac{3}{2}^-$, $\frac{1}{2}^-$, and $\frac{5}{2}^-$ levels are much closer than in ^{55}Fe and ^{57}Ni with a single neutron configuration. ^{57}Ni, ^{59}Ni, ^{61}Ni, ^{55}Fe, and ^{59}Fe have a $\frac{3}{2}^-$ ground state, ^{57}Fe and ^{63}Ni have a $\frac{1}{2}^-$ ground state and ^{65}Ni has a $\frac{5}{2}^-$ ground state. So it is not justified to consider only the $2p_{3/2}$ and the $1f_{7/2}$ states as Gujrathi and Mukherjee[3] and Ehrlich[5] did, nor to compare the ^{61}Fe ground state only with ^{59}Fe as done by Grench, Coop, and Menlove.[4]

B. Properties of levels of ^{61}Co

The γ transitions of 230 keV (Refs. 2 and 3) and 400 keV (Ref. 2) reported by various authors were not found, so we had no arguments to propose a level at 1410 keV.[9] The same holds for the level at 1800 keV, tentatively proposed by Strain and Ross.[2] Both levels were not seen in reaction studies either. The spin and parity assignments as given in Fig. 4 for levels in ^{61}Co are based on L [12] and l_p [8,9] values, the occurrence of a ground-state γ transition, and logft values, supposing that $J^\pi = \frac{3}{2}^-$ for the ^{61}Fe ground state. From the doublet at 1280 keV, as observed by Hudson and Glover,[12] we found only the 1286 keV member. The absence of direct β feeding to this level makes a high spin ($\geq \frac{7}{2}$) probable. The $L = 2$ assignment then selects $\frac{7}{2}^-$, $\frac{9}{2}^-$, or $\frac{11}{2}^-$ for J^π. Because of large energy uncertainties it was not clear which member of the doublet at 1650 keV was fed by β decay. From this study it follows that the 1646 keV member is fed by direct β decay, in contrast with Ref. 9. From the logft and $L = 2$ it follows that $J^\pi = \frac{3}{2}^-$, $\frac{5}{2}^-$, but from the ^{62}Ni(t, α)^{61}Co reaction Hudson and Glover[12] argued that the $\frac{5}{2}^-$ assignment is most probable. From the γ intensities a β feeding of

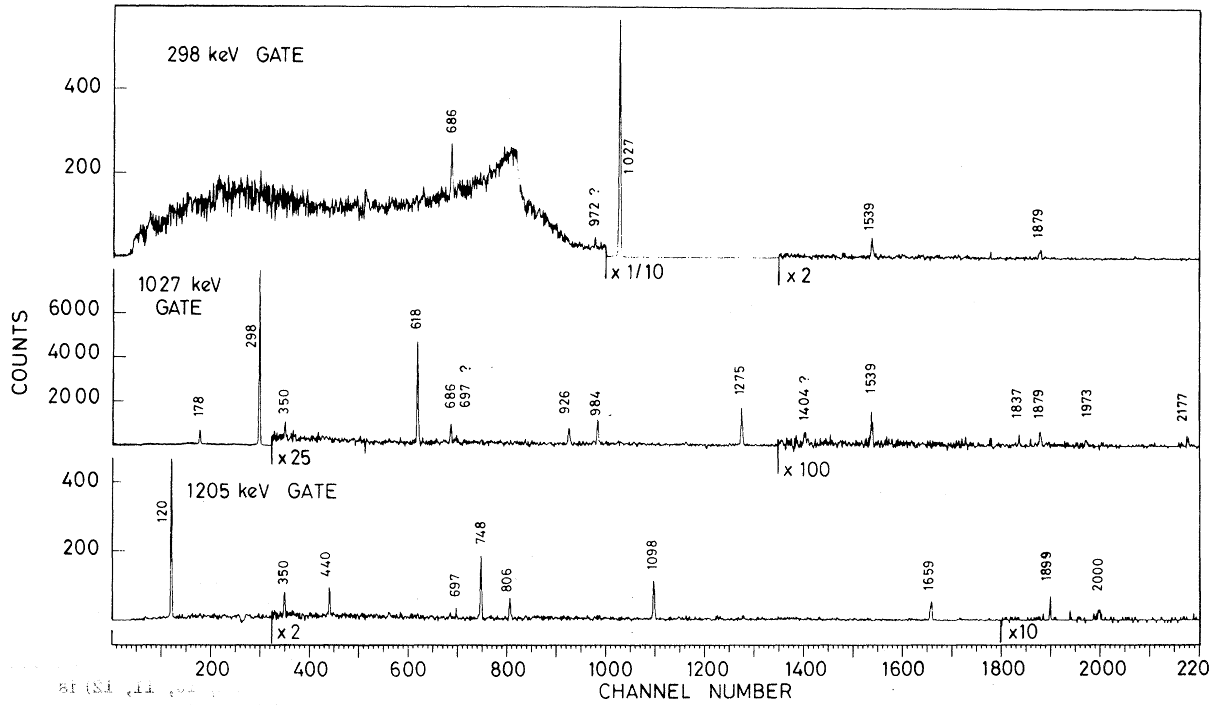

FIG. 3. The γ ray spectra coincident with the 297.90, 1027.42, and 1205.07 keV γ transitions. The background is subtracted.

(0.19 ± 0.08)% can be deduced for the level at 1619 keV; however, the results from the level spectrometer indicate a β feeding of <0.09% at least. In Fig. 4 only an upper limit is given for the β feeding to this level. It was not clear either which member of the triplet at 2000 keV, as observed in reaction studies, was fed by β decay. From the present work it follows that about 85% of the β feeding of this triplet goes to the 2011 keV level. The suppression of the 1889 keV transition, as found in the level-spectrometer experiment, cannot be explained by the intensity of the tentatively assigned 542.8 keV γ transition. Probably the level at 1889 keV is also fed by unobserved γ rays from higher excited levels. At 2247 keV Blair and Armstrong[8] found in the ^{62}Ni$(t, \alpha)^{61}$Co reaction a $\frac{1}{2}^+$ level. Hudson and Glover[12] found in the ^{59}Co$(t, p)^{61}$Co reaction a $L = 2$ (so $\pi = -$) level at 2239 keV. Coop *et al.*[11] observed a state at 2232 keV in the ^{64}Ni$(p, \alpha\gamma)^{61}$Co reaction, deexcited by a 2232 keV γ transition, a 946-1283, and a strong 1205-1027 (or 1027-1205) keV γ ray cascade. We found a level at 2231 keV fed in the β decay. Due to the strong γ transitions from the first excited states in ^{61}Co, the last cascade cannot be observed in the single γ ray spectrum. From our coincidence experiment, however, we found no indication for the mentioned cascade. Obviously both levels are excited in the ^{64}Ni$(p, \alpha\gamma)^{61}$Co reaction, while in the β decay only the level with $L = 2$ is excited. So the data from the ^{64}Ni$(p, \alpha\gamma)^{61}$Co reaction and the data from the β decay strongly support the assignment of a close doublet at 2230 keV. The $L = 2$ value limits J^π to $\frac{3}{2}^- - \frac{11}{2}^-$ for the level

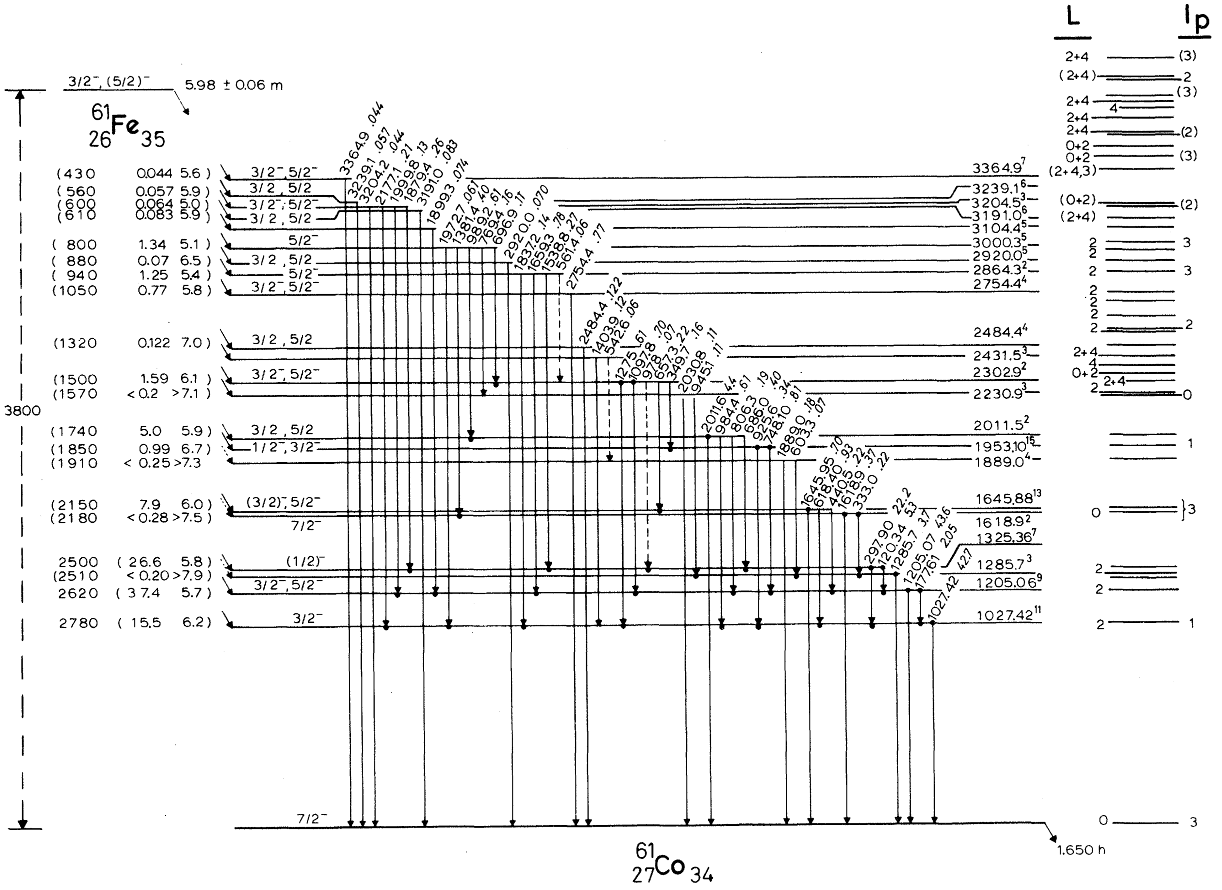

FIG. 4. The proposed decay scheme of ^{61}Fe. The energies are given in keV. The total decay energy, as well as the decay energies to the 1027.42, 1205.06, and 1325.36 keV levels are taken from Ref. 9. Transition intensities are given in percentage per decay. The β feedings are calculated from the relative γ intensities. Uncertain β feedings have been omitted. The logft values are calculated by a program of the Nuclear Data Group. Coincidence relationships which are twice observed are indicated with dots. The level scheme of ^{61}Co as found in reaction work (Refs. 8, 10, 11, 12) is given on the right, together with the transferred angular momentum in the ^{59}Co$(t,p)^{61}$Co (Ref. 12) reaction (L) and in the ^{62}Ni$(t, \alpha)^{61}$Co (Refs. 8 and 9) reaction (l_p). The spins of levels in ^{61}Co are derived by assuming that the g.s. spin of ^{61}Fe is $\frac{3}{2}$.

TABLE II. Branching ratios of some levels in ^{61}Co from the ^{64}Ni(p, $\alpha\gamma$)^{61}Co reaction of Coop *et al.* (Ref. 11) and from the β decay of ^{61}Fe.

Initial state	Final state	Branching ratios Coop *et al.*	 This work
1027.42	0	100	100
1205.06	0	100	95.6 ± 0.4
	1027.42		4.4 ± 0.4
1285.7	0	100	100
1618.9	0	55 ± 8	62 ± 5
	1285.7	45 ± 8	38 ± 5
1645.88	0	88 ± 4	85.8 ± 1.1
	1027.42	12 ± 4	11.5 ± 1.0
	1205.06		2.7 ± 0.6
1889.0	0	50 ± 8	71 ± 9
	1285.7	42 ± 8	29 ± 9
	1645.88	8 ± 3	<15
1953.1	1027.42		30 ± 3
	1205.06	100	70 ± 3
2230.9	0	18 ± 7	50 ± 8
	1027.42 and/or 1205.06	66 ± 9	<40 [a]
	1285.7	16 ± 5	50 ± 8
2302.9	1027.42	100 [b]	35 ± 5
	1205.06		39 ± 4
	1325.36		4 ± 2
	1645.88		13 ± 5
	1953.10		9 ± 2

[a] Cf. Sec. IV B.

[b] Tentative assignment.

fed in β decay; $\frac{11}{2}^-$ is excluded because of the γ transition from the $\frac{5}{2}^-$ level at 3000 keV. The high logft value makes $J^\pi = \frac{3}{2}^-$, $\frac{5}{2}^-$ less probable. For levels above 3100 keV it is difficult to find a (1-1) correspondence between levels found in reaction work and the levels proposed from the present study; the spin and parity assignments are only based on β and γ decay properties.

C. Comparison with neighboring odd Co isotopes

For most of the levels up to 2500 keV in ^{57}Co and ^{59}Co the spins and parities are known. The experimental information about ^{63}Co is still incomplete. As shown in Fig. 5, the seven lowest excited levels in ^{57,59,61}Co lie within a region of 700 keV, followed by small gap of about 250 keV. Among the first seven excited states there is one $\frac{1}{2}^-$, $\frac{5}{2}^-$, $\frac{7}{2}^-$, $\frac{9}{2}^-$, and $\frac{11}{2}^-$ level and there are two $\frac{3}{2}^-$ states. This is in agreement with the proposed J^π values for the levels in ^{61}Co, if the 1205 keV level is the $(\frac{3}{2}^-)_2$ state and if the 1271 and 1286 keV levels are the high spin states with J^π equal $\frac{11}{2}^-$ and $\frac{9}{2}^-$. For the higher excited states a comparison is less conclusive; a possible correspondence for the $(\frac{5}{2}^-)_2$ and $(\frac{7}{2}^-)_3$ levels is given in Fig. 5.

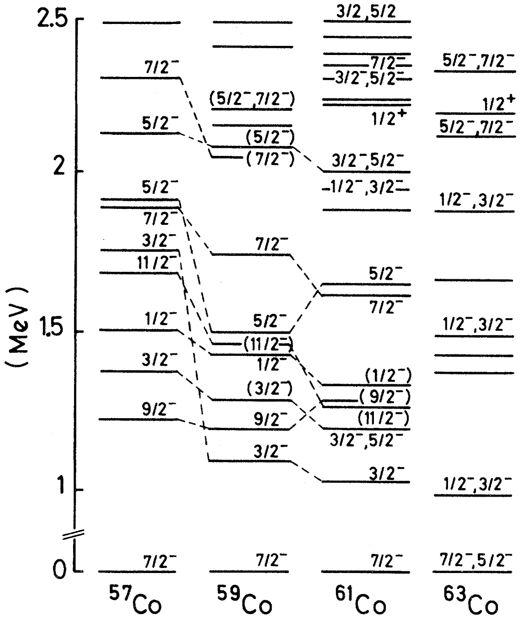

FIG. 5. Energy levels of ^{57,59,61,63}Co. The data about ^{57}Co are taken from Refs. 22 and 23, and data about ^{59}Co and ^{63}Co come from Ref. 24 and Ref. 25, respectively.

D. Comparison with theoretical treatments of ^{61}Co

For the odd cobalt nuclei several types of calculations have been performed, but for ^{61}Co only particle-phonon model calculations, in which a proton hole is coupled to a vibrating Ni core, are known.[13-15] Although it seems that microscopic excitations have to be taken into account, a detailed comparison based on the location of levels alone is not very significant. Unfortunately, no reliable calculated values for transition probabilities are available at the present moment.[14,26]

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