Decay of Ni^{57} and Excited Levels in Co^{57}†

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The decay of Ni^{57} has been investigated in order to obtain detailed information about the level structure of the odd-even Co^{57}. Lithium-drifted germanium detectors as well as standard scintillation-spectrometry techniques have been used. The levels at 1.46, 1.59, 1.75, and 2.62 MeV have been established with direct de-excitation to the Co^{57} ground state, in addition to the already known levels at energies of 1.37, 1.497, and 1.9 MeV. It has been confirmed that the 1.497-MeV level is the only one which decays by a (0.127–1.37)-MeV cascade of gamma rays. The various gamma-gamma coincidence studies have been performed; and based on these results, and on the ratios of electron capture to β^+ decay, a decay scheme of Ni^{57} is proposed, and the results discussed in the light of the Coriolis coupling model. The half-life of the 1.497-MeV level has been measured as $(0.60\pm0.05)\times10^{-9}$ sec and an upper limit for the half-life of the 1.37-MeV level is given as $\sim2\times10^{-10}$ sec.

1. INTRODUCTION

THE radioactive decay of Ni^{57} was first studied by Konijn *et al.*[1,2] The nucleus Ni^{57} decays to Co^{57} by electron capture and by positron emission in about equal intensities[3] with a half-life of 37 h. The beta spectrum contained three branches with end-point energies of 854, 720, and 350 keV.[2] Three gamma rays of 127, 1365, and 1888 keV were observed to decay with the above half-life and assigned to Ni^{57}. Chilosi *et al.*[4] next reported an additional gamma ray at energy of 1.75 MeV associated with the decay of Ni^{57}. Recently, the decay of Ni^{57} was also studied by Piluso *et al.*[5] and the levels at 1.378, 1.50, 1.75, and 1.92 MeV were assigned to Co^{57}. The activity produced by Piluso *et al.* also contained Ni^{56} and due to mixture of the two activities, a weak transition at 1.59 MeV could not be confirmed. From these investigations, the level structure of Co^{57} is known to consist of four excited states at 1.37 ($\frac{3}{2}^-$), 1.49 ($\frac{1}{2}^-$), 1.75, and 1.9 MeV.

The level structure of Co^{57} has a special interest as far as this isotope can be considered a typical single-proton hole nucleus with an even-even spherical or vibrational core. The fact that a new gamma transition at the energy of 1.75 MeV is to be assigned to this decay pointed out the necessity of a revision of the level scheme of Co^{57}.

In this paper we report the results of a detailed investigation of the properties of the levels of Co^{57} excited in the decay of Ni^{57}. Improved experimental data were anticipated through the utilization of Li-drifted Ge detectors, with energy resolution much superior to that of NaI(Tl) detectors used in earlier studies. A search was also made about the reported level[6] at the energy of about 2.6 MeV in the earlier $(p,2p)$ reaction work.

2. SOURCE PREPARATION

The Ni^{57} was produced after bombarding metallic nickel of spectroscopic-purity grade with fast neutrons, as well as by $Fe^{54}(\alpha,n)Ni^{57}$ reaction. The bombarding energy of alpha particles from the Heavy Ion Accelerator was kept below the 22 MeV threshold of the reaction $Fe^{54}(\alpha,2n)Ni^{56}$. The half-life of the whole gamma spectrum, measured over a period of about 9 days, was found to be 37 ± 1 h showing no traces of other activities present in the sample produced by $(n,2n)$ reaction. Hence chemical separation was not necessary. Chemical separation was performed on the samples of natural iron bombarded with alpha particles, and Ni activity was separated out. The chemical separation is described in detail in Refs. 3 and 7.

3. EXPERIMENTAL RESULTS

3.1 Gamma-Ray Spectra

Figure 1 shows the gamma ray spectrum of Ni^{57} taken with a Li-drifted Ge detector (6mm thick$\times$6 cm^2) and a RIDL 400-channel analyzer. The resolution of the detector was 6 keV for the 1.33-MeV photopeak of Co^{60}. The gamma rays of energies 0.127, 1.37, 1.46, 1.59, 1.75, 1.91, and 2.62 MeV are observed. The low-energy part of the spectrum is shown in Fig. 2. The half-life of

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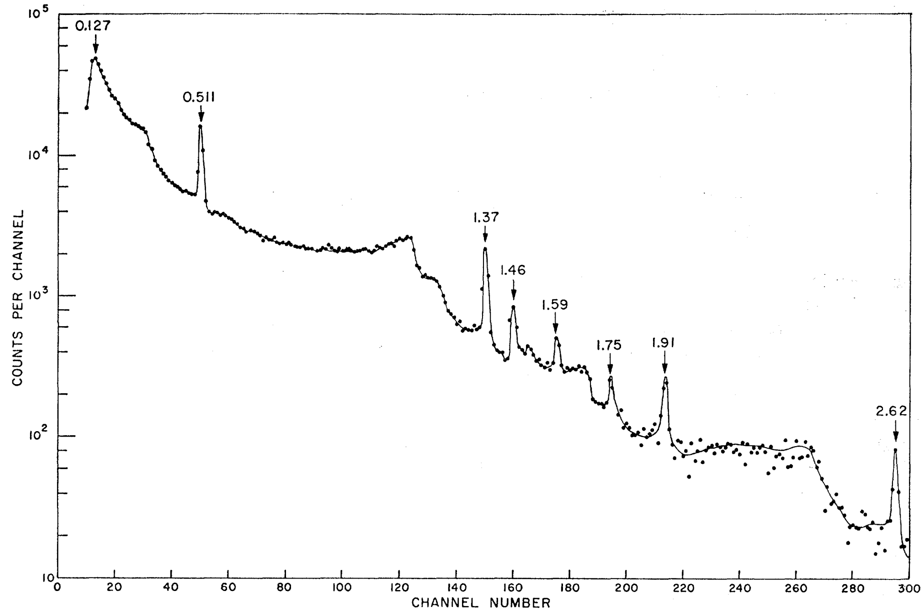

FIG. 1. Gamma spectrum of Ni^{57} taken with a (6-mm thick ×6 cm²) Li-drifted Ge detector.

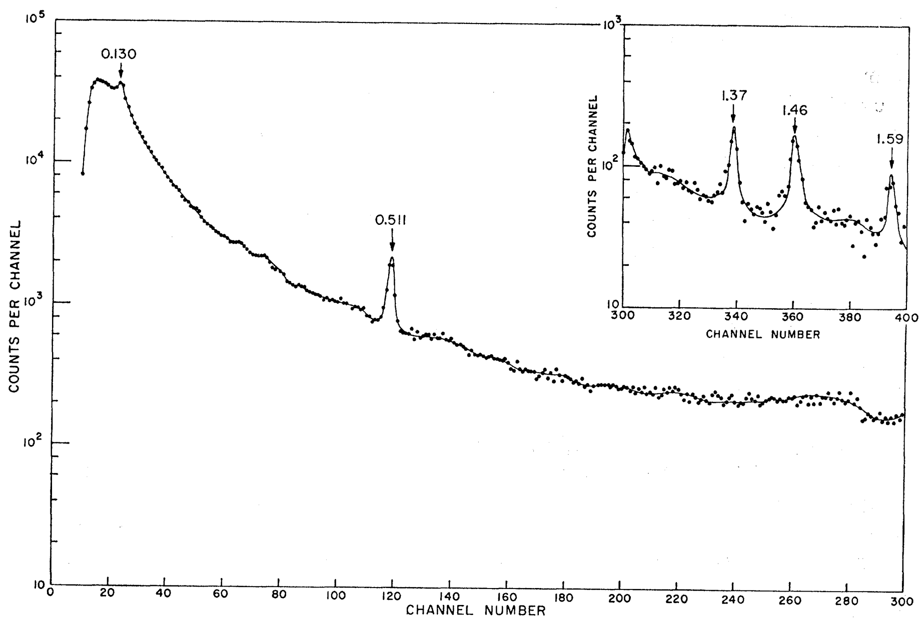

FIG. 2. Low-energy part of the spectrum taken with a (6-mm thick ×6 cm²) Li-drifted Ge detector.

each gamma ray as followed in a single-channel analyzer gave a value of 37±1 h.

The sum spectrum taken with a 5-in.×4-in. cylindrical NaI(Tl) crystal is shown in Fig. 3. It shows two photopeaks at 1.97 and 2.1 MeV in addition to those shown in Fig. 1. These additional peaks could be ascribed to those sum peaks as follows: the 1.97-MeV peak as the sum of 1.46 and 0.511 MeV, and the 2.1-MeV peak as the sum peak of 1.59 and 0.511 MeV.

To test the nature of the various photopeaks, the spectra were taken at various source-to-crystal distances. Comparison of the various spectra taken at source to crystal distance of 1, 5, 10, and 15 cm suggest

TABLE I. Energies and relative intensities of gamma rays.

Energies of the gamma rays (MeV) obtained using Li-drifted Ge detector with better than 10-keV accuracy	Unconverted gamma-ray relative intensity
0.127	16
1.37	100
1.46	25
1.59	12
1.75	7
1.91	12
2.62	8

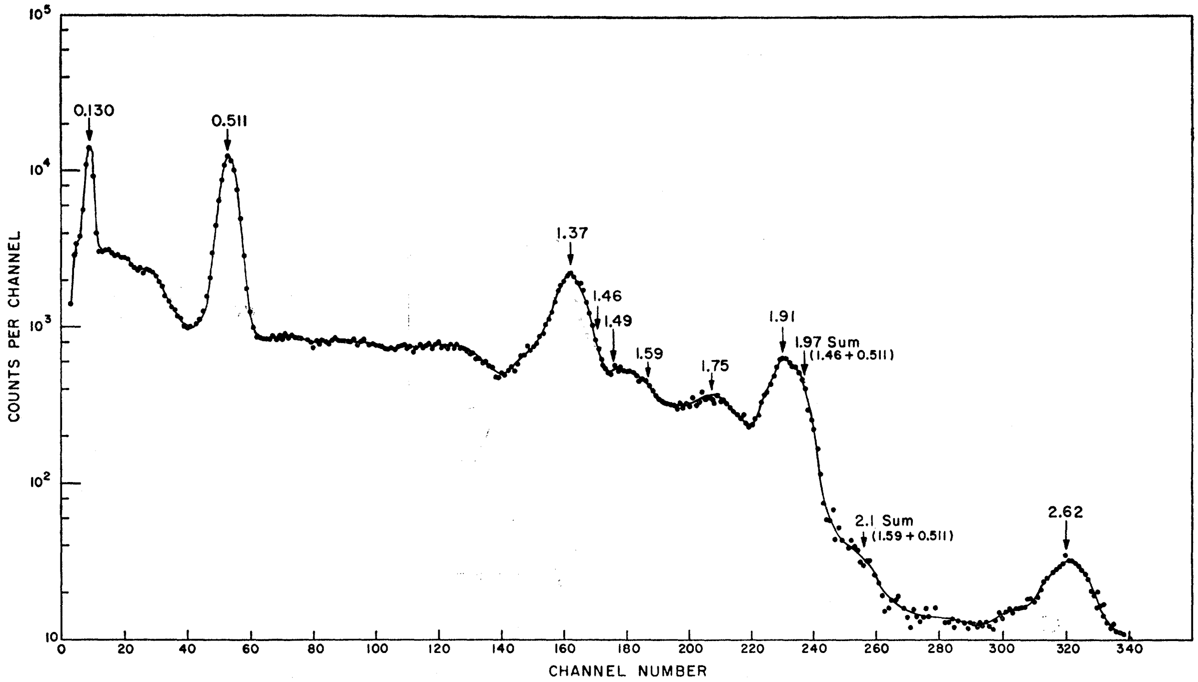

FIG. 3. Sum spectrum taken with the source on the top of a 5-in.×4-in. cylindrical NaI(Tl) crystal.

that the 1.37-, 1.46-, 1.59-, 1.75-, 1.91-, and 2.62-MeV photopeaks are all crossover peaks. The energies and the relative intensities of the various gamma rays are given in Table I.

3.2 Gamma-Gamma Coincidence Spectra

Gamma-gamma coincidence studies were conducted in order to study further the cascade relationship. For this, two 3-in×3-in. NaI(Tl) detectors coupled to 6292 phototubes were used. The transistorized coincidence circuit had a resolving time of approximately 40 nsec. The two detectors were placed at 90° and shielded from each other, with sufficient lead to avoid scattering. In each case the NaI crystal was covered with a Lucite plate to cut off beta particles. Gamma spectra in coincidence with photopeaks at 0.127, 1.37, 1.49, 1.59, 1.75, 1.91 and 2.62 MeV were taken. Figure 4 shows the gamma spectra in coincidence with the 0.127 and 1.37-MeV photopeaks. The results of all the other coincidence experiments are given in Table II.

The first conclusion to be drawn from these measurements is that the 2.62-, 1.91-, 1.75-, and 1.46-MeV transitions are in coincidence only with the 0.511-MeV annihilation peak and that the gamma rays of energies 0.130 and 1.37 MeV are in coincidence with each other and with the 0.511-MeV photopeak. The absence of any other low-energy gamma rays in the direct singles spectrum as well as in coincidence with above selected photopeaks shows that the gamma rays of energies 2.62, 1.91, 1.75, 1.59, and 1.46 MeV are directly populating the ground state of Co^{57}. However, from the spectra shown in Figs. 1 and 2, there is a possibility that the 0.511-MeV photopeak may contain another weak gamma ray of the energy very near to it. Since a 540 ± 10 keV transition between the 1.91 and the 1.37-MeV level is expected, it was considered worthwhile to investigate this point in more detail.

Another series of measurements were performed by selecting the 0.511 MeV photopeak as a gating gamma ray in a 3-in.×3-in. NaI(Tl) crystal and taking the coincidence spectrum with the Ge detector. The two detectors were well shielded from each other, and the geometrical conditions were chosen to avoid the coincidences between the annihilation radiation. Figure 5 shows the gamma spectrum in coincidence with selected 0.511-MeV photopeak. A small photopeak at 0.511 is evidently present. This may be shown as an intensified Compton-edge contribution of high-energy

TABLE II. Gamma-gamma coincidence results.

	Gamma ray in gate (MeV)	Coincident gamma-ray energies (MeV)
x rays	<0.020	0.130, 0.511, 1.37, 1.46, 1.75, 1.91, 2.62
	0.127	0.511, 1.37
	0.511	0.130, 1.37, 1.46, 1.59, 1.75, 1.91
	1.37	0.130, 0.511
	1.46	0.511
	1.59	0.511
	1.75	0.511
	1.91	0.511

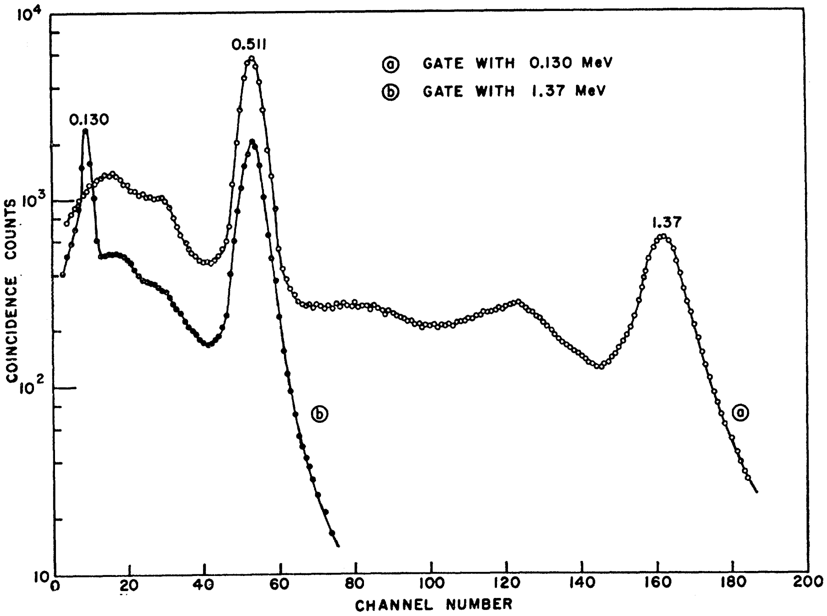

FIG. 4. Gamma spectrum in coincidence with (a): the 0.130-MeV and (b): the 1.37-MeV gamma rays.

gammas which overlap the 0.511-MeV peak. Also, the shape of the coincident spectra for the same geometry was first studied with the Na^{22} source. The absence of any other gamma ray in the above spectrum showed that the 540±10 keV transition between the 1.91 and the 1.37 MeV is not present.

In addition, coincidence studies were conducted to determine the ratios of electron capture to β^+ decay. Positron spectra were taken using a 1.5-in.×3-in. diam plastic phosphor with an energy resolution of 15%. To eliminate the summing of the desired positron pulses with those from interactions originating from the 0.511-MeV annihilation gamma rays within the plastic phosphor, 0.511-MeV coincident pulses were taken from the two 3-in.×3-in. NaI(Tl) crystals. These latter crystals were put as face-to-face in between the plastic phosphor in which the collimated incident positrons annihilated. With a single-channel analyzer gating on the 0.511-MeV peak in each crystal, a triple-coincidence pulse, within a resolving time of 50 nsec was required before a positron pulse was stored on the multichannel analyzer. To record the x-ray spectrum in coincidence with positrons or any one of the gamma rays, the x-ray counter was placed at 30° to one of the NaI(Tl) crystals.

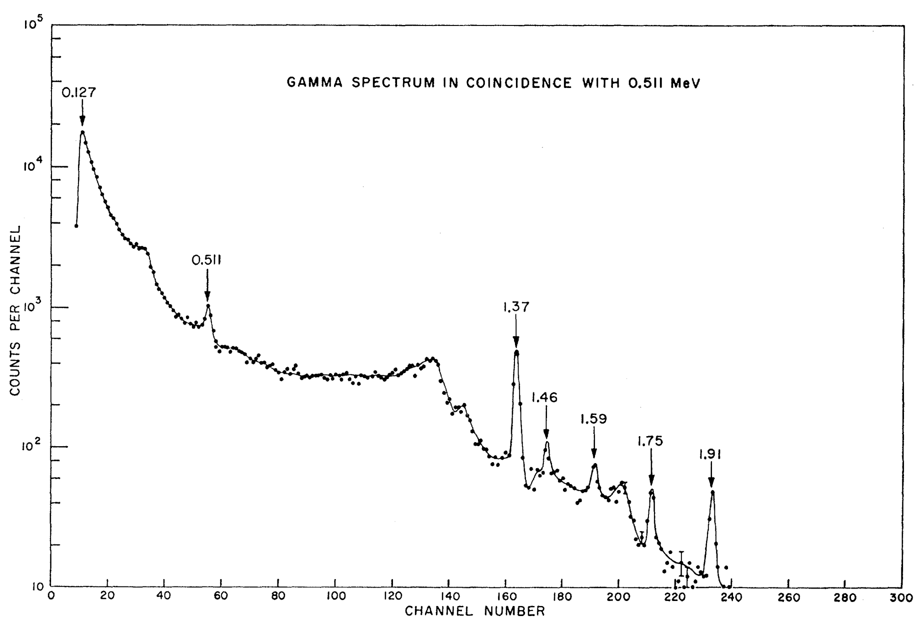

FIG. 5. Gamma spectrum taken with a (6-mm thick ×6 cm²) Li-drifted Ge detector in coincidence with 0.511-MeV annihilation peak.

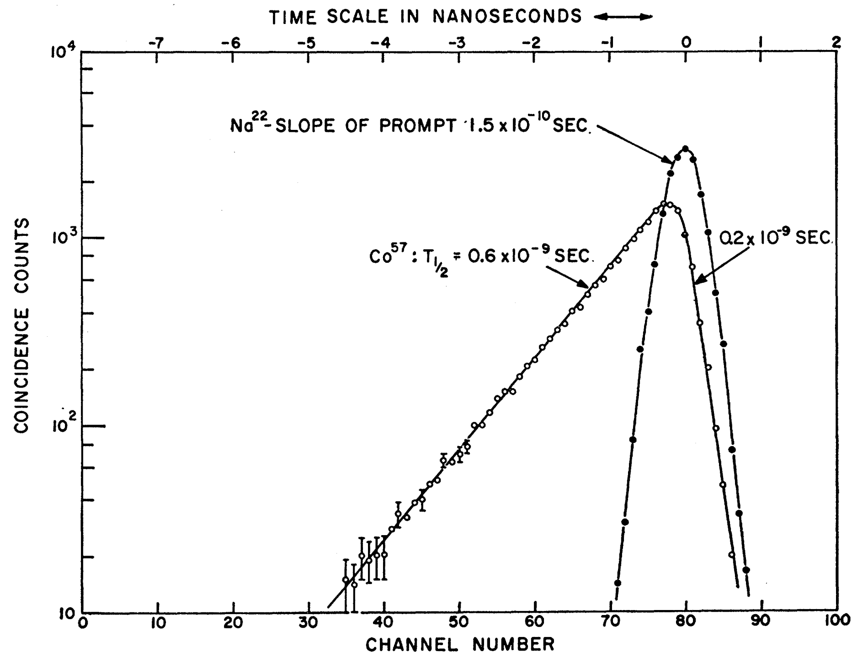

FIG. 6. Half-life of 1.49-MeV level in Co^{57} measured by delayed-coincidence technique.

The entire arrangement was encased in a 3-in. thick lead housing.

Using the appropriate single-channel analyzers and fast-slow coincidence circuits, it was possible to record various coincidence spectra gated on either the 0.511-MeV annihilation peak, K x rays or any one of the gamma rays at the same geometry.

The ratio ϵ/β^+ has been measured by comparing the intensity ratio of annihilation radiation and the 1.37- and 1.28-MeV gamma rays in the decays of Ni^{57} and Na^{22}, respectively. To stop all the positrons, the source was mounted in between two plates of copper. The electron-capture-to-positron ratio in Ni^{57} is found to be 1.14±0.1, assuming the intensity of the 1.37-MeV gamma ray is 65% of the total Ni^{57} transitions. The fluorescent yield is determined by measuring the K x rays in coincidence with each of the gamma rays in the Co^{57} spectrum. A value of $w_K=0.3\pm0.01$ is obtained. Table III gives the calculated ratio of ϵ/β^+ to various levels in Co^{57}.

TABLE III. Ratios of electron capture to positron for various levels of Co^{57}.

Transition energy (MeV)	The ratio of ϵ/β^+ from coincidence data	Theoretical values obtained from Refs. 2 and 4
1.37	1 ±0.1	0.86±0.02
1.46	2.5±1	2.3 ±0.8
1.49	1.5±0.08	1.5 ±0.04
1.59	~5	
1.75	~7	
1.91	22	

3.3 Half-Life of 1.49-MeV Level

The half-life of 1.49 MeV level being populated by electron capture and positron decay of Ni^{57} was measured by delayed coincidence techniques. A 1.5-in.×1.5-in. plastic crystal coupled to a RCA 6810A phototube detected the 0.127-MeV gamma rays while the preceding x rays were detected by a 3 mm×5 cm plastic crystal coupled to a RCA 6810A tube. A 6BN6 time-to-pulse height converter of type Eldorado Model TH-300 was used to determine the lifetime. The "prompt" time distribution of Na^{22} with the same settings gave a slope of 1.5×10^{-10} sec. The slope on the time spectrum shown in Fig. 6, determined the half-life of the 1.497-MeV level of Co^{57} as $T_{1/2}=(0.6\pm0.05)\times10^{-9}$ sec. The prompt contribution in the spectrum of Fig. 6, due to coincidences of the portion of 1370-keV gamma ray with x rays from electron capture, gives an upper limit for the half-life of the 1370-keV level as about 0.2 nsec.

4. DISCUSSION

The above results suggest the decay scheme shown in Fig. 7. As pointed out above, Co^{57} with a hole in the $f_{7/2}$ shell is expected to have levels with spins $\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{7}{2}^-$, $\frac{9}{2}^-$, and $11/2^-$ based principally on the weak-coupling model. However, the level at 1497 keV ($\frac{1}{2}^-$) is not anticipated on the basis of this picture. The levels of Co^{59} are also given in Fig. 7, and the considerable similarity between the level scheme of the two isotopes should be noted, especially with respect to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states. This result is of course not expected on the basis of the single-particle model either.

In addition, an ($E2$) enhancement of two orders of magnitude (Fig. 6) for the 1370-keV ($\frac{3}{2}^-$) to the ($\frac{7}{2}^-$)

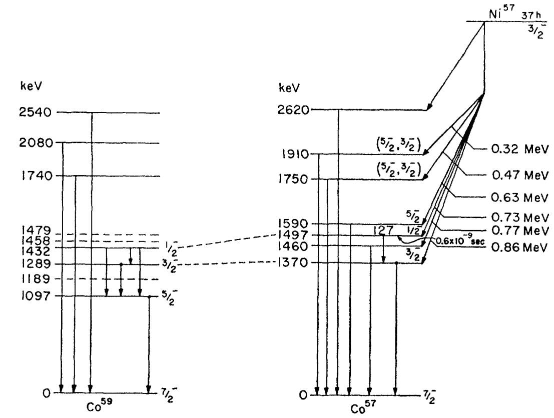

FIG. 7. Proposed decay scheme of Ni^{57} and the excited levels in Co^{57}. The levels of Co^{59} are presented for comparison.

ground state argues strongly for a collective treatment to understand the level structure of Co^{57}. Such a prediction has been noted by Malik and Scholz.[8] The comparison between the predicted level ordering and energy spacing based on the Coriolis coupling[9] is in surprising agreement with our experimental results. That is, the level ordering predicted in this model with the $f_{7/2}$ ground state is $\frac{3}{2}^{-}$, $\frac{9}{2}^{-}$, $\frac{1}{2}^{-}$, and $\frac{5}{2}^{-}$ with energies of about 1.4 MeV for the $\frac{3}{2}^{-}$, and about 1.6 MeV for the $\frac{1}{2}^{-}$ states.

An additional point to be noted is that, to our knowledge, no approach other than the Coriolis-coupling one predicts the $\frac{1}{2}^{-}$ level at an energy of 1497 keV as observed. The state at 1460 keV could indeed be the missing high spin state (e.g., $\frac{9}{2}^{-}$) as predicted and the weak transition of 450 keV from the 1910-keV level to the 1460-keV level may be feeding the above level. However, the sparsity of the data on this point precludes further conjecture.

It appears that the enhancement of both the $(\frac{1}{2}^{-})\rightarrow(\frac{3}{2}^{-})$ and $(\frac{3}{2}^{-})\rightarrow(\frac{7}{2}^{-})$ transitions at 127 and 1370 keV, respectively, the level structure similarity between Co^{57} and Co^{59}, and the presence of the $\frac{1}{2}^{-}$ state in both these nuclei argue strongly for a model, such as the Coriolis-coupling one, predicting marked collective motion.

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