recent analyses of ^{16}O-^{24}Mg and ^{16}O-^{40}Ca scattering data.[10,11] Finally, Fig. 5 shows that the angular distribution at 13 MeV is also predicted well by the Woods-Saxon parameters which fitted the excitation function, although no attempt was made to improve or alter this fit.

Where the figures contain a calculation using a complex potential, the cross sections are for coherent elastic scattering, i.e., no contribution to the elastic channel by way of the compound nucleus is included. This is justified since the compound nucleus ^{32}S is excited to more than 30 MeV for 13-MeV c.m. energy. At such a high excitation the large number of open reaction channels damps the compound elastic contribution considerably.

III. CONCLUSION

The theoretical prediction of a molecular type of potential to describe heavy-ion scattering is an interesting development in the study of such interactions. However, because of the masking of the nuclear interior by the Coulomb potential and the marked effect of other open reaction channels, the elastic scattering of ^{16}O-^{16}O near the Coulomb barrier cannot be used as reliable evidence for a repulsive core in the ^{16}O-^{16}O interaction. On the other hand, the present work does not preclude the possibility of a repulsive core in the ^{16}O-^{16}O potential. High precision experiments involving elastic scattering of heavy ions at higher energies and perhaps inelastic scattering experiments may provide justification for the theoretically predicted repulsive core. There again, great care must be taken to determine the significance of theoretical fits to experimental data using a repulsive core potential, since this potential involves introducing at least two new parameters into the potential function.

ACKNOWLEDGMENT

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Single-Particle and Core-Coupled States in ^{57}Co from the Decay of ^{57}Ni†

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The decay of 36.0-h ^{57}Ni produced by the $^{54}Fe(\alpha, n)^{57}Ni$ reaction has been studied to obtain information on the level structure of ^{57}Co. γ-ray spectra were obtained with high-resolution Ge(Li) detectors, a Compton-suppressed Ge(Li) system, and Ge(Li)-NaI(Tl) γ-γ coincidence spectroscopy. The γ-ray energies in keV (and the relative photon intensities) observed in this investigation are as follows: 127.1$\pm$0.1 (200), 161.8$\pm$0.3 (0.22), 252.5$\pm$0.6 ($\leq$0.4), 380.0$\pm$0.2 (0.96), 673.4$\pm$0.2 (0.58), 906.8$\pm$0.3 (1.1), 1046.4$\pm$0.2 (1.6), 1223.5$\pm$0.4 (1.1), 1377.6$\pm$0.2 (1000), 1730.6$\pm$0.3 (0.72), 1757.6$\pm$0.2 (77), 1896.5$\pm$0.4 (0.28), 1919.5$\pm$0.2 (170), 2132.9$\pm$0.3 (0.47), 2730.6$\pm$0.2 (0.3), 2803.9$\pm$0.2 (1.7), and 3176.9$\pm$0.3 (0.24). On the basis of Ge(Li)-NaI(Tl) coincidence experiments, energy sums, and earlier nuclear reaction data, levels in ^{57}Co were assigned at 0 (7/2$^-$), 1223.5$\pm$0.4 (9/2$^-$), 1377.6$\pm$0.2 (3/2$^-$), 1504.7$\pm$0.2 (1/2$^-$), 1757.6$\pm$0.2 (3/2$^-$), 1896.5$\pm$0.4 (7/2$^-$), 1919.5$\pm$0.2 (5/2$^-$), 2132.9$\pm$0.3 (5/2$^-$), 2730.6$\pm$0.2 (5/2$^-$, 3/2$^-$), 2803.9$\pm$0.2 (3/2$^-$, 5/2$^-$), 3108.2 ($\leq$5/2$^-$), and 3176.9$\pm$0.3 (5/2$^-$) keV. The spin assignments are based on data from nuclear reaction studies, logft values, and relative photon intensities. An attempt was made to explain the experimental results and the structure of ^{57}Co in terms of single-particle states and particle-plus-core states based on coupling the 2$^+$ collective core vibration to the $f_{7/2}$ odd proton hole. Previous work on ^{57}Co and ^{59}Co indicates that levels in ^{57}Co at 1223.5 (9/2$^-$), 1683 (11/2$^-$), 1757.6 (3/2$^-$), and 2132.9 (5/2$^-$) keV belong to a core-coupled multiplet. Our γ-ray branching ratios are in agreement with this characterization of the states at 1223.5 and 1757.6 keV.

INTRODUCTION

The properties of the low-lying states of ^{57}Co have been studied extensively by β- and γ-ray spectroscopy of the radioactive isotope ^{57}Ni and by studies of the nuclear reactions $^{56}Fe(p, \gamma\gamma)$, $^{58}Ni(t, \alpha)$, $^{56}Fe(He^3, d)$, and $^{54}Fe(\alpha, p)$.[1–11] Although several low-lying states have been observed in both the

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nuclear reaction and decay studies, there still exist a number of conflicting assignments of energies, spins, and parities. A level at 1920 keV, for instance, was consistent with a $\frac{5}{2}^-$ assignment based on the ^{56}Fe($p, \gamma\gamma$) reaction data[8] and the ^{57}Ni decay studies.[4-6] The ^{58}Ni(t, α) results, however, indicated a $\frac{7}{2}^-$ assignment for a level in this energy region.[9]

Since it was reasonable that a number of differences in the level structure of ^{57}Co and its interpretation might be due to unresolved structure, it was decided to investigate these levels under higher resolution using a Compton-suppressed lithium-drifted germanium detector system. The very high Compton background usually encountered in unsuppressed systems often limits the investigation of possible low-energy γ rays. Thus, assignments of spins sometimes must be based on upper limits for possible γ-ray transitions. The high resolution of lithium-drifted germanium detectors combined with Compton suppression permitted clarification of several discrepancies. Together with the reaction data, a very precise level scheme could be established in which a number of low-spin states at low energy, observed in reaction spectroscopy, were confirmed. Since earlier shell-model calculations[12,13] do not account for the known low-spin levels, the confirmation of these and additional levels led us to consider two other possibilities: (i) the excitation of protons from the $f_{7/2}$ to the $p_{3/2}, f_{5/2}$, and $p_{1/2}$ orbits, and (ii) the description of some levels in terms of coupling of single-particle states with core excitations.[14,15]

After the experimental work had been completed at Lawrence Radiation Laboratory (LRL), recent investigations by Lingeman *et al.*[7] came to our attention. The latter is a study of the ^{57}Ni decay using a Ge(Li) detector system with somewhat poorer resolution than the detectors used at Livermore. Although our results are in general agreement with the findings of Lingeman *et al.*,[7] some disagreement exists with respect to the interpretation of low-intensity high-energy transitions and the assignment of levels. In addition, a number of low-energy cascades observed in the present study would not be observed in Ge(Li) systems with intense Compton continua. A summary of the recent results by Lingeman *et al.*[7] is shown in Table I, together with the recent information on low-lying excited states of ^{57}Co obtained by Piluso *et al.*[5] in their studies of the β^+ decay of ^{57}Ni.

EXPERIMENTAL PROCEDURE

The ^{57}Ni sources were produced by a variety of reactions, the principal one being the irradiation of 2-mil foils of enriched ^{54}Fe (97%)[16] with 12-MeV α particles at the Livermore 90-in. cyclotron. In addition, metallic nickel of natural isotopic abundance was irradiated with fast neutrons forming ^{57}Ni by the ^{58}Ni ($n, 2n$) reaction. The ^{57}Ni produced in these bombardments was radiochemically purified by standard techniques.[17] γ-ray spectra taken as a function of time over a period of several days were used to determine the radiochemical purity of each source. The nickel isolated from neutron bombardments did show the presence of γ rays that were associated with 6.1-day ^{56}Ni. Since the α-particle bombardments were below the ($\alpha, 2n$) threshold, sources prepared in this fashion were free of all interfering activities and a 37-hr half-life was measured for each γ ray reported in this investigation. γ-ray spectra were obtained with 7- and 30-cc Ge(Li) detectors and Ge(Li)-Na(I) coincidence spectroscopy. The Compton-suppressed spectra were obtained with a lithium-drifted germanium detector of 12-mm depletion depth and 6-cm^2 sensitive area surrounded by two 9-in.-diam$\times$ $4\frac{1}{2}$-in.-thick NaI(Tl) scintillation detectors. The signals from the two NaI(Tl) detectors were paralleled and operated in anticoincidence with the Ge(Li) signal. Details of this spectrometer have been discussed by Camp[18] and will not be elaborated here. Data acquired with a 4096-channel pulse-height analyzer were read out on magnetic tape and computer-analyzed. The system energy resolution was 2.4 keV at 1332.5 keV and 1.2 keV at 122.97 keV.

In order to obtain accurate energies for all the γ rays reported here, several calibrations using ^{207}Bi, ^{88}Y, ^{22}Na, and ^{60}Co as standards were run together with the ^{57}Ni source in the Compton-suppressed mode. Energies of the stronger γ rays obtained in this manner were then used to determine accurate energies for the less intense peaks. For energies greater than 2000 keV, the double-escape peaks observed without Compton suppression were used for precise energy assignments. Since each double-escape peak is associated with a peak 1022.0 keV higher in energy, several peaks in our sources were used as internal energy calibrations. In addition, the nonlinearity of this system was checked over the entire region of interest with a precision pulser. The test pulse fed into the preamplifier was used to produce a series of peaks in the pulse-height analyzer spectrum, and the

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TABLE I. γ-ray energies E_γ and relative intensities I_γ reported by Lingeman *et al.* (Ref. 7), Piluso *et al.* (Ref. 5), and present work.

Lingeman *et al.*[a] E_γ (keV)	I_γ	Piluso *et al.*[b] E_γ (keV)	I_γ	Present work E_γ (keV)	I_γ
127.6±0.5	176	127.2±0.1	150	127.1±0.1	200
				161.8±0.3	0.22
				252.5±0.6	≤0.4
				380.0±0.2	0.96
				673.4±0.2	0.58
				906.8±0.3	1.1
				1046.4±0.2	1.6
				1223.5±0.4	1.1
1378.0±0.5	1000	1378.0±0.5	1000	1377.6±0.2	1000
				1730.6±0.3	0.72
1758.2±0.6	95	1757.7±0.2	69	1757.6±0.2	77
				1896.5±0.4	0.28
1919.9±0.6	224	1920.2±0.1	147	1919.5±0.2	170
				2132.9±0.3	0.47
2731±2	0.15			2730.6±0.2	0.3
2805.1±0.9	0.88			2803.9±0.2	1.7
3151±3	0.10				
3177.3±1.2	0.21			3176.9±0.3	0.24

[a] Reference 7.
[b] Reference 5.

channel locations of these peaks were located and fitted with Gaussian functions by a computer code. A polynomial equation derived by a least-squares fit of channel position and pulser voltage setting was used to correct for nonlinearity. Appropriate corrections were then applied to the calibration data to remove the nonlinearities. Energy assignments based on this method of calibration were consistent within about 0.3 keV with energy sums and differences for most cases in which more than one path of the deexcitation was possible. For the more intense transitions the internal consistency was better than 0.2 keV.

The absolute full-energy peak efficiency of the Ge(Li) Compton-suppressed system was determined as a function of energy by comparing photopeak areas for a large number of sources of known strength. These absolute standards were obtained from the IAEA.[19] A number of runs were carried out at various source-detector distances to obtain intensity calibration curves for various geometries. The ^{57}Ni sources were counted initially at very low geometry, and as decay progressed the geometry was increased to improve counting statistics. Photopeak areas calculated by both graphical and computer techniques agreed to within 5% for most γ rays and to better than 3% for the most intense radiations. After the appropriate corrections for efficiency were made, the experimentally determined half-life of each γ ray was found to be consistent with a value of 37 h.

[19] International Atomic Energy Agency, Vienna, Austria.

RESULTS

Table I lists the γ rays observed in the present study. The pulse-height spectra observed with the Compton-suppression spectrometer are shown in Figs. 1 and 2. The photopeaks at 127.1, 511, 1377.6, 1757.6, and 1919.5 keV were observed in earlier studies. In addition, Lingeman *et al.*[7] also observed the peaks at 2132.9, 2730.6, 2803.9, and 3176.9 keV. The peaks at 866.6, 1246.6, and 1408.5 are single-escape peaks from the 1377.6-, 1757.6-, and 1919.5-keV γ rays, respectively. In the Compton-suppressed mode, double-escape peaks are reduced by a factor of about 8. As a result, only the most intense γ rays will have a clearly visible double-escape peak associated with them. The only double-escape peak appearing in the spectra shown in Fig. 1 is from the 1919.5-keV γ ray and occurs at 897.5 keV. Because the double-escape peak is suppressed almost completely, we have recorded spectra with and without Compton suppression as a means of determining which peaks were single- and double-escape peaks associated with higher-energy γ rays and which peaks were, in fact, full-energy peaks. A typical spectrum taken with a 6-cm^3 Ge(Li) detector without suppression is shown in Fig. 3. The spectra taken with Compton suppression also exhibit peaks which result from backscattering of γ rays from 140° to 180° out of the detector. These show up as very asymmetric peaks in Figs. 1 and 2, and are easily differentiated from true photopeaks.

In addition to the well-established γ rays mentioned above, the spectrum shown in Fig. 1 also exhibits eight previously unreported transitions of 161.8,

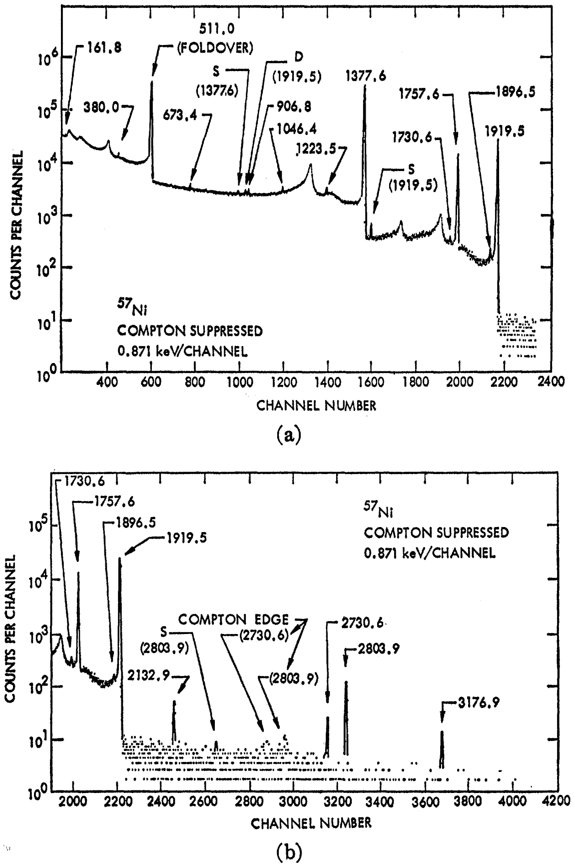

FIG. 1. Energy spectrum of γ rays obtained with Compton-suppressed spectrometer (a) from 150 to 1950 keV and (b) from 1700 to 3500 keV. Peaks labeled S and D are single- and double-escape peaks, respectively.

380.0, 673.4, 906.8, 1046.4, 1223.5, 1730.6, and 1896.5 keV. The γ ray at 2132.9 keV was observed by Lingemen *et al.*[7] and was interpreted as being the double-escape peak from a 3151-keV transition. In their spectra the peak at 3177 keV is clearly visible. Our spectra also show a well-defined peak at this energy whose double-escape peak would occur at 2155 keV. A peak in this region is hardly detectable in the Compton-suppressed spectra (Figs. 1 and 2). The photopeak at 2132.9 keV, however, has considerable intensity. If this were associated with a 3151-keV transition, it would then be necessary that a 3151-keV photopeak appear in our

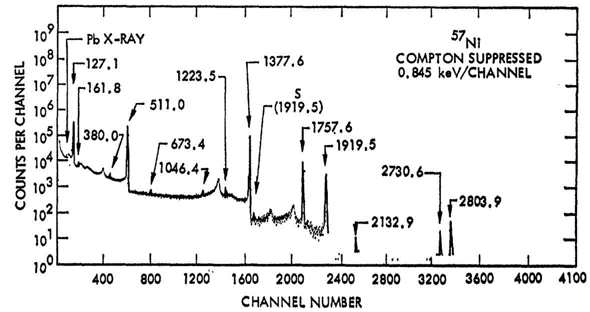

FIG. 2. Energy spectrum of γ rays obtained with Compton-suppressed spectrometer showing relative intensities of most intense peaks.

spectra with an intensity much greater than the 3177-keV peak. Since no evidence for this is shown, we must conclude that the 2132.9-keV peak cannot be due to double escape, but must be related to a transition of this energy. Indeed, a level at approximately 2130 keV has been excited in the stripping and pickup reaction studies mentioned earlier, but was hitherto unobserved in decay scheme work.

The γ ray at 1896.5 keV is one of the most interesting and definitive experimental results of the present investigation. In both the ^{58}Ni(t, α) and ^{56}Fe$(p, \gamma\gamma)$ reaction studies a state at approximately 1.90 MeV was excited. The spin assignments deduced from the angular distributions were different in each case and strong arguments supported each assignment. In order to explain this result, Blair and Armstrong[9] suggested the presence of a doublet at 1.89 and 1.92 MeV with spins and parities consistent with the observed angular distributions. The well-resolved doublet at 1896.5 and 1919.5 keV shown in Fig. 1 supports this contention. More recently, the proton spectra observed in the

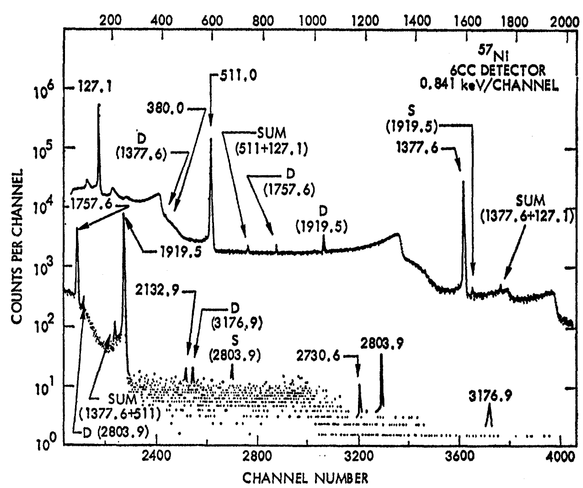

FIG. 3. Energy spectrum of γ rays obtained with a 6-cm^3 Ge(Li) detector without suppression. (Upper scale refers to top spectrum.)

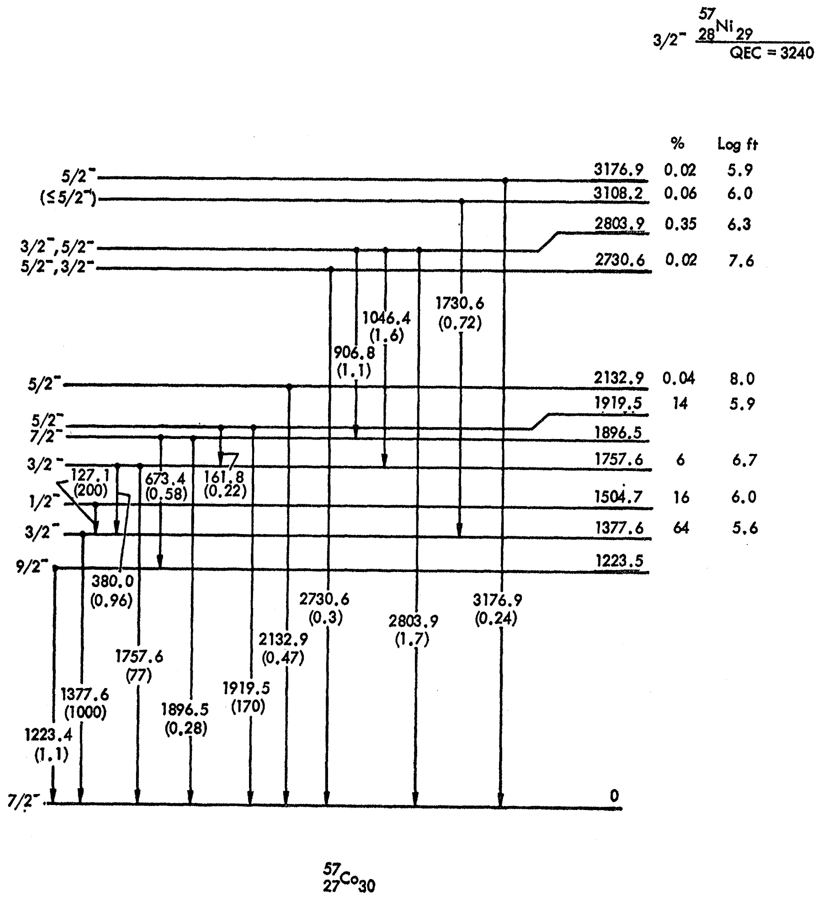

FIG. 4. Proposed decay scheme of ^{57}Ni. The relative transition intensities are shown in parentheses. All energies are in keV.

^{54}Fe(α, p) study[11] indicate the possible existence of a doublet in this energy region.

The photopeak at 1730.6 keV could not be assigned by taking sums and differences of any levels observed in the present study. The possibility that the (1747± 15)- and (1760±20)-keV levels excited in the (t, α) and (p, $\gamma\gamma$) experiments, respectively, are two different levels was considered but the value of 1730.6±0.2 keV is somewhat outside the allowed values of the reaction data. Nevertheless, a doublet at 1.75 MeV was observed in the ^{54}Fe(α, p) work which may, indeed, be the source of the 1730.6- and 1757.6-keV γ rays we observe. It seems more likely, however, that the 1730.6-keV γ ray consists of a transition from a level at 3108.2 keV to the well-known level at 1377.6 keV. Attempts to verify this contention by coincidence counting were unsuccessful largely because of intensity considerations. However, a level at 3100±30 keV excited in the (p, $\gamma\gamma$) and (α, p) studies is consistent with a 1730.6-MeV stopover transition through the 1377.6-keV state. On this basis, and along with further evidence to be presented, we tentatively show a new level in the decay scheme of ^{57}Ni at 3108.2±0.5 keV.

The γ ray at 1223.5 keV has not been observed in earlier decay studies, but it is consistent with the level excited at 1218±15 keV by the ^{58}Ni(t, α) and ^{54}Fe(α, p) reactions and is thus shown in our scheme. The 161.8-, 380.0-, 673.4-, 906.8-, and 1046.6-keV γ rays (all previously unreported) have been assigned as stopover transitions between the observed levels on the basis of energy fit.

DECAY SCHEME

The proposed decay scheme for ^{57}Ni is shown in Fig. 4. The logft values for the different β^+ transitions to states in ^{57}Co were calculated from the relative γ-ray intensities of the present work shown in Table I, and from the earlier results of the relative positron branch intensities. The present decay scheme is considerably different and more complex than previous decay studies of ^{57}Ni have indicated. However, it is entirely consistent with the nuclear reaction studies. A comparison of the γ rays observed in this work with the reaction data is shown in Table II.

Levels at 1223.5, 1896.5, 2132.9, and 3108.2 keV were not established in decay studies prior to this, and the low-intensity stopover transitions had not been observed. No evidence was found for a level at 1.59 MeV as reported by Chilosi *et al.*[4] and we can find no support for levels at 1.46, 1.59, and 2.62 MeV

TABLE II. Energy levels in ^{57}Co below 3.3 MeV.

γ-ray energy (keV)	Origin	J, π	Levels observed in reaction studies Ni^{58} (t, α)[a]	Fe^{56} (He^3, d)[b]	Fe^{56} $(p, \gamma\gamma)$[c]	Fe^{54} (α, p)[d]
			3259±25	3259	3270±30	3248±10
3176.9±0.3	level	$\frac{5}{2}^-$	3171±25	3176	3180±30	3165±10
(1730.6)	(3108.2−1377.6)		···	···	3110±30	3110±10
			2970±25	2978	···	2980±10
			···	2880	2880±30	2870±10
2803.9±0.2	level	$\frac{3}{2}^-, \frac{5}{2}$	···	···	2800±30	2794±30
2730.6±0.2	level	$\frac{5}{2}^-, \frac{3}{2}^-$	2721±25	···	2740±30	2730±10
			2591±20	···	2600±30	2606±10
			2489±20	···	···	2483±10
			2302±20	2309	···	2305±10
2132.9±0.3	level	$\frac{5}{2}^-, (\frac{5}{2}^+)$	2130±20	2129	2136±20	2127±10
1919.5±0.2	level	$\frac{5}{2}^-$	···	···	1921±20	1896±10[e]
1896.5±0.4	level	$\frac{7}{2}^-$	1890±15	···	···	···
1757.6±0.2	level	$\frac{3}{2}^-, (\frac{5}{2}^-)$	1747±15	1763	1760±20	1747±10[e]
			1683±15	···	···	1679±10
			···	1506	1506±20	1502±5
1377.6±0.2	level	$\frac{3}{2}^-$	1369±15	1379	1381±10	1374±5
1223.5±0.4	level	$\frac{9}{2}^-$	1218±15	···	···	1219±5

[a] Reference 9.
[b] Reference 10.
[c] Reference 8.
[d] Reference 11.
[e] Doublet observed.

as given by Bakhru and Preiss.[6] This is consistent with the results of Piluso *et al.*[5] and Lingeman *et al.*[7] We differ with the latter study, however, in that we find no evidence for a level at 3151 keV. The information from the nuclear reaction studies and our accurate γ-ray energy data were relied on almost exclusively in constructing the present decay scheme. Also, in in this study all observed γ rays have been incorporated in the decay scheme without proposing levels other than those previously known from the reaction studies.

Spins and parities have been assigned where possible on the basis of the β-decay log*ft* values, γ-ray branching ratios observed in this work, and reaction data previously reported. The ground state spin of ^{57}Co is $\frac{7}{2}$ as determined by Baker *et al.*[20] Measurements by γ-γ and β-circularly polarized γ angular correlation have established the spins of the states at 1377.6 and 1504.7 keV in ^{57}Co and the ground state of ^{57}Ni as $\frac{3}{2}$, $\frac{1}{2}$, and $\frac{3}{2}$, respectively.[21] Furthermore, the recently measured lifetime of the 1504.7-keV state (0.6 nsec[6]) is consistent only with a spin of $\frac{1}{2}$. The parities of the above-mentioned states are all similar to the ^{57}Co ground state ($\frac{7}{2}^-$) as shown by the reaction data as well as β and γ decay.

Lingeman and co-workers[7] have observed several of the same excited states we observed and assigned spins and parities on the basis of decay and reaction data. Our conclusions on the 1757.6-keV state disagree with Lingeman's, which favor a $\frac{5}{2}^-$ assignment. We observe a branching ratio between the ground-state transition and the 1377.6-keV state of 80, compared with Lingeman's value of $\gtrsim 90$. This favors a spin of $\frac{5}{2}^-$ ($M1$ γ rays), whereas the reaction data, although not all in agreement, seem to indicate $J^\pi = \frac{3}{2}^-$. This latter value is not incompatible with the decay data, since the ground-state transition ($E2$ in this case) could be enhanced by a factor of 10 or more over the single-particle estimates and the ($M1$ 380-keV transition could be retarded by ~100, which would then still agree with the observed branching ratio. Further argument for assigning the spin as $\frac{3}{2}^-$ is deferred to the next section of this paper.

We observe a doublet of γ rays which presumably are the ground-state transitions from a doublet of levels at 1896.5 and 1919.5 keV. This doublet has been suggested in the reaction work, the ^{56}Fe$(p, \gamma\gamma)$ reaction exciting a state at 1921±20 keV with $J^\pi = \frac{5}{2}^-$ and the ^{58}Ni(t, α) reaction a state at 1890±15 keV

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with $J^\pi=\frac{7}{2}^-$. Indeed, a doublet at 1900 keV has been indicated in the recent ^{54}Fe(α, p) measurements. As pointed out by Lingeman *et al.*,[7] a spin of less than $\frac{5}{2}$ for the 1919.5-keV state would require the (unobserved) stopover transitions to the 1377.6- and 1504.7-keV levels to be hindered by $\sim 10^4$ and $\sim 10^3$, respectively. This argument is not so significant for the state at 1896.5 keV since here, in contrast to the 1919.5-keV state, the level is populated very weakly and a hindrance of only $\sim$10 would account for our failure to detect the stopover transitions. The β-decay logft values to these states indicate an allowed decay to the 1919.5-keV state (hence $J\leq\frac{5}{2}$) and a possibly second-forbidden decay to the 1896.5-keV state (hence consistent with $J^\pi=\frac{7}{2}^-$). All of the abovementioned data on this doublet are therefore consistent with the assignments in Fig. 4.

The fact that only the 1896.5-keV level decays to the 1223.5-keV level suggests a high spin for the 1223.5-keV state, as does the limit set on the logft value to this level. Also, the spin of this state very probably is greater than $\frac{7}{2}$ since this level was unobserved in the (p, $\gamma\gamma$) and (^{3}He, d) reaction studies. The properties of this state agree well with the first excited state, having $J^\pi=\frac{9}{2}^-$, observed at 1218±15 keV in the ^{54}Fe(α, p) reaction.[22]

We observe a γ ray of 2132.9 keV which presumably is the ground-state transition from the state observed at this energy in the reaction studies. The spin of this state is questionable, since the various reaction studies indicate $\frac{5}{2}^+$, $\frac{5}{2}^-$, or $\frac{3}{2}^+$. A spin of $\frac{3}{2}^+$ is quite unlikely, since the $M2$ transition to the ground state would not normally compete with the $E1$ cascade transitions.

As pointed out by Lingeman *et al.*,[7] the logft values feeding the states at 2730.5, 2803.9, and 3177.1 keV (allowed or first-forbidden β decay) restrict the possible spins to $\leq\frac{5}{2}$. Furthermore, the decay of these levels to the ground state makes $\frac{1}{2}^+$ and $\frac{3}{2}^+$ assignments very unlikely. Beyond this, no definite statement can be made about spins and parities of these states. However, the ^{56}Fe(He^3, d) reaction shows a level at 3176 keV with $J^\pi=\frac{5}{2}$.$^-$ Also, the logft value and the detected γ rays from the 2803.9-keV state are more consistent with an assignment of $\frac{3}{2}^-$.

Since the level at 3108.2 keV decays with detectable intensity only to the 1377.6-keV level, we can assign a spin of $\frac{1}{2}$ or $\frac{3}{2}$. From the logft value to this level its parity can be either + or − (allowed or first-forbidden β decay). Our evidence for this level is a bit nebulous, since we do not detect a γ transition to the ground state and were not able to detect the 1730.6-keV γ ray in coincidence with the 1377.6-keV γ ray, because of its weak intensity. The 1730.6-keV ray presents a problem in that it could represent either a ground-state transition from a possible $\frac{5}{2}^-$ level or a transition from the 3108-keV level. If the 1730-keV γ ray represented a ground-state transition, the intensity would correspond to a logft of almost 9 for decay to this level (since no other γ rays could be detected which would correspond to additional decay from this level). Such a value would be the highest logft value detected in this work. As stated earlier, the assignment of the 1730-keV γ to the transition from a 3108.2-keV level to the 1377.6-keV ($\frac{3}{2}^-$) level is more consistent with known data.

A level with spin and parity of $\frac{1}{2}^-$ and with an energy of 2880 keV has been proposed by Rosner and Holbrow.[10] If such an assignment is correct, we should expect to see it populated in the decay of ^{57}Ni. However, we have only been able to detect a very weak γ ray with an energy of 1499±1 keV which might correspond to a transition from this level to the $\frac{1}{2}^-$ level at 1377.6 keV. There is rather weak evidence for two γ rays of energy 746±2 and 1122±4 keV which would correspond to a possible transition to the 2132.9-keV ($\frac{5}{2}^-$) and 1757.6-keV ($\frac{3}{2}^-$) levels. Consequently, we can only tentatively propose that a level at 2877 keV is populated in the electron capture (EC) decay of ^{57}Ni.

Several other levels have been proposed from experiments in reaction spectroscopy. These are levels at 1683, 2302 ($\frac{7}{2}^-$ or $\frac{5}{2}^-$), 2489, 2600, and 2970 keV. No γ rays corresponding to transitions from these levels could be identified in the spectra taken with the use of the 6- to 7-cc Ge(Li) detectors, 30-cc Ge(Li) detector, or the Compton-suppression spectrometer.

DISCUSSION

Although a number of theoretical models have been recently developed which attempt to predict and explain the level structure of many odd-A nuclei, very poor agreement with experiment has been realized when these models are applied to the levels of ^{57}Co. Vervier[13] has calculated the energy levels of nuclei with $20\leq Z\leq 28$, $N=29$ and 30 under the assumptions that the protons and neutrons outside $Z=20$ and $N=28$ are in the $1f_{7/2}$ and $2p_{3/2}$ orbits, respectively, and that the effective nucleon-nucleon interactions are given by experimental spectra. In this analysis it was assumed that the influence of other orbits ($p_{1/2}$ and $f_{5/2}$ for the neutrons), core excitations, and other configurations for the protons would be absorbed in the effective interactions deduced from the experimental data. The results of Vervier's calculations of levels in ^{57}Co given in Fig. 5 show only a qualitative agreement with experiment. A notable disagreement with this experiment is the absence of any calculated $\frac{1}{2}^-$ state in the vicinity of 1504 keV.

A shell-model calculation of the structure of ^{57}Co was previously reported by one of us (J.B.Mc.).[12] In that calculation, an inert ^{48}Ca core was assumed,

[22] B. Cujec, R. Dayras, and I. Szöghy, Bull. Am. Phys. Soc. **13**, 723 (1968).

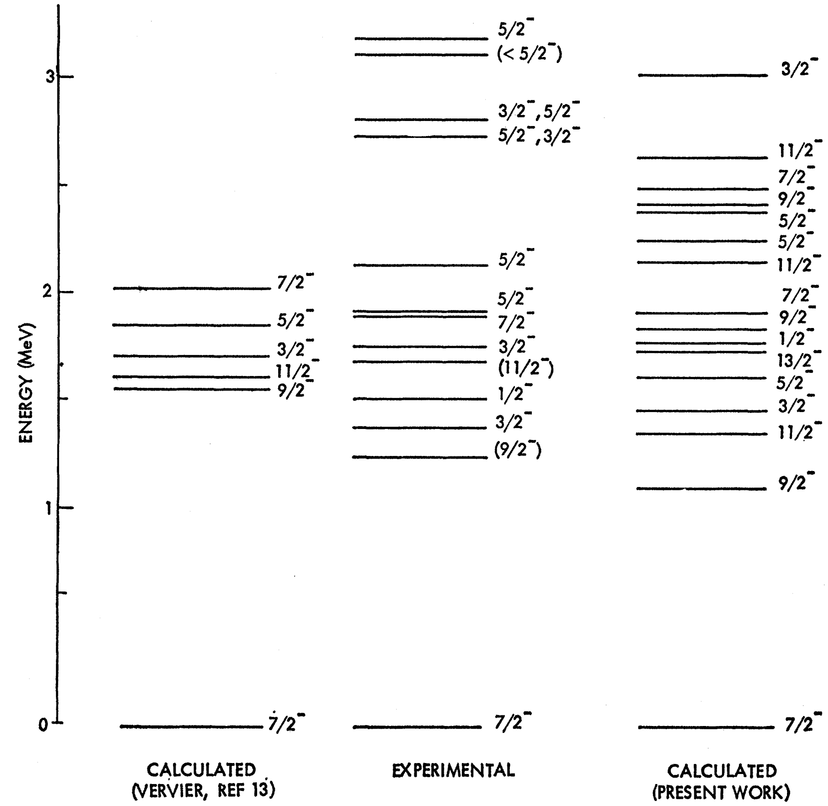

FIG. 5. Comparison between the experimental and calculated energy levels of ^{57}Co below 3.2 MeV.

all protons were restricted to the $f_{7/2}$ shell, and the two active neutrons were distributed among the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ single-particle orbits. The residual interaction used gave reasonable agreement with experiment for other nuclei in this mass region with $N=30$. However, in the case of ^{57}Co, the agreement of the calculated and known experimental spectrum was poor. In particular, there were no calculated $J=\frac{1}{2}^-$ or $J=\frac{3}{2}^-$ states below 2.5 MeV, while such states were observed below 1.5 MeV. It was suggested that perhaps the excitation of protons from the $f_{7/2}$ to the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ orbits might be important in the low-lying states of this nucleus. Therefore, a shell-model calculation of ^{57}Co in which such excitations are included has been made. Results of this calculation are shown in Fig. 5.

In this calculation, an inert ^{40}Ca core is assumed, and particles are distributed in the $f_{7/2}$, $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ orbits. We include the following configurations in our model space:

$$\left.\begin{matrix} f_{7/2}{}^{14}, j_1j_2j_3 \\ \\ f_{7/2}{}^{15}, j_1j_2 \end{matrix}\right\} j_1, j_2, j_3 = p_{3/2},\ p_{1/2},\ f_{5/2}. \qquad (1)$$

For the two-body part of the shell-model residual interaction we use the reaction matrix elements derived from the Hamada-Johnston free two-nucleon potential by Kuo and Brown.[23] The interaction is calculated specifically for ^{42}Ca, and includes some renormalization effects due to particle-hole excitations of the ^{40}Ca core. The remaining question is the one of single-particle energies. There are uncertainties as to what single-particle energies should be used due to the change in the ^{40}Ca core as particles are added to form the heavier nuclei. We determined the energies by a search technique. The energies of the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ orbits relative to the $f_{7/2}$ orbit were varied to give a best fit to the lowest two observed $J=\frac{7}{2}$ states, the lowest two $J=\frac{3}{2}^-$ states, and the lowest $J=\frac{1}{2}^-$ state. The calculation was found to be sensitive mainly to the $f_{7/2}-p_{3/2}$ splitting. The final set of single-particle energies which we used to obtain the results given here are summarized below, where the $f_{7/2}$ energy is arbitrarily set to zero:

$$f_{7/2},\quad 0;\qquad p_{3/2},\quad 3.4;$$
$$p_{1/2},\quad 8.2;\qquad f_{5/2},\quad 5.6.$$

In ^{41}Ca, the $p_{3/2}$ level is observed to be about 2 MeV above the $f_{7/2}$, so we see that we have increased this splitting by 1.4 MeV. This is consistent with the observed behavior of these single-particle energies as

[23] J. T. S. Kuo and G. E. Brown (to be published).

TABLE III. Configuration of lowest $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ levels.

Spin	Description of component[a]	Percent
$J^\pi=\frac{1}{2}^-, T=\frac{3}{2}$	$[(f_{7/2}^{14}, J=0, T=1)\times(P_{3/2}^2, J=0, T=1)]_{J=0,T=2}\times P_{1/2}$	20
	$(f_{7/2}^{14}, J=0, T=1)\times(P_{3/2}^3, J=\frac{1}{2}, T=\frac{1}{2})$	11
	$(f_{7/2}^{14}, J=2, T=1)\times(P_{3/2}^3, J=\frac{3}{2}, T=\frac{1}{2})$	24
$J^\pi=\frac{3}{2}^-, T=\frac{3}{2}$	$(f_{7/2}^{14}, J=2, T=1)\times(P_{3/2}^3, J=\frac{3}{2}, T=\frac{1}{2})$	10
	$(f_{7/2}^{14}, J=0, T=1)\times(P_{3/2}^3, J=\frac{3}{2}, T=\frac{1}{2})$	33
$J^\pi=\frac{5}{2}^-, T=\frac{3}{2}$	$[(f_{7/2}^{15}, J=\frac{7}{2}, T=\frac{1}{2})\times(P_{3/2}^1)]_{J=3,T=1}\times f_{7/2}$	18
	$(f_{7/2}^{15}, J=\frac{7}{2}, T=\frac{1}{2})\times(P_{3/2}^2, J=2, T=1)$	43

[a] All components of lowest state of $J=\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ which contribute more than 10% to the total wave function in the shell-model calculation of ^{57}Co.

extracted from stripping data by sum-rule techniques.[24] The calculated energy levels of this model are compared with the experimental spectrum in Fig. 5. The inclusion of the $f_{7/2}$ excitations leads to a significantly altered theoretical spectrum, and improved agreement with experiment. All the levels up to 2 MeV are accounted for, with one extra $J=\frac{9}{2}^-$ theoretical state. The wave functions for these states are extremely collective in that there are very few large components in any of the functions, and in no case is there any one component which constitutes as much as 50% of the wave function. As an example, in Table III, we give all components which contribute more than 10% to the lowest $J=\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ states. The vectors in this calculation have up to 454 components. With such large dimensionalities and with strengths spread over a large number of states, large collective enhancements and retardations in various nuclear transition rates are possible. The calculation of such electromagnetic and β-decay transition rates with the wave functions from this calculation is in progress.

If some of the low-lying states in ^{57}Co involve strong $p_{3/2}$ single-particle nature in their configuration, the logft values are, on the average, at least one order of magnitude too large. One possible explanation of this is found in the pairing-plus-quadrupole model of Kisslinger and Sorensen,[25] which has been successful in explaining a majority of the levels in nuclei with atomic weight greater than approximately 80. In their model β decay is broken into two categories of quasiparticle transitions: those of "odd-jumping" and "even jumping." In the case of ^{57}Ni decay to ^{57}Co their odd-jumping case would apply. For such a case they find that the ft value is proportional to $(U_nU_p)^{-2}$, where U is the nonoccupancy of the neutron (proton) quasiparticle orbital. Since the U's will be small in ^{57}Co, the transitions will be slowed down.

TABLE IV. Log ft values for selected levels in ^{57}Co and ^{59}Co.

J^π	^{57}Co E_{level}	^{57}Co Log ft	^{59}Co E_{level}	^{59}Co Log ft
$\frac{3}{2}^-$	1757.6	6.7	1099	6.7
$\frac{3}{2}^-$	1377.6	5.6	1292	6.0

Another effect which could account for larger ft values is phonon mixing in the levels of ^{57}Co. In recent years it has been suggested that some of the low-lying levels of nondeformed odd-A nuclei may be described in terms of coupling of the odd nucleon to collective modes of vibration of the even-even core.[14,26–29] Calculations based on this model have restricted the particle to only one orbital, which is then weakly coupled to the even-even core which may be in its ground state or its first excited state. Thus, on the basis of this model, some of the low-lying levels in ^{57}Co may be formed by coupling the odd $f_{7/2}$ proton hole to the first phonon state in ^{58}Ni. The ground state of ^{57}Co is therefore $\frac{7}{2}^-$, and there should be excited states with $J^\pi=\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{7}{2}^-$, $\frac{9}{2}^-$, and $\frac{11}{2}^-$, corresponding to the coupling of the spin of the proton hole to the first 2^+ state of ^{58}Ni at 1450 keV.[30] The center of gravity of this quintet of states should lie at approximately the energy of the core state. Early attempts by Chilosi *et al.*[4] to characterize the ^{57}Co levels in this way were inconclusive, partly because of the paucity of information on the level scheme available at that time.

If the excited state of the core is collective in nature, the model predicts that this collective nature will be carried over to the excited states of the odd-A nucleus when these states are described in these terms.[31] For

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[25] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).
[26] B. F. Bayman and L. Silverberg, Nucl. Phys. **16**, 625 (1960).
[27] A. de-Shalit, Phys. Rev. **122**, 1530 (1961).
[28] L. S. Kisslinger, Nucl. Phys. **78**, 341 (1966).
[29] L. S. Kisslinger and K. Kumar, Phys. Rev. Letters **19**, 1239 (1967).
[30] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley-Interscience, Inc., New York, 1967), 6th ed.
[31] H. E. Gove, Phys. Letters **4**, 249 (1963).

states of this type, Elbek *et al.*[32] pointed out that one can obtain a measure of the collective part of the wave function from Coulomb excitation. Since the same phonon is involved in the decay of each member of the quintet, the reduced transition probabilities $B(E\lambda)\downarrow$ for the decay to the ground state should be equal to each other and to the $B(E\lambda)\downarrow$ for decay of the one-phonon state in ^{58}Ni. Nordhagen *et al.*[15] recently investigated the low-lying energy levels of ^{59}Co by Coulomb excitation with ^{16}O ions and inelastic deuteron scattering. They showed that levels in ^{59}Co at 1099, 1189, and 1458 keV were strongly excited and had $B(E2)\downarrow$ values approximately equal to that of the core state as required by the model.

Unfortunately, states in ^{57}Co which may be of vibrational origin cannot be investigated by Coulomb excitation, since ^{57}Co is unstable. Nordhagen *et al.*[15] noted, however, that reactions such as (t,α), which lead to hole states in the final ^{59}Co nucleus, enhance the states which are members of this multiplet. By comparison with reaction spectroscopy data of other workers,[9,10] Nordhagen *et al.*[15] correlated the levels in ^{59}Co at 1099, 1189, and 1458 keV with those in ^{57}Co at 1763, 1218, and 1683 keV, respectively. If these correlations are correct, they indicate that the levels we observe at 1223.5 and 1757.6 keV should be the $\frac{9}{2}^-$ and $\frac{3}{2}^-$ members of a phonon-coupled multiplet.

The 1757.6-keV state in ^{57}Co rather than the 1377.6-keV state was correlated to the 1099-keV state in ^{59}Co on the basis of the spectroscopic factors measured for the two lowest $\frac{3}{2}^-$ states in ^{57}Co and ^{59}Co.[9] This correlation is consistent with the γ-decay properties insofar as it suggests a stronger collective nature for the 1757.6-keV level in ^{57}Co in contrast to the more single-particle nature proposed for the 1377.6- and 1504.7-keV levels. We do not know the half-life of the 1757.6-keV γ ray, but we know that its "counterpart" in ^{59}Co (the 1099-keV transition with $t_{1/2}\approx 5$ psec) has an $E2$ enhancement of six times the single-particle speed.[15] Assuming an enhancement of this same order of magnitude for the 1757.6-keV γ ray leads, with our branching ratios, to $M1$ retardations of ≈ 100 for the 380-keV transition to the 1377.6-keV level and $\gtrsim 100$ for a possible 252.5-keV transition to the 1504.7-keV level. While these are not large as $M1$ retardations go, they are certainly consistent with the picture of a largely collective 1757.6-keV state and single-particle 1377.6- and 1504.7-keV states. The analogous situation in ^{59}Co has the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ single-particle (i.e., non-Coulomb-excited) levels at 1434 and 1292 keV, respectively. Here using the data of Gatrousis *et al.*,[33] the decay of the 1434-keV level to the 1099-keV level is found to be hindered by a factor of 40 ± 2 relative to its decay to the 1292-keV level (assuming $M1$ radiation). These arguments indicate at least a different major configuration for the state at 1757.6 keV in ^{57}Co than for the states at 1504.7 and 1377.6 keV, and they also support Nordhagen's correlations between levels in ^{57}Co and ^{59}Co. The fact that the 1919.5-keV level decays detectably to the 1757.6, but not to the 1377.6-keV level, may indicate that the $\frac{5}{2}^-$ member of the multiplet is mixed appreciably in this level. Further support for these correlations is seen in the similar logft values of corresponding states in the two nuclei (Table IV).

CONCLUSIONS

We have considered the various alternatives to a description of the levels in ^{57}Co on the basis of data found in this work, reaction spectroscopy, and recent Coulomb excitation studies of levels in ^{59}Co. Shell-model calculations with configuration mixing give a reasonable description of the low-lying energy spectra. In the representation used in this calculation, the strengths of various shell-model states are spread out over a number of eigenvectors, which suggests a complicated structure for these states. In terms of a collective picture, it appears that some levels may be considered as being predominantly formed by an $f_{7/2}$ proton hole coupled to core vibrations. If, however, the phonon strength is spread over many states, several excited states may have substantial single-particle components even when belonging to a multiplet of states which are strongly Coulomb-excited. Since a description based on this model should be most valid when the coupling between core and particle states is weak and when the core and particle states are well separated in energy, it is not clear that this model should give a good description of states in ^{57}Co. Indeed, Thankappan and True[34] have shown that the coupling between the core and the particle is not weak in the case of ^{63}Cu. In their approach, the exact nature of the excited states of the core is not specified. Since the large single-particle nature of some states in ^{63}Cu, as well as the collective nature of some of the states in ^{63}Cu, was explained in a consistent manner by Thankappan and True,[34] perhaps this model would also provide a good description of the levels in ^{57}Co.

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