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The gamma decay of $g_{9/2}$ and $d_{5/2}$ analogue resonances in ^{57}Co

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Abstract. An investigation of the γ decay of the $g_{9/2}$ and $d_{5/2}$ analogue states in ^{57}Co has been performed using the ^{56}Fe(p, p′γ) and ^{56}Fe(p, γ)^{57}Co reactions. Excitation functions in the energy range $E_p = 3694$–3855 keV revealed resonances at the energies $E_p = 3720$, 3727, 3774 and 3793 keV. For the first two resonances their decay scheme along with angular distributions indicate that they are the fragmented analogues of the $E_x = 2455$ keV, $J^\pi = \frac{9}{2}^+$ parent state in ^{57}Fe. The $E_p = 3774$ and 3793 keV resonances were identified as the fragmented analogue resonances of the $E_x = 2506$ keV, $J^\pi = \frac{5}{2}^+$ parent state in ^{57}Fe. The $E_x = 2611$ and 4586 keV states in ^{57}Co were uniquely determined as $\frac{7}{2}^-$ and $\frac{9}{2}^+$ respectively.

NUCLEAR REACTIONS ^{56}Fe(p, γ) and (p, p′γ), $E = 3694$–3855 keV; measured $\sigma(E, E_\gamma, \theta)$. ^{57}Co deduced levels, analogue resonances J^π, δ, M1, resonance strengths. Enriched target.

1. Introduction

The gamma decay of isobaric analogue states (IAS) with $J = l + \frac{1}{2}$ has been the subject of many investigations. In the 2s–1d shell nuclei the IAS decay mainly to the antianalogue states (AIAS) by strong M1 transitions of about the single-particle strength (Maripuu 1969). In the 1f–2p shell odd-A nuclei, the IAS → AIAS transitions are strongly inhibited compared with the single-particle value and most of the M1 strength populates core-polarised states (CPS) (El-Kateb and Griffiths 1975 and references therein).

In the case of $g_{9/2}$ IAS, the parent $\frac{9}{2}^+$ states and the AIAS exhibit large spectroscopic factors in the single-nucleon transfer reactions. However, in (p, γ) reactions only a small fraction of the single-particle strength appears in the IAS → AIAS transitions (Schrader *et al* 1975, Klapdor *et al* 1975). Such a reduction in the M1 strength has been understood in terms of an interference of IAS → AIAS and IAS → CPS transition amplitudes. Furthermore, shell-model calculations for the 1f–2p shell nuclei require significant core polarisation to provide even qualitative fits to observed energy levels (Vervier 1966, Comfort *et al* 1971).

Recently the decay of the $g_{9/2}$ IAS in ^{57}Co has been investigated through a (p, γ) reaction by two different groups (Fodor *et al* 1978, Rangacharyulu *et al* 1979). Both groups have examined the energy region where the $g_{9/2}$ analogue states in ^{57}Co are expected, but they disagree on the number of $g_{9/2}$ fragments observed. Fodor *et al* (1978)

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identified the closely spaced doublet at $E_p=3728$ and 3735 keV as candidates for the expected $g_{9/2}$ IAS. Rangacharyulu *et al* (1979) have independently performed a (p, γ) experiment which completely overlaps the measurements of Fodor *et al* (1978) and have observed the same doublet at $E_p=3721$ and 3728 keV; howver, they rejected the resonance at $E_p=3721$ keV from the analogue candidate.

In a high-resolution experiment (Watson *et al* 1981) using the (p, p) and (p, p$'\gamma$) reactions on ^{56}Fe, five $g_{9/2}$ fragments at $E_p=3698$, 3704, 3718, 3731 and 3751 keV were identified. In another high-resolution experiment (Arai *et al* 1982) using the ^{56}Fe(p, p_0) reaction, only one $g_{9/2}$ resonance was observed at $E_p=3732$ keV. The $d_{5/2}$ IAS fine structure has been investigated recently via the (p, p), (p, p$'$) and (p, p$'\gamma$) reactions on ^{56}Fe (Watson *et al* 1981) and the ^{56}Fe (p, p_0) reaction (Arai *et al* 1982).

The aim of the present work was a more thorough investigation of the energy region where the $g_{9/2}$ and $d_{5/2}$ IAS in ^{57}Co are expected to appear in order to resolve the above discrepancies.

2. Procedure

For the measurements described below a proton beam obtained from the Demokritos $T_{11/25}$ tandem van de Graaff accelerator was utilised. An excitation function over the proton energy range $E_p=3694$–3855 keV was measured in steps of 1.6 keV (in the vicinity of the resonances in 1 keV steps) using a 20 μg cm^{-2} ^{56}Fe target (99.93% enrichment) on a 20 μg cm^{-2} carbon backing. The energy calibration of the accelerator was performed through the ^{13}C(p, γ) reaction, and was found to be within 1 keV of the energy inferred from the nuclear magnetic resonance (NMR) value of the analysing magnet.

The gamma rays were detected with a 95 cm^3 Ge(Li) detector, with a resolution of 1.95 keV (FWHM) and 19.1% efficiency, placed at $\theta_{Lab}=55°$. Gates were set to detect the 845 keV ($2^+\rightarrow$GS) transition in ^{56}Fe, γ rays with energies between 4 and 5 MeV, 7 and 10 MeV and 8.6 and 10 MeV. The uncertainty in energy measurements for the excitation functions was estimated to be ± 1 keV.

Gamma-ray spectra were measured using the 95 cm^3 Ge(Li) detector placed at $\theta=55°$ at the $E_p=3720$, 3727, 3774 and 3793 keV resonances. Off-resonance spectra were also measured at $E_p=3712$ and 3786 keV to allow for background subtraction, proper analysis of the spectra and establishing the decay schemes. High-energy calibration points were provided by the 6129.41 ± 0.18 keV line from the ^{19}F(p, $\alpha\gamma$)^{16}O reaction and the 5269.6 ± 0.3 keV from the ^{18}O(p, $\alpha\gamma$) reaction (De Meijer *et al* 1974), which were present as contaminants.

Gamma-ray angular distributions were measured at four angles $\theta=0°$, 45°, 55° and 90° relative to the beam direction. A 20 μg cm^{-2} ^{56}Fe target (99.93% enrichment) on a 0.13 mm thick tantalum backing was used. The 95 cm^3 Ge(Li) detector was used as a movable detector while another 48 cm^3 Ge(Li) detector served as a monitor. The asymmetry of the system was measured using the 844 keV (2^+) gamma ray arising from the ^{27}Al (p, p$'\gamma$) reaction.

Angular distribution data were taken at four angles and were analysed to determine those spins and mixing ratios which minimise the function $Q^2=N^{-1}\Sigma_i\Delta W_i(W(\theta_i)-W^*(\theta_i))^2$ where N is the number of degrees of freedom, ΔW_i is the statistical weight factor, $W(\theta_i)$ is the experimental intensity measured at the ith set of detector angles θ_i and $W^*(\theta_i)$ is the theoretical intensity at θ_i. The quantity $W^*(\theta_i)$ is a function of the assumed spins and multipole mixing ratios. For each possible spin sequence the Q^2 value was calculated in steps of 2° in x where $x = \tan^{-1}\delta$. Spins were rejected if Q^2 did not fall below the value corresponding to the 0.1% confidence level for any value of x.

3. Results and discussion

Figure 1 shows the yield curve for the ^{56}Fe(p, γ) and ^{56}Fe(p, p'γ) reactions for the different gates mentioned earlier. There are four strong resonances evident in the yield curve,

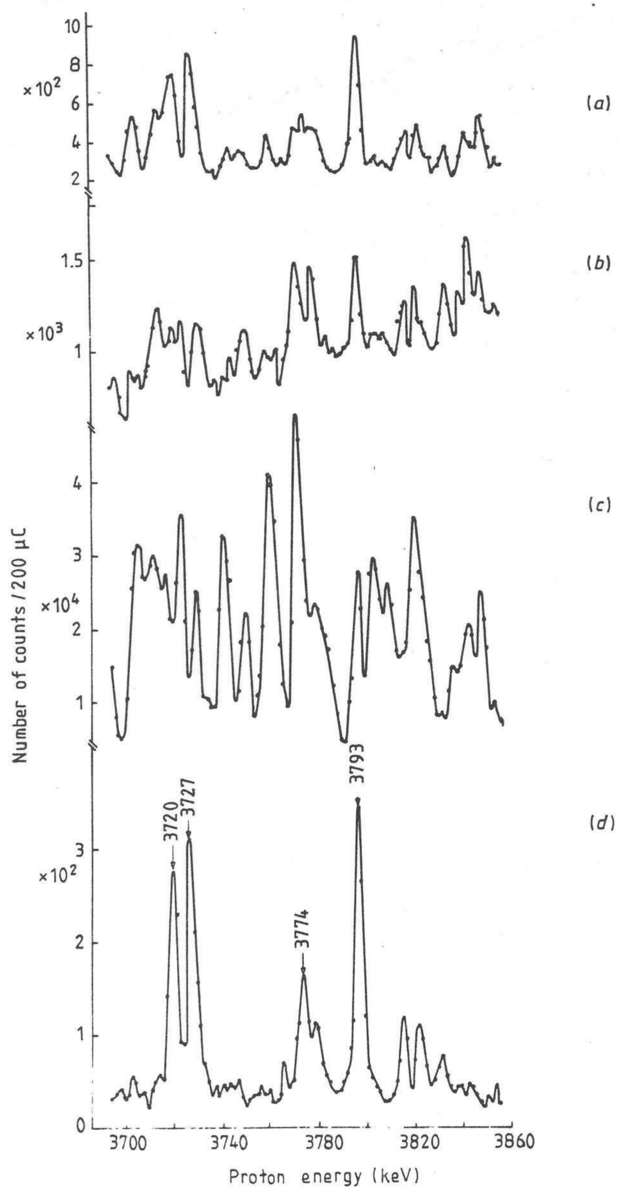

Figure 1. Excitation functions of the ^{56}Fe(p, γ)^{57}Co reaction in three different gates: (*a*) $7 \leqslant E_\gamma$ (MeV) $\leqslant 10$, (*b*) $4 \leqslant E_\gamma$ (MeV) $\leqslant 5$, (*d*) $8.6 \leqslant E_\gamma$ (MeV) $\leqslant 10$; and (*c*) the (p, p'γ) reaction ($840 \leqslant E_\gamma$ (keV) $\leqslant 855$) taken simultaneously with a 95 cm^3 Ge(Li) detector.

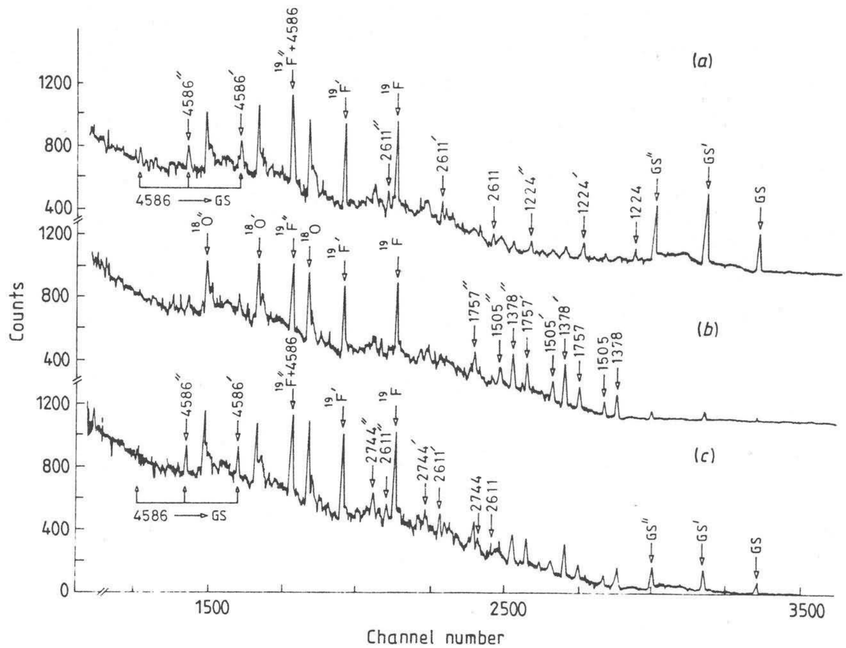

Figure 2. Gamma-ray spectra from the ^{56}Fe (p, γ)^{57}Co reaction taken at 3720, 3712 and 3727 keV incident proton energy. (*a*) On resonance, $E_p = 3727$ keV; (*b*) before resonance, $E_p = 3712$ keV; (*c*) on resonance, $E_p = 3720$ keV.

namely at $E_p = 3720$, 3727, 3774 and 3793 keV. Other resonances which are clear in the 4.0–5.0 MeV gate were found to be due to the contaminant γ ray at 5270 keV arising from

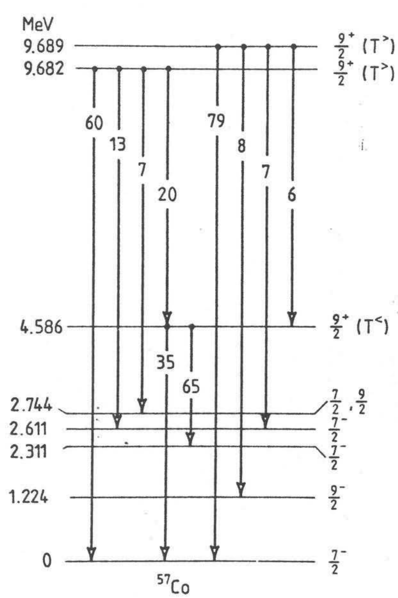

Figure 3. The gamma decay scheme of the $\frac{9}{2}^+$ IAS at $E_p = 3720$ and 3727 keV. The branching ratios are in per cent.

the ^{18}O(p, $\alpha\gamma$) reaction (Din 1969). The γ-ray spectra of these resonances were found to populate the contaminant γ rays at 6130 and 5270 keV which were mentioned earlier as well as low-spin states in ^{57}Co. Figure 2 shows the high-energy portions of the γ-ray spectra obtained at the 3720 and 3727 keV resonances together with a spectrum taken at $E_p = 3712$ keV for comparison with the above spectra at an off-resonance energy. All four resonances show an intense γ-ray transition to the ground state of ^{57}Co.

The decays of the $E_p = 3720$ and 3727 keV resonances including branching ratios are shown in figure 3. As can be seen, these resonances decay mostly to the $\frac{7}{2}^-$ ground state of ^{57}Co, indicating that both resonances have a high-spin value. Furthermore, they were found to decay to the 4586 keV state which decays to the $\frac{7}{2}^-$ ground state and the $\frac{7}{2}^-$ state at 2311 keV. The mode of decay of both resonances indicates that both are the $\frac{9}{2}^+$ IAS. In the work of Rangacharyulu *et al* (1979), the 3721 keV resonance was ruled out as a candidate for the $\frac{9}{2}^+$ IAS on the basis of the γ-ray spectrum. They indicated that the $E_p = 3721$ keV resonance was found to populate strongly both the ground state ($\frac{7}{2}^-$) and the level at 1757 keV, $J^\pi = \frac{3}{2}^-$, while no tansition feeding other high-spin states in ^{57}Co was observed with significant strength. To further investigate the nature of the 3720 keV resonance, angular distributions for the R→GS, R→2611 keV and R→4586 keV transitions were measured together with the 845 keV ($2^+ \rightarrow$ GS) transition from the ^{56}Fe(p, p′γ) reaction. Figure 4 shows the least-squares fits to the experimental data and

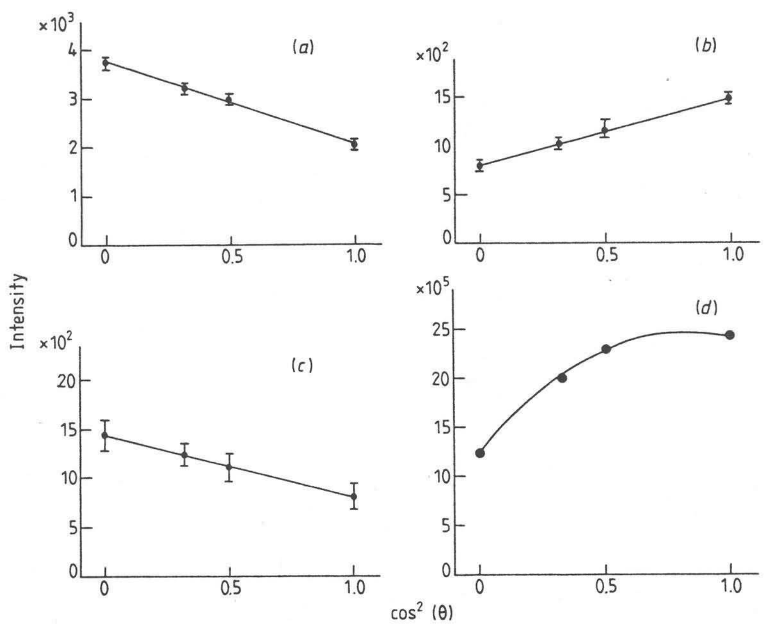

Figure 4. Least-squares fits to the experimental angular distribution for γ rays at $E_p = 3720$ keV resonance. R and GS represent the resonance and ground state respectively. The corresponding Legendre polynomial coefficients are given below.

Transition	a_2	a_4
(*a*) R→GS	-0.314 ± 0.013	-0.025 ± 0.011
(*b*) R→4586 ($T^<$)	0.404 ± 0.027	-0.017 ± 0.029
(*c*) R→2611	-0.338 ± 0.025	0.007 ± 0.027
(*d*) ^{56}Fe(p, p′γ)	0.470 ± 0.065	-0.165 ± 0.067

the corresponding Legendre polynomial coefficients a_2 and a_4 are given in the caption. Figure 5 shows the experimental data and theoretical fits for assumed spin sequences for the first three transitions mentioned earlier.

Based on the mode of decay of the $E_p = 3720$ keV resonance, various spin values for this resonance were assumed. The χ^2 analysis of the R→GS ($\frac{7}{2}^-$) angular distribution data (figure 6) indicates that the spin value for this resonant state at $E_x = 9682$ keV is either $\frac{5}{2}$ (with $\delta = -0.176 + 0.011$) or $\frac{9}{2}$ (with $\delta = 0.035 \pm 0.011$). The $J^\pi = \frac{5}{2}^\pm$ assignment can be ruled out when compared with the single-particle transition strengths (Weisskopf estimate). A spin value of $\frac{9}{2}$ with negative parity for this resonance is quite unlikely using similar arguments as above (see figures 4(*a*) and 5(*a*) and table 1). As a result, a $J^\pi = \frac{9}{2}^+$ is assigned to this resonant state at $E_x = 9682$ keV. The analysis of the angular distribution data for the 845 keV ($2^+ \rightarrow$ GS) transition shown in figure 4(*d*) and table 2 provides further supporting evidence that the $E_p = 3720$ keV resonance is indeed a $\frac{9}{2}^+$ resonance.

On the basis of the assignment $J^\pi = \frac{9}{2}^+$ for the $E_p = 3720$ keV resonance, the R→4586 keV χ^2 fits (figure 7) indicate that the only acceptable spin value for the $E_x = 4586$ keV state is $\frac{9}{2}$. Based on the single-particle transition strengths, a positive parity is very likely (see table 1) and as a result a $J^\pi = \frac{9}{2}^+$ for the $E_x = 4586$ keV state is

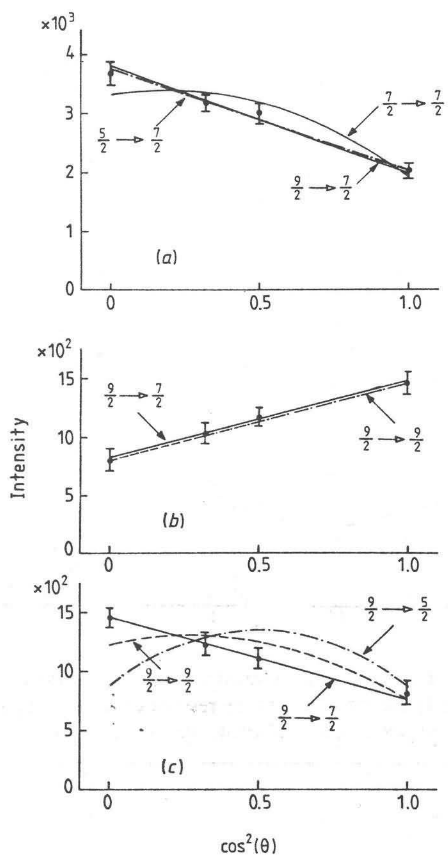

Figure 5. The experimental data and the theoretical fits for three of the ^{56}Fe(p, γ)^{57}Co transitions studied at $E_p = 3720$ keV resonance. R and GS represent the resonance and ground state respectively. (*a*) R→GS, (*b*) R→4586, (*c*) R→2611.

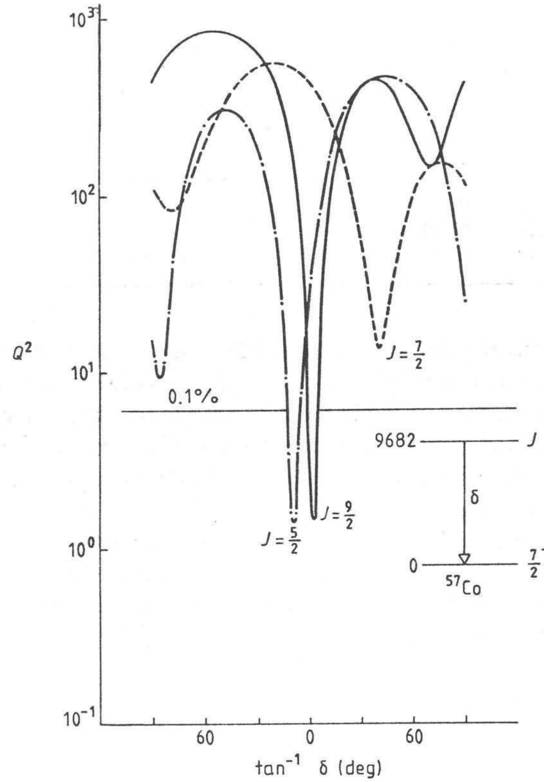

Figure 6. χ^2 test for the ground-state gamma transition at the $E_p = 3720$ keV resonance.

being assigned and this level is identified as the $T^<$ antianalogue state. The above assignment is supported by the $^{56}Fe(^3He, d)^{57}Co$ data of Rosner and Holbrow (1967) who identified a $l = 4$ proton transfer at the excitation energy 4600 ± 20 keV in ^{57}Co. Banu *et al* (1978) have identified the same level to occur at 4590 keV excitation energy in ^{57}Co as a result of $l_p = 4$ from the $^{56}Fe(^3He, d)^{57}Co$ reaction.

Table 1. Experimental mixing ratios δ compared with Weisskopf values for the transitions studied at $E_p = 3720$ keV.

Transition $E_i \rightarrow E_f$ (keV)	Transition $J_i^\pi \rightarrow J_f^\pi$	Character	Weisskopf estimate for $\lvert\delta\rvert$	Experimental mixing ratio δ	Assigned J^π
9682→0	$\frac{5}{2}^+ \rightarrow \frac{7}{2}^-$	E1 (M2)	0.0045	-0.176 ± 0.011	$J_i^\pi = \frac{9}{2}^+$
	$\frac{5}{2}^- \rightarrow \frac{7}{2}^-$	M1 (E2)	0.219	-0.176 ± 0.011	
	$\frac{9}{2}^+ \rightarrow \frac{7}{2}^-$	E1 (M2)	0.0045	0.035 ± 0.011	
	$\frac{9}{2}^- \rightarrow \frac{7}{2}^-$	M1 (E2)	0.219	0.035 ± 0.011	
9682→4586	$\frac{9}{2}^+ \rightarrow \frac{9}{2}^-$	E1 (M2)	0.0024	0.035 ± 0.020	$J_f^\pi = \frac{9}{2}^+$
	$\frac{9}{2}^+ \rightarrow \frac{9}{2}^+$	M1 (E2)	0.11	0.035 ± 0.020	
9682→2611	$\frac{9}{2}^+ \rightarrow \frac{7}{2}^-$	E1 (M2)	0.0033	0.035 ± 0.013	$J_f^\pi = \frac{7}{2}^-$
	$\frac{9}{2}^+ \rightarrow \frac{7}{2}^+$	M1 (E2)	0.16	0.035 ± 0.013	

Table 2. Comparison of theoretical and experimental Legendre polynomial coefficients for the 845 keV ($2^+ \rightarrow 0^+$) γ ray from ^{56}Fe(p, p'γ) at $E_p = 3720$ keV.

J^π resonance	Theory a_2	Theory a_4	Experiment a_2	Experiment a_4
$\frac{3}{2}^-$	0.18	0		
$\frac{5}{2}^-$	0.24	0.001		
$\frac{9}{2}^+$	0.30	−0.19	0.470 ± 0.065	-0.165 ± 0.067

Using $J = \frac{9}{2}$ for the resonant state at $E_x = 9682$ keV, the χ^2 fits of the R→2611 keV transition (figure 8) indicate that a $J(2611 \text{ keV}) = \frac{7}{2}$ (with $\delta = 0.035 \pm 0.013$) is the only acceptable spin value for the 2611 keV state. From the single-particle transition strengths (table 1) a negative parity is more likely and as a result a J^π (2611 keV) $= \frac{7}{2}^-$ is assigned to this state. Previous (p, γ) measurements on ^{56}Fe targets failed to assign a unique spin value to the 2611 keV state in ^{57}Co (Auble 1977).

The decay scheme of the $E_p = 3774$ and 3793 keV resonances is shown in figure 9. These two resonances are reported in the present work for the first time. From their mode of decay (see figure 9), it can be seen that both resonances would have a spin less than $\frac{9}{2}$ based on structural considerations of the ^{57}Co nucleus. Based on the Coulomb

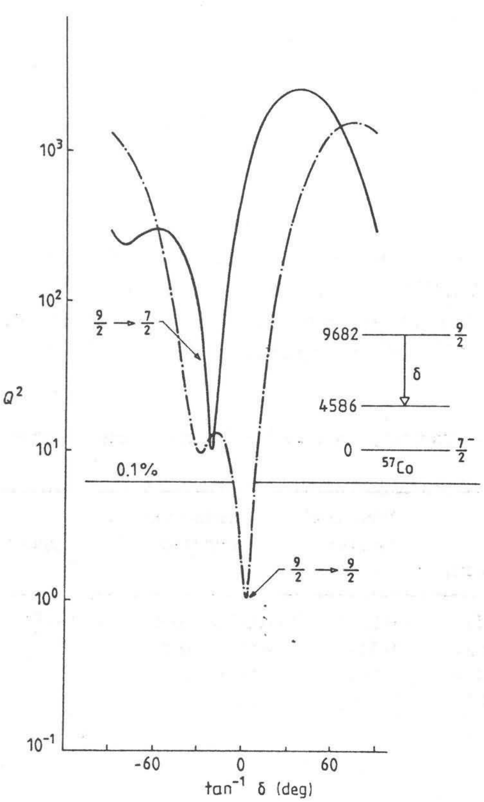

Figure 7. χ^2 test for the gamma transition to the level at 4586 keV in ^{57}Co ($E_p = 3720$ keV).

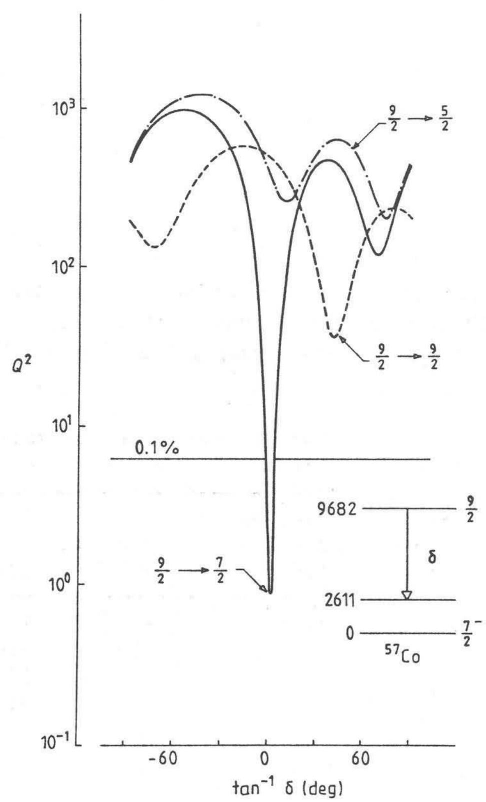

Figure 8. χ^2 test for the gamma transition to the level at 2611 keV in ^{57}Co ($E_p = 3720$ keV).

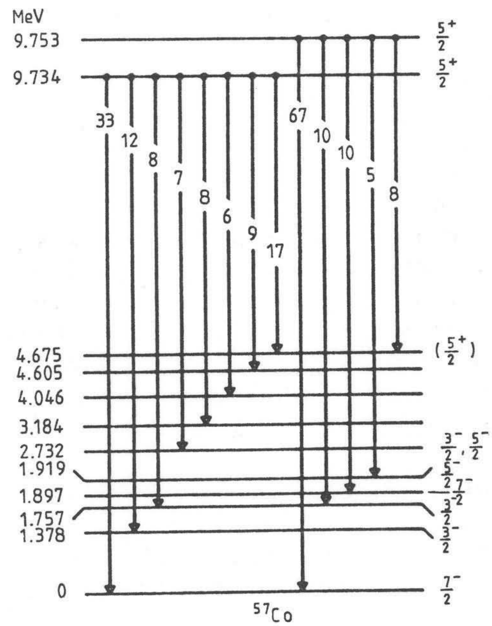

Figure 9. The gamma decay scheme of the $\frac{5}{2}^+$ IAS at $E_p = 3774$ and 3793 keV. The branching ratios are in per cent.

displacement energy $\Delta E_C = 8876 \pm 6$ keV (El-Kateb and Griffiths 1975) the expected position of the $d_{5/2}$ IAS is at $E_p^{Lab} = 3758$ keV. Both resonances are tentatively assigned $\frac{5}{2}^+$ and are identified as the split analogue of the 2506 keV ($\frac{5}{2}^+$) state in the parent nucleus ^{57}Fe. The 4675 keV state can be identified with the one observed by Rosner and Holbrow (1967) at 4689 ± 20 keV in the ^{56}Fe(^{3}He, d)^{57}Co reaction as a result of an $l = 2$ proton transfer. From preliminary angular distribution results the state at $E_x = 4675$ keV is probably the $T^<$ AIAS of the $d_{5/2}$ IAS. Table 3 shows a comparison between the predicted proton energies for the analogues of the 2455 keV, $J^\pi = \frac{9}{2}^+$, and 2506 keV, $J^\pi = \frac{5}{2}^+$, states with those resonances observed in the present work.

The resonance strength $\omega_\gamma = (2J+1)\, \Gamma_p \Gamma_\gamma / \Gamma$, where Γ_p, Γ_γ and Γ are the proton, gamma and total widths respectively, was estimated using the area from the thin-target γ

Table 3. Comparison of the $g_{9/2}$ and $d_{5/2}$ resonances observed in the present work with those expected for analogues of states of ^{57}Fe.

Parent state, ^{57}Fe		Expected analogue state, ^{57}Co			Observed state		
E^* (keV)	J^π	E_x† (keV)	E_p (keV)	J^π	E_x (keV)	E_p (keV)	J^π
2455	$\frac{9}{2}^+$	9712	3707	$\frac{9}{2}^+$	9682	3720	$\frac{9}{2}^+$
					9689	3727	$\frac{9}{2}^+$
2506	$\frac{5}{2}^+$	9763	3758	$\frac{5}{2}^+$	9734	3774	$\frac{5}{2}^+$
					9753	3793	$\frac{5}{2}^+$

† Based on $\Delta E_C = 8876 \pm 6$ keV (El-Kateb and Griffiths 1975).

yield. If it is assumed that $\Gamma_p \gg \Gamma_\gamma$, then the γ-ray width can be obtained from the resonance strengths. The partial widths $\Gamma_{\gamma'}$ (IAS→AIAS) was obtained from the branching ratio. The IAS–AIAS parameters and B(M1) transition strengths as a result of the present experiment for both $J^\pi = \frac{9}{2}^+$ fragments at $E_p = 3720$ and 3727 keV are summarised in table 4. The B(M1) strength summed over the two fragments is 2.81×10^{-2} Wu.

If the IAS and AIAS are assumed to be the ones that a $g_{9/2}$ particle weakly couples to an inert $J=0$, $T=2$ core, the B(M1) for the IAS→AIAS M1 transition is 1.98 Wu (this value has been calculated using the definition of the isovectorial M1 single-particle strength given by Maripuu (1969)). The measured B(M1) of 2.81×10^{-2} Wu is hindered by a factor of 0.014. Such strong hindrance of the IAS→AIAS M1 strength is due to the mixing between the antianalogue configurations and core-polarised configurations in which the active nucleons outside the doubly closed inert part of the core are coupled to a spin $J_c \neq 0$ (Maripuu 1970, Hirata 1970). A similar investigation on the ^{55}Co nucleus (Martin *et al* 1976) indicated that the measured B(M1) of 0.13 Wu for the $g_{9/2}$ IAS→AIAS is hindered by a factor of 0.048.

Such a decrease in B(M1) with increasing mass number can be explained by the effect of the unclosed $1f_{7/2}$ proton shell. In the Cu nuclei (Szentpétery and Szücs 1972) the unclosed $2p_{3/2}$ proton shell plays the same role as the unclosed $1f_{7/2}$ proton shell plays in the lighter 1f–2p shell nuclei such as ^{49}Sc and near the closure of the $1f_{7/2}$ proton shell as indicated by the present results on ^{57}Co.

In conclusion, the results of the present experiment indicate that the $g_{9/2}$ analogue resonance in ^{57}Co is split into two fragments over a 7 keV interval, contrary to the results of a previous experiment (Rangacharyulu *et al* 1979). The evidence for two $g_{9/2}$ resonances supports the results reported previously by Fodor *et al* (1978) although there is some disagreement on some of the decay branches of the resonances. In particular, no feeding of the 2723 keV level is observed in the present experiment and a 35% branching of the 4586 keV level to the ground state reported here was not observed by Fodor *et al* (1978). The strong reduction of the $g_{9/2}$ IAS→AIAS M1 strength in ^{57}Co can be explained as a consequence of mixing core excitations into the wavefunction describing the antianalogue final state for the radiative transition, thereby reducing their single-particle character. Such an explanation is supported by the fact that the $g_{9/2}$ AIAS has a low experimental spectroscopic factor $(2J+1)C^2S = 2.6$ (Banu *et al* 1978) from the ^{56}Fe(^{3}He, d)^{57}Co reaction.

Our data also indicate the presence of two $d_{5/2}$ IAS fragments in ^{57}Co. From the observed analogue–antianalogue splitting for both $g_{9/2}$ and $d_{5/2}$ states, a value of $V_1 =$ 114 MeV is obtained for the symmetry potential (Lane 1962), which is in good agreement with the systematics ($V_1 \sim 100$–150 MeV) in this mass region.

Table 4. B(M1) strength for IAS→AIAS transition of the $\frac{9}{2}^+$ analogue resonances in ^{57}Co of the 2455 keV, $J^\pi = \frac{9}{2}^+$ state of ^{57}Fe.

Resonance E_p (keV)	Resonance strength ω_γ (eV)	Γ_γ (eV)	Transition $E_i \to E_f$ (keV)	E_γ (keV)	Partial width $\Gamma_{\gamma'}$ (eV)	$B(\mathrm{M1}) = \Gamma_{\gamma'}/\Gamma_{\gamma w}$ (Wu)
3720	3.1 ± 0.5	0.31 ± 0.05	9682→4586	5096	0.062 ± 0.01	2.23×10^{-2}
3727	2.7 ± 0.5	0.27 ± 0.05	9682→4586	5103	0.016 ± 0.003	0.58×10^{-2}

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References

Arai E, Futakuchi M, Kamada H, Komaki J, Matsuzaki T, Ogawa M and Oguri Y 1982 *Nucl. Phys.* A **378** 259
Auble R L 1977 *Nuclear Data Sheets* **20** 327
Banu H, Sen Gupta H M and Watt F 1978 *Nucl. Phys.* A **307** 106
Comfort J R, Wasielewski P, Malik F B and Scholz W 1971 *Nucl. Phys.* A **160** 385
De Meijer R J, Plendl H S and Holub R 1974 *Atomic Data and Nuclear Data Tables* **13** 1
Din G U 1969 *Nucl. Phys.* A **134** 655
El-Kateb S and Griffiths G M 1975 *Z. Phys.* A **301** 189
Fodor I, Sziklai J, Kardon B, Rama Rao J, Beckert K, Herrmann F and Schobbert H 1978 *J. Phys. G: Nucl. Phys.* **4** 1117
Hirata M 1970 *Phys. Lett.* **32B** 656
Klapdor H V, Schrader M, Bergdolt G and Bergdolt A M 1975 *Nucl. Phys.* A **245** 133
Lane A M 1962 *Nucl. Phys.* **35** 676
Maripuu S 1969 *Nucl. Phys.* A **123** 357
—— 1970 *Phys. Lett.* **31B** 181
Martin D J, McLatchie W, Robertson B C and Szücs J 1976 *Nucl. Phys.* A **258** 131
Rangacharyulu C, Szoghy I M, St Pierre C and Ramavataram K 1979 *Phys. Rev.* C **19** 1762
Rosner B and Holbrow C H 1967 *Phys. Rev.* **154** 1080
Schrader M, Klapdor H V, Bergdolt G and Bergdolt A M 1975 *Phys. Lett.* **60B** 39
Szentpétery I and Szücs J 1972 *Phys. Rev. Lett.* **28** 378
Vervier J 1966 *Nucl. Phys.* **78** 497
Watson W A, Bilpuch E G and Mitchell G E 1981 *Phys. Rev.* C **24** 1992