1.E.1:3.A Nuclear Physics A170 (1971) 369—394; © North-Holland Publishing Co., Amsterdam

LEVEL STRUCTURE OF ^{58}Co VIA ^{55}Mn(^{4}He, nγ) PROMPT γ-RAY SPECTROMETRY

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Received 12 January 1971

Abstract: The level structure of ^{58}Co was investigated in some detail via prompt γ-ray energy and intensity measurements utilizing a NaI(Tl)–Ge(Li) anti-Compton spectrometer via the ^{55}Mn (^{4}He, nγ) reaction with ^{4}He^{++} energies in the range 7.5–12.5 MeV. Many of the γ-rays associated with levels in ^{58}Co were identified with the (^{4}He, nγ) reaction by means of nγ coincidence experiments employing an NE 213 scintillator as the fast-neutron detector and a 29 cm^3 Ge(Li) γ-ray detector. Characterization of many levels in ^{58}Co was achieved from $\gamma\gamma$ coincidence relationships established in on-beam $\gamma\gamma$ coincidence measurements in the ^{55}Mn (^{4}He, nγ) reaction at 8.00 and 12.50 MeV of bombarding energy employing a NaI(Tl) and a Ge(Li) detector. It was possible to observe the population of 28 excited states of ^{58}Co in this reaction. The levels at 1044.4, 1555.4, and 1757.6 keV have not been reported previously. The rest of the levels have been studied previously by means of (p, nγ), (p, γ), (n, p), (p, d), (^{3}He, d), (d, α) and (^{4}He, nγ) reactions. The present γ-ray decay information is used in conjunction with the results of previously reported (^{3}He, d) and (d, α) reactions to make definite J^π assignments to some stripping levels and to place limits for the J^π values for several other levels. When the level structure of ^{58}Co is compared with previously reported shell-model calculations, which included configurations of only lowest seniority, qualitative agreement for the first seven states is observed.

E | NUCLEAR REACTIONS ^{55}Mn(^{4}He, nγ), $E = 7.50$–12.50 MeV; measured E_γ, I_γ, nγ coinc. and $\gamma\gamma$ coin. ^{58}Co deduced levels, J, π. NaI(Tl), NE 213 scintillation detectors, Ge(Li) detectors; NaI(Tl)-Ge(Li) anti-Compton spectrometer.

1. Introduction

Although the levels in ^{58}Co are accessible by a variety of nuclear reactions, they have not been studied extensively by high-resolution techniques.

According to the shell model, ^{58}Co has seven protons (one hole) in the 1f$_{\frac{7}{2}}$ shell and three neutrons (one hole) in the 2p$_{\frac{3}{2}}$ shell. From this configuration, states with J^π of 2^+, 3^+, 4^+ and 5^+ are expected at low excitation energy. The complex low excitation energy spectrum of the ^{58}Co nucleus indicates, however, that such a simple shell-model description is not satisfactory for nuclei in this region. Thus, the three p$_{\frac{3}{2}}$, f$_{\frac{5}{2}}$ and p$_{\frac{1}{2}}$ closely spaced neutron orbits can simultaneously be occupied by the three neutrons lying outside the closed neutron shell. The coupling of these three

† This work was supported in part by the US Atomic Energy Commission under contract nos. AT(11-1)-1530 and AT(11-1)-1760.

neutron orbits with the $f_{\frac{7}{2}}$ proton hole will create twelve discrete states with J^{π} of $1^+, 2^+, 3^+, 4^+, 5^+$ and 6^+ of mixed configuration with an unequal contribution from all the possible neutron orbits.

Detailed studies of the properties of the states with excitation energy up to about 2 MeV may provide information about the extent to which neutron states of seniority three and occupation of the $g_{\frac{9}{2}}$ neutron orbit should be included in the configuration interaction calculations for nuclei in this region. The (^{4}He, nγ) reaction was used in the present study as it is expected to excite states with a wealth of J^{π} values.

The levels in ^{58}Co have been studied by the (p, d) reaction by several investigators [1-3] but with low-resolution techniques. The (d, t) neutron pick-up reaction leading to ^{58}Co has been investigated by Zeidman *et al.* [4]. The levels in ^{58}Co have been studied via the (^{3}He, d) reaction by Trier *et al.* [5] who measured angular distributions of the outgoing deuterons and assigned l_p values using a DWBA analysis. Trier *et al.* [5] reported 28 levels in ^{58}Co up to 3676 keV in excitation. The ^{58}Fe(p, nγ) reaction was studied by Gorodetzky *et al.* [6] who reported γ-ray branching ratios, for levels in ^{58}Co up to 1437 keV of excitation. Assignments of L-transfer in the (d, α) reaction have been made by Hjorth [7] for levels in ^{58}Co up to 3.48 MeV. A more detailed study of the decay properties of the ^{58}Co levels via the ^{57}Fe(p, γ) reaction at proton energies 1.2 – 1.7 MeV has been presented recently by Erlandsson and Marcinkowski [8]. These authors assigned 26 levels up to 3512 keV in ^{58}Co and reported γ-ray branching ratios for the decay of a few levels. During the course of the present investigation Tanaka *et al.* [9] reported the excitation of 36 levels up to 2441 keV in ^{58}Co by means of high-resolution neutron time-of-flight techniques. Also, very recently Robertson and Summers-Gill [10] reported on a study of the levels of ^{58}Co by the (^{4}He, nγ) reaction utilizing a Ge(Li) γ-ray detector. These authors reported 36 γ-rays to de-excite levels at 24.87, 52.96, 111.52, 365.52, 373.72, 457.40, 885.45, 1040.3, 1049.9, 1076.2, 1184.5, 1236.3, 1351.4, 1353.4, 1378.3, 1424.0, 1434.9, 1513.6, 1522.8, 1524.8, 1606.2 and 1928.5 keV.

The present investigation of the decay properties of levels in ^{58}Co by means of the ^{55}Mn(^{4}He, nγ) reaction was undertaken because it was believed that with the use of high-resolution and high-efficiency Ge(Li) detectors in conjunction with nγ and $\gamma\gamma$ in-beam coincidence experiments many uncertainties in the decay properties of many levels could be clarified and a consistent and detailed scheme constructed. Thus we were able to assign 65 γ-rays to de-excite 28 levels in ^{58}Co in an improved decay scheme.

2. Experimental procedures

In these experiments the external beam facility of the Washington University cyclotron was used to provide the 7.50–12.50 MeV ^{4}He ion beam required. The experimental arrangement employed has been described previously in some detail [11]. Since the lowest beam energy presently available at the Washington University cyclotron is 12.50 MeV, experiments at lower energies were performed by degrading the beam energy by means of high-purity Au foils. This resulted in a slight increase in the background radiations from the Coulomb excitation in the Au foils. Beam currents employed varied between 1–200 nA. In all the experiments a miniature scattering chamber was employed and itself served as a Faraday cup. In that arrangement the beam passed through a 4.0 mm lead collimator, then through the target and finally stopped in lead. For the energies employed in these experiments nuclear reactions in Pb that produced γ-rays (other than Pb X-rays) were not detected. In most instances the γ-ray detectors employed were collimated so that they observed only the target and neither the Pb collimator nor the Pb beam stop.

2.1. TARGET PREPARATION

The targets employed in the ^{55}Mn(^{4}He, nγ) studies were prepared by vacuum deposition of high-purity (> 99.99 %)^{55}Mn metal on a thick ($\approx$ 5 mg/cm^2) Au backing. The targets employed had thicknesses between 2–7 mg/cm^2.

2.2. DETECTION EQUIPMENT AND METHODS OF COUNTING

For γ-ray counting both NaI(Tl) and Ge(Li) detectors were employed. The NaI(Tl) detector was an integrally mounted 7.5 × 7.6 cm crystal. Two Ge(Li) detectors were used in these experiments. The first of them was a closed-end cylindrical Ge(Li) crystal with an active volume of 29 cm^3 and typical resolution (FWHM) of 2.8 keV at 1332 keV. The second detector was a true-coaxial Ge(Li) detector with an active volume of 40.8 cm^3 and a typical resolution of 2.1 keV at the 1332 keV line from ^{60}Co. The first detector was mounted in an anti-Compton arrangement with a 19.0 cm diameter by 12.7 cm long annular NaI(T1) detector. A full description of this system and its calibration has been given elsewhere [12]). This spectrometer was housed in a lead shield which was positioned on an angular-correlation table which allowed measurements to be taken between 0°–90° with respect to the beam direction. In all the precision γ-ray energy measurements the spectrometer was positioned at 90° with respect to the beam in order to minimize the distortion of the γ-peaks due to Doppler shift and broadening.

For nγ coincidence measurements the 29 cm^3 Ge(Li) detector was used without the anti-Compton shield in order to maximize the solid angle. For these nγ coincidence experiments the Ge(Li) detector was placed at $\approx$ 120° with respect to the beam at a distance of 4.0 cm from the target. For fast-neutron counting a 5.1 × 5.1 cm cylinder consisting of fast organic phosphor NE 213 was used as the detector and it was positioned at a distance of 3.0 cm from the target at 0° with respect to the beam direction. The scintillator was coupled to an RCA 8575 photomultiplier tube which was connected to an Ortec Model No. 264 photomultiplier base equipped with a fast-timing discriminator and preamplifier. Standard techniques of discrimination by pulse shape were employed. A schematic diagram of the circuitry employed in the nγ coincidence experiments has been given earlier [11]). In these experiments discrimination against γ-pulses was complete (> 95 %) for the accepted neutron energy range of 0.5 – 10.0 MeV. The prompt coincidence peak between the neutrons and γ-rays had a full width at 0.01 height of $\approx$ 90 ns for γ-rays in the energy range 100–2200 keV. Since the period between beam bursts at the frequency used was 140 ns, complete rejection of the random events from satellite bursts was possible. With the arrangement described, the overall random rate was not allowed to exceed 8 % of the total coincidence rate. This was possible because for the bombarding energies used the ^{55}Mn(^{4}He, nγ) reaction accounts for most of the total reaction cross section, thus allowing one to lower the beam intensity so that no more than one γ-ray producing event occurs per beam burst. It should be noted here that although timing resolutions of the order of 15 ns can be achieved to date with Ge(Li) detectors over a narrow energy range, this would not reduce the random events because of the pulsed character of the cyclotron beam giving a width of $\approx$ 4 ns for each burst. The random rate therefore limited the rate of accumulation of acceptable coincidence events to $\approx$ 30 c/s which in turn required periods of continuous data acquisition between 30–72 h for spectra of good statistical quality.

For $\gamma\gamma$ coincidence measurements a 7.6 × 7.6 cm NaI(Tl) and a 29 cm^3 Ge(Li) detector were employed. Here, the NaI(Tl) detector was positioned at $\approx$ 10 cm from the target at an angle of $\approx$ 120° with respect to the beam. To reduce the Compton background in the NaI(Tl) detector a collimator was employed that limited the γ-flux to the cone subtended by the target and the back face of the NaI(Tl) crystal. The Ge(Li) detector was positioned at $\approx$ 4.0 cm from the target at an angle of $\approx$ 120° with respect to the beam. The coincidence circuitry employed was the same as that used in the nγ coincidence experiments, except that the NE 213 scintillator was replaced by the NaI(Tl) detector and the section for the pulse-shape discrimination was bypassed. The $\gamma\gamma$ coincidence experiments were performed at 12.5 and 8.0 MeV of ^{4}He^{++} bombarding energies. The prompt-coincidence timing resolution expressed as full width at 0.01 maximum was $\approx$ 80 ns which again adequately separated the prompt from the random events due to the satellite bursts. With the random rate maintained below $\approx$ 10 % of the total coincidence rate it was possible to accumulate data at a rate of $\approx$ 60 c/s for periods of 25–35 h.

For pulse-height analysis a Nuclear Data Model No. 161 4096-channel two-parameter pulse-height analyzer was used. This analyzer was equipped with a buffer tape and a read-search control unit. In many experiments 4096-channel Compton-suppressed spectra were recorded directly in the memory of the analyzer. In the nγ coincidence experiments the neutron energy pulses were recorded in a 128-channel resolution and the Ge(Li) γ-ray pulses in a 2048-channel resolution. In the $\gamma\gamma$ coincidence experiments the analyzer was used in a 128 × 2048 or 256 × 1024 channel configuration.

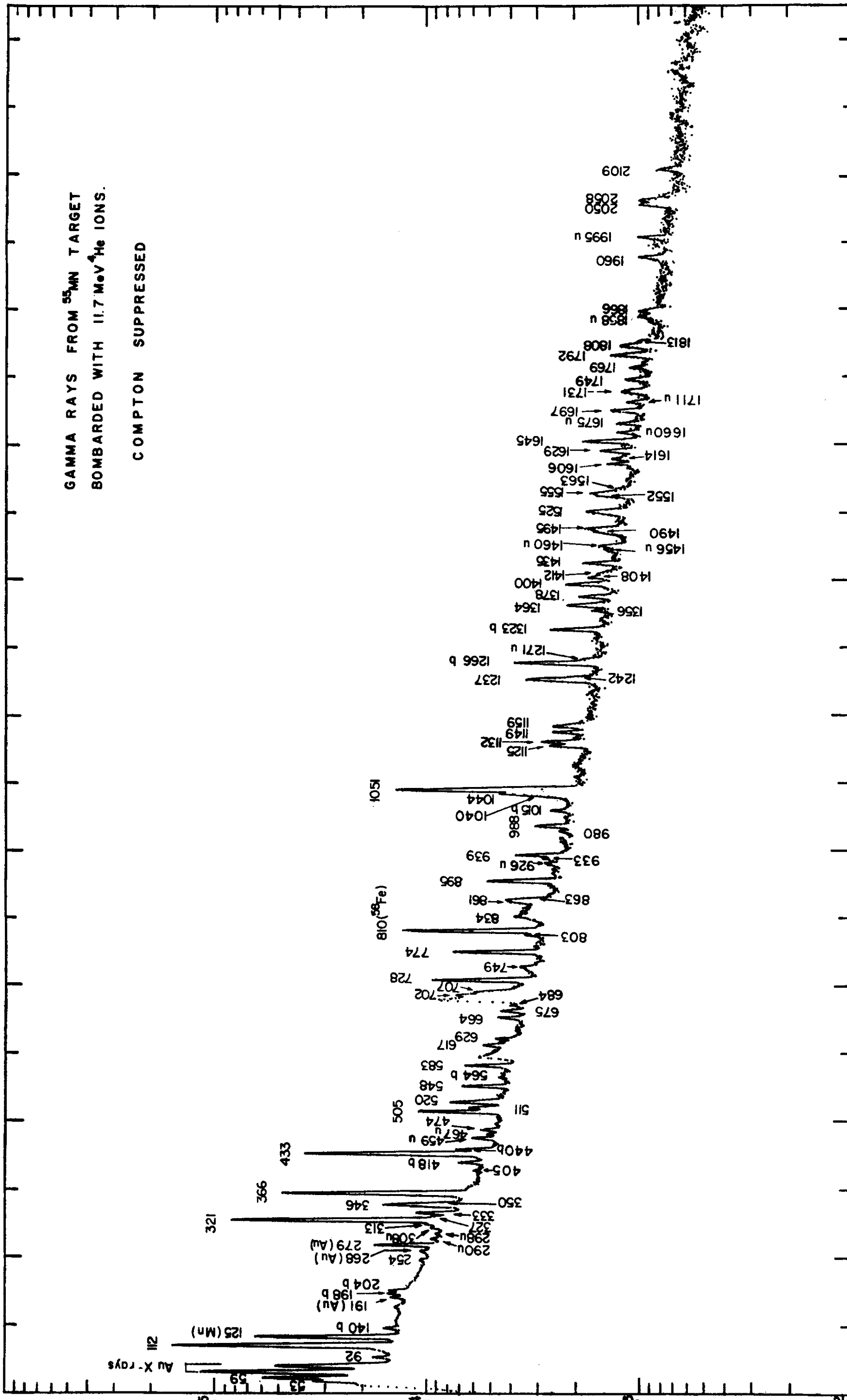

Fig. 1. Compton-suppressed spectrum of the prompt γ-rays emitted in the reaction ^{55}Mn(^{4}He, nγ)^{58}Co at 11.7 MeV of bombardment energy. This spectrum was recorded with the anti-Compton spectrometer positioned at 90° to the beam direction. Peaks labelled b originate from background radiation, peaks labelled (Au) come from Coulomb excitation in the Au degrading foil, peaks labelled u are unidentified and peaks labelled (Mn) and (^{58}Fe) come from the (^{4}He, α') and (^{4}He, α') reactions in ^{55}Mn.

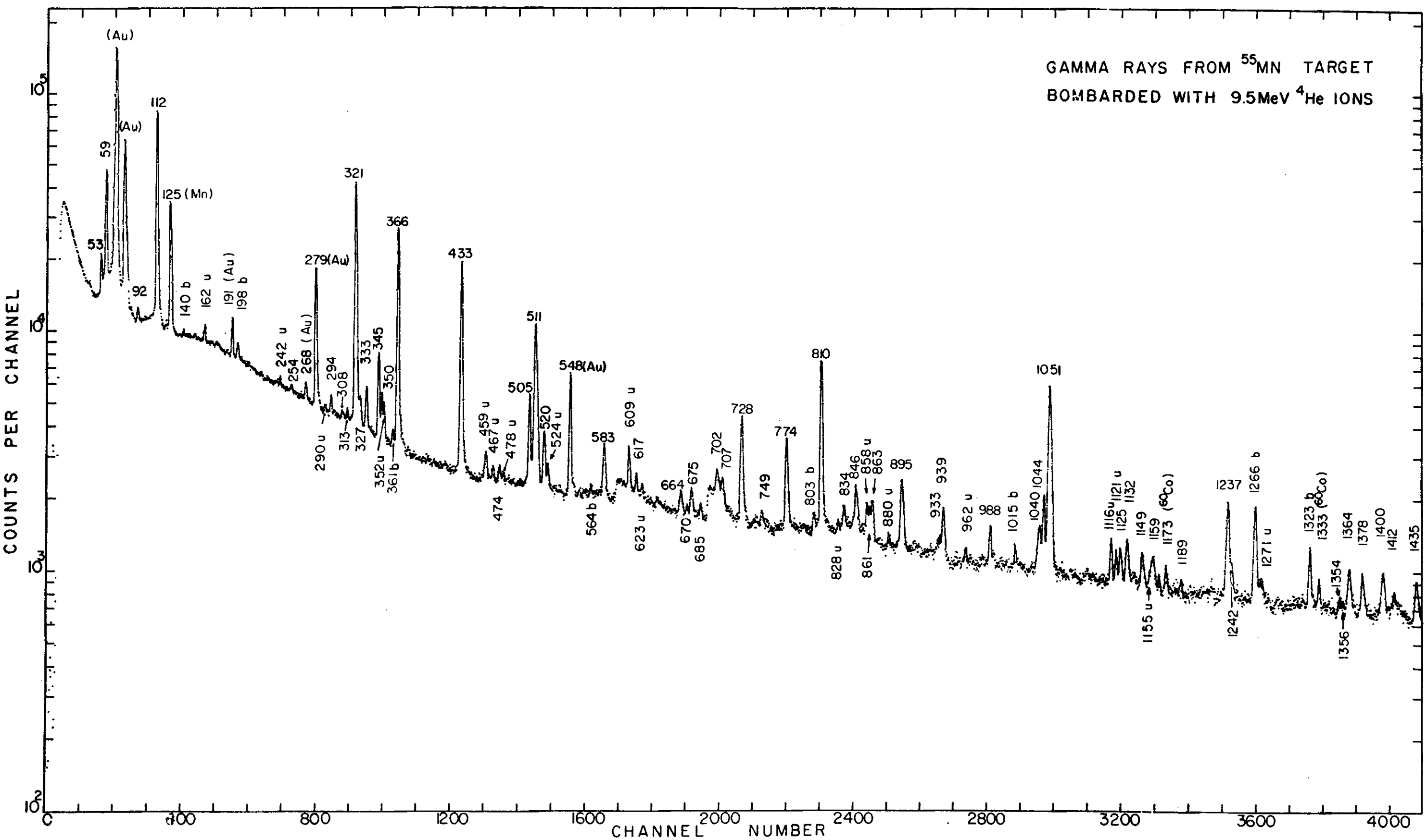

Fig. 2. A higher-resolution spectrum of the prompt γ-rays from the ^{55}Mn(^{4}He, nγ)^{58}Co reaction recorded with a 40.8 cm^3 Ge(Li) detector from a 9.5 MeV ^{4}He^{++} bombardment. Foreign peaks are labelled as in fig. 1.

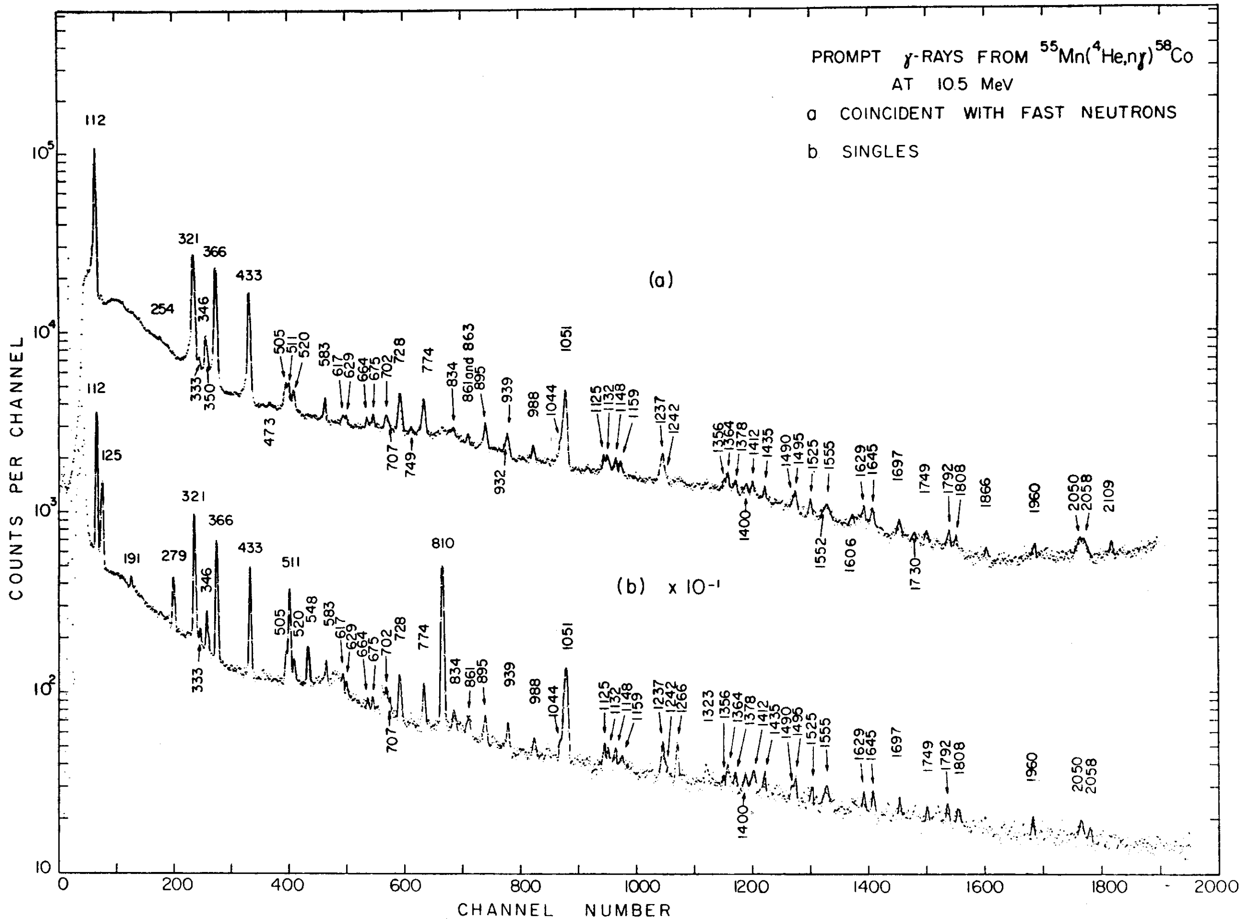

Fig. 3. Spectrum of the γ-rays from a 10.5 $^4He^{++}$ bombardment of ^{55}Mn recorded in prompt coincidence with fast-neutron pulses (upper spectrum). The lower spectrum (b) gives a sample of the prompt singles γ-rays recorded for a short time under the same gain for purposes of comparison. Some γ-rays at 125, 191, 279, 511, 548, 810, 1266 and 1323 keV are seen in the lower singles spectrum but not in the spectrum coincident with neutron pulses.

3. Experimental results

3.1. ENERGIES AND INTENSITIES OF SINGLE γ-RAYS

Singles measurements of the γ-rays emitted in 11.7 and 12.2 MeV of $^4He^{++}$ bombardments of ^{55}Mn were taken under Compton suppression at 90° to the beam direction with the 29 cm^3 Ge(Li) detector. Due to target thickness and degrading foils the beam energy in these experiments covered the range 12.0 − 12.5 MeV and 11.4 − 11.9 MeV. Fig. 1 shows a typical Compton-suppressed spectrum obtained in a 11.7 MeV bombardment of ^{55}Mn. Additional singles γ-ray spectra were obtained at 90° without Compton suppression employing a 40.8 cm^3 Ge(Li) detector. The bombardment energies in the latter experiments covered the ranges 8.2–8.7 and 9.2–9.7 MeV. Fig. 2 shows the spectrum of single γ-rays emitted when ^{55}Mn is bombarded with 9.5 MeV $^4He^{++}$. For different bombarding energies some of the γ-rays were seen intensified, and this intensification made some of the weakest γ-rays observable. Under the present experimental conditions there were several sources of background radiation. Firstly, the γ-radiation from induced short-lived radioactivity in the target was determined by pulsing the low-level rf supply of the master oscillator. For a period of 400 ms the beam was on, followed by another 400 ms period with the beam off. The on-beam and off-beam γ-radiation was stored in the first and second-halves of the 4096-channel pulse-height analyzer. The contribution from radioactivity was thus found to be negligible. Secondly, the background with the beam on, but without the target, was measured and it was also found to be negligible. A strong background radiation was found to originate from the gold foils that were used as target backing and for degrading the beam energy. Finally, significant background radiation was found to originate from nuclear reactions and radioactivity induced by the fast neutrons, emitted in the (^{4}He, n) reaction, in the materials surrounding the Ge(Li) detector.

Gamma-ray energies were measured from spectra taken at 90° to the beam direction to eliminate Doppler shifts. The γ-ray energies were calculated from calibrations determined by least-squares fitting of a third-order polynomial to the standard energies of γ-lines from ^{110}Ag, ^{228}Th, ^{226}Ra, ^{56}Co, ^{60}Co, ^{139}Ce, ^{57}Co and ^{88}Y sources that were counted simultaneously with the prompt γ-rays in several combinations. The energies of the γ-rays above 1 MeV, due to their low intensity, were determined only from several long mixed calibration measurements.

The γ-rays associated with the $^{55}Mn(^4He, n\gamma)$ reaction are summarized in table 1. Column 1 in table 1 gives the level numbers specifying each transition in ^{58}Co as established in this work. The energies given in column 2 are weighted averages from 3–10 different spectra. The energies given in column 3 are the transition energies obtained from the proposed level scheme by difference between level energies, which in turn have been obtained as weighted averages of the proper energy sum of observed γ-rays leading to these levels. The given uncertainties in the energy values of column 2 are the weighted averages of the deviations of the experimentally measured

TABLE 1

Energy and intensity of the γ-rays from ^{58}Co following the ^{55}Mn(^{4}He, nγ) reaction below 12.5 MeV

Transition	E_γ measured (keV)		E_γ from scheme [a] (keV)		I_γ (90°) from E_α = 11.7 MeV		Observed in nγ coincidence
2 → 0	53	1	53.1	2			
3 → 2	58.9		58.9		67	8	
6 → 4	92.0	2	91.9	2	1.1	1	
3 → 0	111.9	1	111.9	1	63	2	yes
4 → 3	254.0	2	254.0	1	0.6	1	yes
15 → 8	313.1	5	313.1	5	weak		
5 → 2	321.1	1	321.2	2	99	3	yes
16 → 10	326.6	4	326.9	5	0.8		
16 → 9	333.0	2	333.2	5	5.0	2	yes
6 → 3	345.9	1	345.9	2	14.2	6	yes
5 → 1	349.5	3	349.3	3	3.4		yes
4 → 0	365.9	1	365.9	1	65	2	yes
6 → 2	404.7	3	404.8	3	0.6	1	
6 → 1	432.9	1	432.9	3	73	3	yes
14 → 7	466.5	3	466.4	4	1.4	1	
	473.5	3			1.8	3	(yes)
22 → 10	504.8	1	504.7	3	20.8	10	yes
7 → 4	520.3	2	520.4	3	10.5	6	yes
8 → 6	582.9	2	582.8	4	7.7	4	yes
	616.9	2			3.4	4	yes
	629.2	4			1.5	2	yes
21 → 7	663.5	4	663.4	5	3.6	3	yes
9 → 5	670.1	5	670.2	3	weak		
8 → 4	674.7	2	674.7	3	3.9	4	yes
10 → 4	684.5	4	684.8	2	0.8	3	(yes)
11 → 5	702.0	2	702.0	2	11.6	6	yes
26 → 10	707.2	3	706.8	5	7.0	4	yes
12 → 6	727.6	2	727.5	3	28.5	10	yes
	748.6	6			1.5	4	yes
7 → 3	774.5	2	774.4	3	22.7	8	yes
	833.7	2			2.7	3	yes
7 → 1	861.2	2	861.4	4	6.5	6	yes
25 → 7	863.3	2	863.3	4	4.9	6	yes
14 → 6	894.8	2	894.9	3	17.7	6	yes
9 → 3	932.5	5	932.5	3	3.2	5	yes
10 → 3	938.6	2	938.8	2	8.9	10	yes
27 → 7	979.9	5	979.8	5	1.5	5	
15 → 4	987.9	2	987.8	4	7.1	10	yes
8 → 0	1040.3	4	1040.6	5	5.1	7	(yes)
9 → 0	1044.4	3 [b]	1044.4	3	} 14.8	7	yes
17 → 5	1044.4	3 [b]	1044.4	4			yes
10 → 0	1050.9	2	1050.7	2	100.0	2	yes
13 → 3	1125.2	2	1125.3	3	6.5	7	yes
12 → 2	1132.2	2	1132.3	3	8.6	9	yes
23 → 6	1148.5	3	1148.6	3	5.5	8	yes
20 → 4	1158.8	4	1158.7	4	5.7	5	yes
22 → 4	1189.4	4	1189.5	3	weak		
13 → 0	1237.4	3	1237.2	3	19.3	10	yes
15 → 3	1241.5	5	1241.8	4	3.0	7	yes

TABLE 1 (continued)

Transition	E_γ measured (keV)	E_γ from scheme [a] (keV)	I_γ (90°) from E_α = 11.7 MeV	Observed in nγ coincidence
15 → 0	1353.6 5	1353.7 4	2.5 6	(yes)
24 → 5	1356.1 5	1356.2 3	1.8 6	(yes)
24 → 4	1364.4 4	1364.5 3	8.5 5	yes
16 → 0	1378.1 4	1377.6 5	5.6 5	yes
	1399.8 3		8.7 6	yes
27 → 6	1408.1 4	1408.3 5	weak	yes
19 → 3	1411.6 5	1411.6 4	1.9 4	yes
18 → 0	1435.3 3	1435.2 3	6.4 5	yes
	1489.6 6		5.2 10	yes
23 → 3	1494.7 3	1494.5 3	7.9 9	yes
20 → 0	1524.6 3	1524.6 3	5.1 5	yes
	1551.9 4		5.4 8	yes
22 → 0	1555.3 3	1555.4 3	8.1 14	yes
	1562.8 6		1.1 5	(yes)
23 → 0	1606.3 4	1606.4 3	2.8 4	yes
	1614.4 6		2.3	(yes)
	1628.7 4		5.7 5	yes
26 → 3	1645.2 4	1645.6 4	10.1 15	yes
25 → 2	1696.9 5	1696.6 6	2.6 3	yes
24 → 0	1730.5 4	1730.5 5	1.1 3	yes
25 → 0	1749.4 5	1749.6 6	3.1 5	yes
	1792.1 5		8.2 10	yes
	1807.7 4		3.0 7	yes
27 → 2	1813.3 6	1813.1 5	1.3 3	
27 → 0	1866.0 10	1866.1 5	2.5 1	yes
	1960.2 8		2.2 4	yes
	2050.4 12		3.0 9	yes
	2058.1 11		2.9 9	yes
	2109.4 7		2.6 6	yes

[a]) This is the transition energy deduced from the proposed scheme for ^{58}Co. The level energies are weighted averages of energy sums leading to each level and are listed in table 4.
[b]) Transition that can be assigned in two places in the scheme.

energies from the average. The intensities given in column 4 were obtained from the Compton-suppressed spectrum taken at 11.7 MeV bombardment energy at 90° to the beam direction. The intensities are given relative to the intensity of the 1050.9 keV γ-ray, taken as 100. The given uncertainties in the intensities include only the statistical errors, and may therefore be underestimated. The relative intensity of the prompt γ-rays varies both with bombarding energy and angle of observation with respect to the beam direction. The branching ratios are independent of the bombarding energy, but they depend on the angular distribution pattern of the γ-rays. Since the angular distributions of the γ-rays were not determined, branching ratios are not reported.

The γ-rays that were observed as background, interfering or as unidentified radiations are summarized in table 2. The last two columns list the unidentified γ-rays ob-

TABLE 2

Summary of the observed γ-rays from background and from other competing reactions

Background		E_γ (keV) ^{197}Au(^{4}He, $\alpha'\gamma$)		E_γ (keV) unidentified	E_γ (keV) unidentified (cont)
140.0	3	68.0	K_α	162.2	858
198.0	5	77.9	K_β	241.9	880
204	1	191.3	3	289.6	925.8
361.0	5	268	1	294	962.2
417.8	3	279.3	3	298.2	980.0
439.8	3	548	1	308.2	1116
564	1			352	1121
803				458.9	1166
1015				466.5	1271
1266	1			477.6	1456.1
1323				523.6	1459.5
				531	1659.8
				609	1675
				623	1711
				828	1769
				846	1858

TABLE 3

Summary of the observed prompt $\gamma\gamma$ coincidence relationships in ^{58}Co following the ^{55}Mn(^{4}He, nγ) reaction

Fig. no.	NaI gate (keV)	γ-rays in the gate (keV)	γ-rays in coincidence (keV)
4a	55– 115	59, 92, 112	254, 346, 505, 520, 583, 728, 774, 895, 933, 939, 988, 1125, 1149, 1242, 1412, 1495, 1629, 1646
5d	250– 320	254, 313, 321, 327, 333	333, 520, 702, 1044, 1051
5a	320– 355	321, 327, 333, 346, 349, 366	92, 520, 675, 702, 988, 1044, 1149, 1159
5b	355– 388	346, 359, 366	92, 333, 520, 675, 988, 1149, 1159, 1365
5c	388– 455	405, 433	583, 728, 895, 1149
[a]	520– 590	520, 583	92, 346, 366, 433
[a]	590– 665	583, 617, 664, 670, 675	336, 366, 433, 520, 617, 774, 895, 1044, 1237
[a]	665– 735	663, 670, 675, 684, 702, 707, 728	92, 346, 366, 433, 520, 617, 895
6a	735– 803	728, 749, 774	346, 520, 664, 863, 895
[a]	803– 872	834, 861, 863	346, 861, 895, 1237
[a]	872– 938	861, 863, 895, 933, 939	327, 346, 366, 863, 895
6b	1010–1078	1041, 1044, 1051	321, 327, 333, 505
[a]	1010–1044	1041, 1044, 1051	321
[a]	1044–1078	1041, 1044, 1057	327, 505

[a]) Not shown in the illustrations.

served in the $^4He^{++}$ bombardments of ^{55}Mn. The first column lists the background γ-rays produced by secondary processes. The second column gives the γ-rays believed to be associated with the $^{197}Au(^4He, \alpha')$ reaction. Finally the 810.4 and 125.9 keV γ-rays are believed to be associated with the $^{55}Mn(^4He, p\gamma)$ and $^{55}Mn(^4He, \alpha'\gamma)$ reaction respectively.

3.2. NEUTRON-GAMMA COINCIDENCE MEASUREMENTS

Two nγ coincidence experiments were performed at 12.5 and 10.5 MeV bombardment energies. The data from the 10.5 MeV experiment were stored in a two-parameter configuration. In that experiment, the pulses from the neutron detector were recorded in a 128-channel resolution and the pulses from the Ge(Li) detector in a 2048-channel resolution. Fig. 3a shows the spectrum of the γ-rays obtained in coincidence with pulses of neutrons emitted at all energies at $E_\alpha = 10.5$ MeV. This spectrum was accumulated over a period of 72 h of continuous data acquisition. For comparison, a singles γ-ray spectrum taken under the same gain is shown in fig. 3b. Certain peaks, such as those at 125, 191, 279, 548, 810, 1266 and 1323 keV, are not seen in the nγ coincidence spectrum, indicating that these γ-rays have originated either from competing reactions, mainly (^{4}He, $\alpha'\gamma$) and (^{4}He, pγ), or from background radiation. However, a few γ-rays that were too weak to be observed in the nγ coincidence spectra were assigned to the ^{58}Co scheme on the basis of good energy agreement.

In the 10.5 MeV nγ coincidence experiment an attempt was made to establish coincidence relationships of γ-rays with neutron pulses of a limited energy range. For that purpose, the neutron detector was calibrated for energy according to the method proposed by Verbinski *et al.* [13]). However, establishment of nγ coincidence relationships with neutrons populating only the low-lying levels of ^{58}Co was not possible because, as it was observed, the cross section for direct population of the low-lying states was very small. Finally, it should be mentioned that both of the above nγ coincidence measurements were carried out at such a bombarding energy so that the (^{4}He, 2n) reaction was energetically excluded.

3.3. GAMMA-GAMMA COINCIDENCE MEASUREMENTS

In order to establish the $\gamma\gamma$ coincidence relationships, two in-beam $\gamma\gamma$ coincidence experiments were performed, following the ^{58}Co level excitation by the (^{4}He, nγ) reaction for two bombarding energies of 12.5 and 8.0 MeV. In these experiments, the coincidence events were accumulated in a two-parameter 128×2048 channel configuration for the NaI $\times$ Ge(Li) axes, respectively. Both axes covered approximately the same energy range of 30–2000 keV. It was observed that the coincidence spectra obtained in the experiment at lower bombarding energy were simpler and less ambiguous when compared with those obtained at 12.5 MeV. At higher bombardment energies the large number of states that are excited produce an intense continuous background, which contributes substantially to every coincidence gate. This causes many γ-rays to appear in true coincidence in every selected gate.

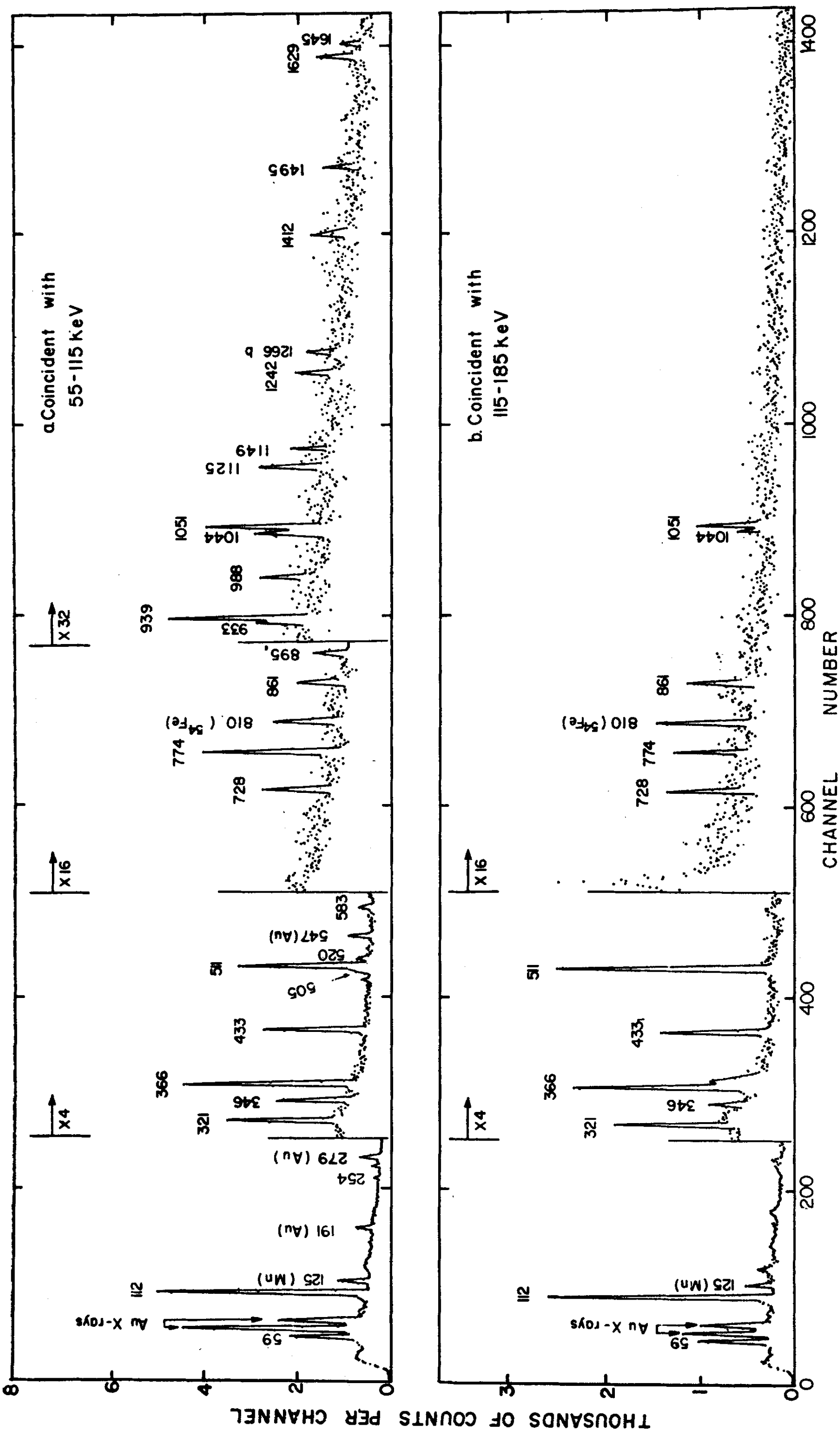

Fig. 4. Spectra of the prompt γ-rays from the ^{55}Mn(^{4}He, nγ) reaction recorded with the 29 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the NaI(Tl) detector.

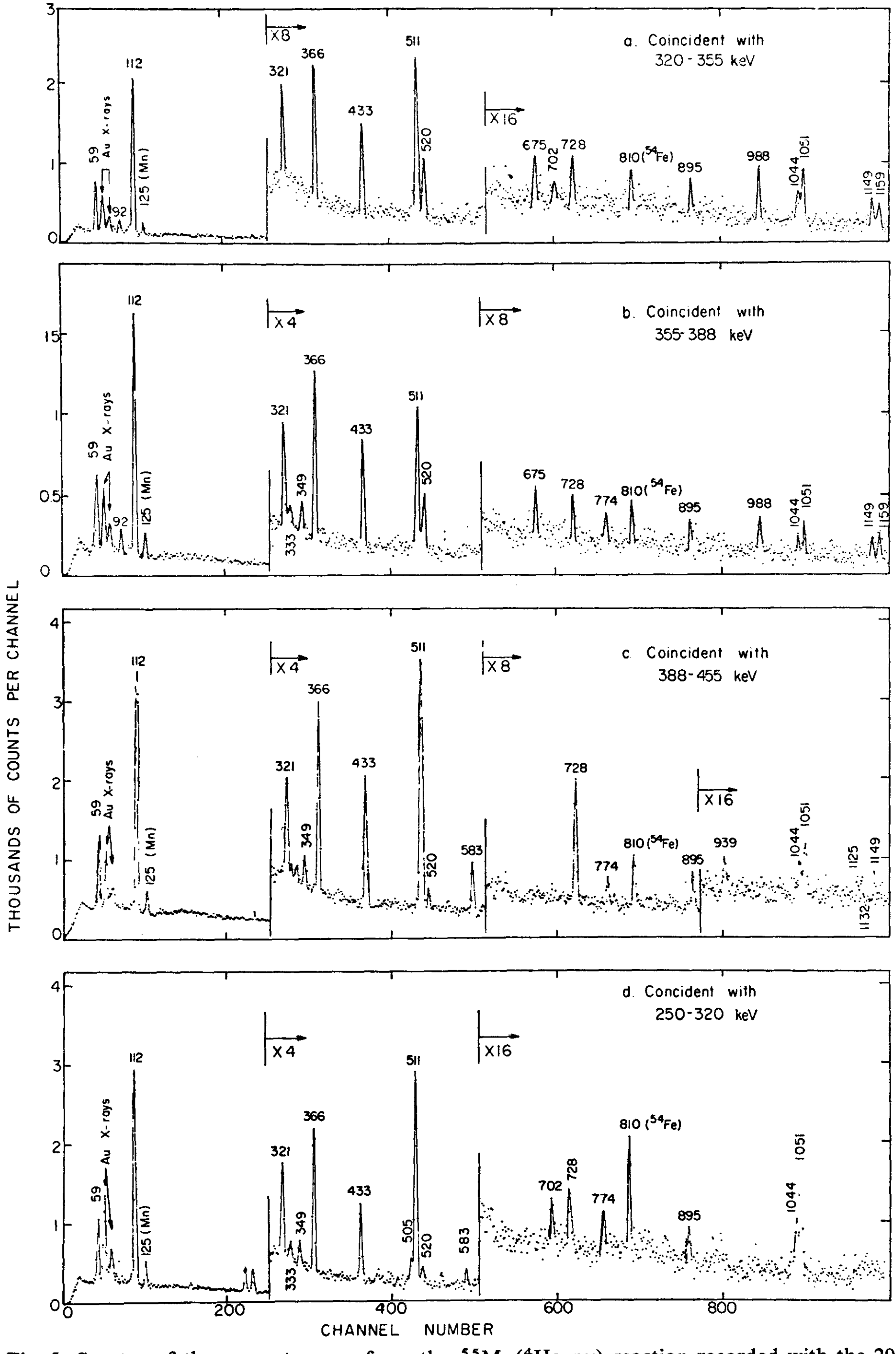

Fig. 5. Spectra of the prompt γ-rays from the $^{55}Mn(^{4}He, n\gamma)$ reaction recorded with the 29 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the NaI(Tl) detector.

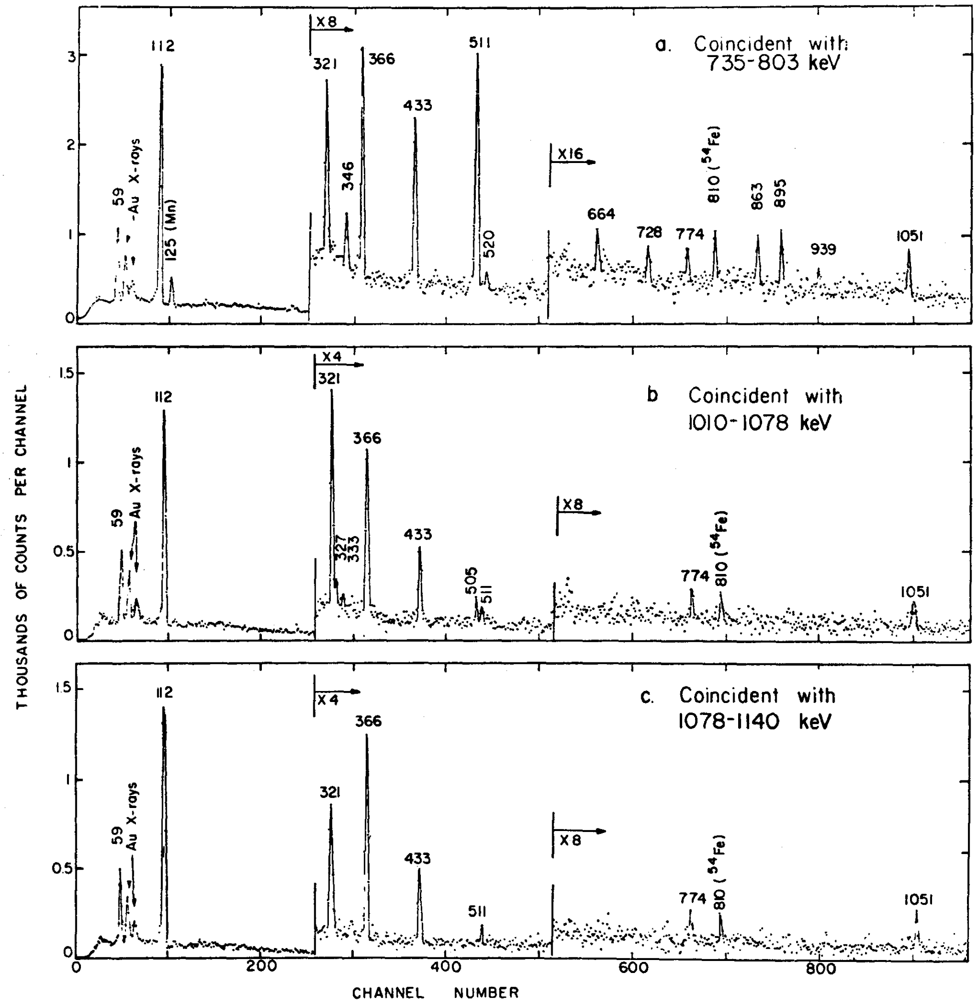

Fig. 6. Spectra of the prompt γ-rays from the ^{55}Mn (^{4}He, nγ) reaction recorded with the 29 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the NaI(Tl) detector.

The established γγ coincidence relationships are summarized in table 3, and the spectra of the γ-rays in coincidence with the most prominent γ-peaks are shown in figs. 4–6. The second column in table 3 gives the energy range in the gated NaI axis, the third column lists the γ-ray peaks in the gate and the last column lists the γ-rays observed in the coincidence spectrum of each gate.

4. Construction of the decay scheme and assignment of J^π values

On the basis of the evidence obtained in this work it was found that most of the γ-rays observed in 8.0–12.5 MeV $^{4}He^{++}$ bombardment of ^{55}Mn were associated

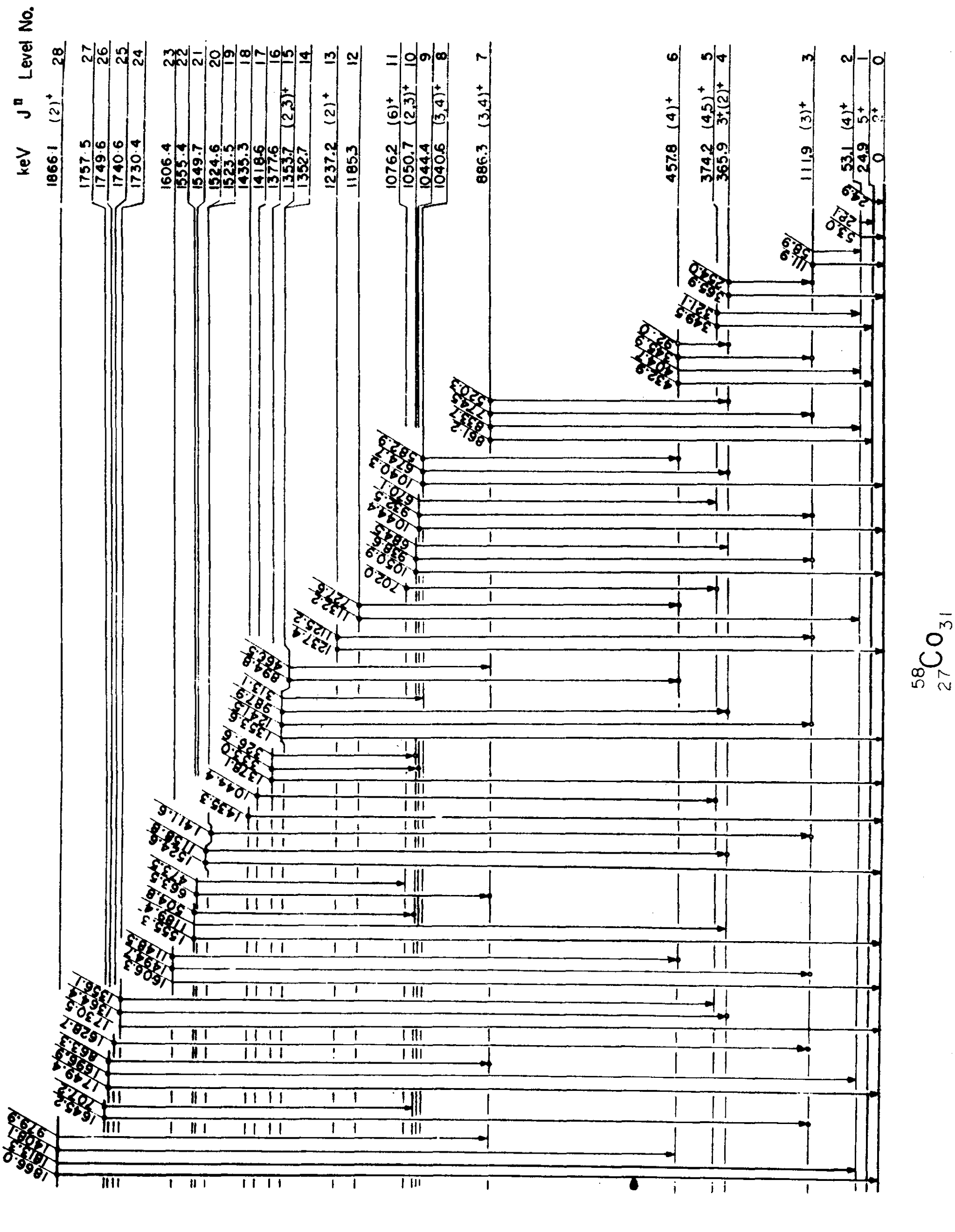

Fig. 7. Proposed scheme for the de-excitation of levels in ^{58}Co deduced from the $^{55}Mn(^4He, n\gamma)$ reaction below 12.5 MeV. The closed circles indicate observed coincidences with neutron pulses and open circles indicate established $\gamma\gamma$ coincidence relationships.

with the decay of levels in ^{58}Co. The proposed decay scheme is shown in fig. 7 and the energy levels deduced from this work are compared with previous results in table 4. Column 1 in table 4 gives the level number, column 2 gives the level

TABLE 4

Summary of levels in ^{58}Co populated in the ^{55}Mn(^{4}He, nγ) reaction

Level no.	This work (keV)	Ref. [19] (keV)	Ref. [10] (keV)	Ref. [8] (keV)	Ref. [9] (keV)	J^{π} this work
0	0	0	0	0	0	2^+
1	24.9 2	24.9	24.87	25	25 2	5^+
2	53.1 2	54	52.96	53.6 10	52 3	$(4)^+$
3	111.9 1	116	111.52	112.2 10	112 3	$(3)^+$
4	365.9 1	} 367	365.52	} 365.9 10	} 366	$3^+, (2)^+$
5	374.2 2		373.72			$(4, 5)^+$
6	457.8 2	432	457.40		455 3	$(4)^+$
7	886.3 3		885.45		884 4	$(3, 4)^+$
8	1040.6 5		1040.3		1037 4	$(3, 4)^+$
9	1044.4 3				1044 5	$(2^+, 3^+, 4^+)$
10	1050.7 2	1051	1049.9	1048.5 10		$(2, 3)^+$
11	1076.2 2		1076.2			$(6)^+$
12	1185.3 3	1188	1184.5		1180 5	$(3, 4, 5)^+$
13	1237.2 3	1238	1236.3	1235.8 10	1236 5	$(2)^+$
14	1352.7 3		1351.4	} 1351.9 10	} 1352 5	$(3\text{–}6)^+$
15	1353.7 4		1353.4			$(2, 3)^+$
16	1377.6 5	1378	1378.3	1376.7 10	1376 5	$(0\text{–}4)^+$
17	1418.6 5				1415 5	$(3, 4, 5)^+$
18	1435.3 3	1438	1434.9	1433.7 10	1433 5	$(0, 1, 2)^+$
19	1523.5 4		1522.8	} 1522.4 10	} 1520 5	
20	1524.9 4		1524.8			
21	1549.7 3	} 1552			1545 5	
22	1555.4 3					
23	1606.4 3	1615	1606.2		1602 5	$(2, 3, 4)^+$
24	1730.4 3			1730.2 10	1725 5	
25	1740.6 4	1743			1734 5	
26	1749.6 5				1745 5	$(2^+, 3^+, 4^+)$
27	1757.5 4					
28	1866.1 5	1870			1864 6	$(2)^+$

energy in keV from this work, obtained as weighted average of the sums of γ-ray energies that de-excite that level, columns 3–6 give the level energies from refs. [19, 10, 8, 9], respectively, and the last column gives the J^{π} assignments deduced from this work. The arguments that led to these assignments and comments on the properties of some of the individual levels are given below.

The ground state. The total angular momentum of the ground state has been measured by paramagnetic resonance and by $\beta\gamma$ circular-polarization techniques [14]) and was found to be 2(⁺).

The 24.9 keV *level.* Strauch [15]) first established the existence of an isomeric state levels with an intensity ratio of $\approx 100:1$. This information limits J^π for this level to 1^+, 2^+ or 3^+. The value of 1^+ can be eliminated as a possibility on the basis of observed γ-decay from a level at 457.8 keV shown below to be 4^+, leaving the 2^+ and 3^+ values as the most probable ones.

The 374.2 keV *level.* A level at 367 keV, probably a member of an unresolved doublet, has been assigned [19]) as $(3)^+$ on the basis of an $L = 2+4$ assignment from the (d, α) reaction [7]) and an $l_p = 3$ from the (^{3}He, d) reaction [5]). In the present work two γ-rays at 321.1 and 349.5 keV have been assigned to de-excite this level. Both these γ-rays were observed in prompt coincidence with neutrons and have been assigned to populate two isomeric states at 53.1 keV and 24.9 keV, respectively. Robertson *et al.* [10]) have observed the 321 keV γ-ray in delayed coincidence with the 53.1 keV γ-ray. Since this level decays only to levels with J^π of 4^+ and 5^+ below, its J^π value can be limited to $(3, 4, 5)^+$. The considerably larger intensity of the 321.2 keV γ-ray to the 4^+ keV level and the absence of decay of the 2^+ ground state make the 3^+ value unlikely. This leaves the $(4, 5)^+$ as the most probable assignment for this level.

The 457.8 keV *level.* This level has been observed in the (p, n), (d, t) and (p, d) reactions [9, 10, 3]). From their (p, d) study Ball and Sweet [3]) favor a 4^+ assignment for this level. In the present work four γ-rays at 92.0, 345.9, 404.7 and 432.9 keV have been assigned to de-excite this level. The 345.9 and 432.9 keV γ-rays have been observed in coincidence with neutrons. The 92.0 keV γ-ray was not seen in the nγ coincidence spectra because of the lower-level discriminator position in the Ge(Li) detector. The 404.7 keV γ-ray is rather weak to be observed in coincidence with neutrons. The 92.0 and 345.9 keV γ-rays were observed in coincidence with the 365.9 and 111.9 keV γ-rays, respectively. Since this level decays to levels with $J^\pi = 3^+, 4^+$ and 5^+ below, its J^π value can be limited to $3^+, 4^+, 5^+$. The fact that this level decays to the 5^+ 24.9 keV level and to the 4^+ 53.1 keV level with an approximate branching ratio of 117:1, helps eliminate the 3^+ as a possibility. A 3^+ value for the 457.8 keV level would require an E2 character from the 423.9 keV transition and this gives from single-proton estimates $(\text{E2}, 433)/(\text{M1}, 405) = 3\times10^{-4}$ or $(\text{E2}, 433)/(\text{E2}, 405) = 1.4$, values that make the 3^+ assignment unlikely. This leaves the 4^+ value as the most probable one for this level.

The 886.3 keV *level.* This level has been observed in the (p, n) reaction [9]) and was reported from the (d, t) study [10]) to have $l_n = 1+3$. The four γ-rays at 520.3, 774.5, 833.7 and 861.2 keV have been observed in coincidence with the fast-neutron pulses and have been assigned to de-excite this level. The 520.3 and 774.5 keV γ-rays were observed in coincidence with the 365.9 and 111.9 keV γ-rays, respectively. Furthermore, the 833.7 and 861.2 keV γ-rays have been assigned on the basis of energy agreement to de-excite this level and populate the two isomeric states. Since this level decays to levels with $J^\pi = 3^+, 4^+, 5^+$ below, its J^π value can be limited to $3^+, 4^+$, or 5^+. The fact that a $J^\pi = 2^+$ level at 1866.1 keV de-excites to this level can be utilized to exclude the 5^+ possibility.

The 1040.6 keV *level.* This level has been assigned in the (^{4}He, nγ) reaction and a

$J^\pi = 3^+$ or 4^+ was proposed [10]). In the present work three γ-rays at 582.9, 674.7 and 1040.3 keV were assigned to de-excite this level. These three γ-rays have been observed in coincidence with fast neutrons. The 582.9 and 674.7 keV γ-rays were observed also in coincidence with the 432.9 and 365.9 keV γ-rays, respectively. A level at 1050 keV has been reported from a (d, t) study [10]) to have $l_n = 1+3$. The closely lying triplet at 1040.6, 1044.4 and 1050.7 keV assigned in the present work makes doubtful the J^π and l-values assigned from the direct-reaction work. Since the 1040.6 keV level decays to levels with $J^\pi = 2^+$, $(2^+, 3^+)$ and (4^+) levels below, its J^π value can be limited to 2^+, 3^+ and 4^+. The fact that this level decays to the (4^+) 457.8 keV level and to the 2^+ ground state with an approximate branching ratio of 1.5:1 helps to eliminate the 2^+ possibility. A 2^+ value for the 1040.6 keV level would require an E2 character for the 582.9 keV transition and this gives the single-proton estimates (E2, 583)/(M1, 1040) $= 7.7\times10^{-5}$ or (E2, 583)/(E2, 1040) $= 5.5\times10^{-2}$, values that render the 2^+ possibility as unlikely.

The 1044.4 keV *level.* Three γ-rays at 670.1, 932.6, and 1044.4 keV have been assigned to de-excite this level. The 932.6 and 1044.4 keV γ-rays have been observed in coincidence with fast neutrons. The 932.6 keV γ-ray has also been observed in coincidence with the 111.9 keV γ-ray. The fact that this level decays to levels with J^π values of 2^+, 3^+ and $(3^+, 4^+, 5^+)$ below is used to set a limit $(2-4)^+$ for J^π. A 1044.4 keV γ-ray has also been assigned to de-excite a different level at 1418.6 keV.

The 1050.7 keV *level.* A level at 1049 keV has been observed in the (^{3}He, d) reaction [5]) with an $l_p = 1$ value. In the present work the 1050.6 keV level was established on the evidence of the 938.6 keV γ-ray observed in coincidence with the 111.9 keV transition. Two more γ-rays at 684.5 and 1050.9 keV have been assigned to de-excite this level on the basis of good energy agreement. The 938.6 and the 1050.9 keV γ-rays have also been observed in coincidence with the neutron pulses. The mode of decay of this level limits the J^π value for this level to $(1-4)^+$. The values of 1^+ and 4^+ seem unlikely due to strong population of the 2^+ and 3^+ levels below and absence of population of the 4^+ or 5^+ levels below.

The 1076.2 keV *level.* This level has been assigned an $l_n = 3$ value from the (d, t) reaction [10]). In the present work this level has been established on the evidence of a 702.0 keV γ-ray that has been observed in coincidence with neutrons and with the 321.1 keV γ-ray. Since this level was seen to decay only to the $(4, 5)^+$ level at 374.2 keV a broad limit of $(3-6)^+$ can only be set for its J^π value. The fact, that no $l_n = 1$ component has been observed in the (d, t) reaction [10]) favors a $J^\pi = 6^+$ assignment for this level.

The 1185.3 keV *level.* This level has been assigned a $J^\pi = (3^+, 4^+, 5^+)$ value from the (d, α) reaction [7]) and it has also been reported to be populated in the (p, n) reaction [9]). In the present work two γ-rays at 727.6 and 1132.2 keV have been assigned to de-excite this level. These two γ-rays have been observed in coincidence with neutrons and the 727.6 keV γ-ray in coincidence with the 432.9 keV γ-ray. The decay mode of this level is consistent with $J^\pi = (3^+, 4^+, 5^+)$ values proposed in the (d, α) study [7].

The 1237.2 keV *level.* This level has been assigned an $l_p = 1$ value in the (^{3}He, d) reaction [5]) and it has also been reported to be populated in the (p, n) reaction [9]), the (p, γ) reaction [8]), the (^{4}He, nγ) reaction [10]) and the (p, nγ) reaction [6]). These findings are confirmed in this work by the observation of the 1125.2 keV γ-ray in coincidence with the 111.9 keV γ-ray. The 1125.2 and the 1237.4 keV γ-ray that have been assigned to de-excite this level have also been observed in coincidence with fast-neutron pulses. The decay mode of this level is consistent with the 1^+ or 2^+ values reported in ref. [19]), although the 1^+ value is unlikely in view of the strong population of the 3^+ level at 111.9 keV.

The 1352.7 keV *level.* This level has been observed in the (p, n) reaction [9]), the (p, γ) reaction [8]), and the (^{4}He, nγ) study [10]). In the present work two γ-rays at 466.5 and 894.8 keV have been assigned to de-excite this level. The 894.8 keV γ-ray has been observed in coincidence with neutrons and with the 432.9 keV γ-ray. The 466.5 keV γ-ray is rather weak to be observed in the nγ coincidence spectra and it has been assigned on the evidence of the proper energy difference to populate the level at 886.3 keV. Since it decays only to 4^+ and $(3^+, 4^+)$ levels below its J^π value may be limited to $(3, 4, 5, 6)^+$.

The 1353.7 keV *level.* This level has been observed in the (^{4}He, nγ) study [10]). From the present work four γ-rays at 313.1, 987.9, 1241.5 and 1353.6 keV have been assigned to de-excite this level. The 987.9 and 1241.4 keV γ-rays were observed in coincidence with neutron pulses and with the 365.9 and the 111.9 keV γ-rays, respectively. The 1353.7 keV level decays to states with J^π values of 2^+, 3^+, $(2^+, 3^+)$ and $(3^+, 4^+)$ below and this fact can be utilized to limit the J^π for this level to $(2, 3)^+$.

The 1377.6 keV *level.* A level at 1380 keV has been assigned an $l_p = 1$ from the (^{3}He, d) reaction [5]). This level has been also observed by the (p, nγ) reaction [6]), by the (p, n) reaction [9]), the (^{4}He, nγ) reaction [10]), and the (^{3}He, p) reaction [18]). In the present work, three γ-rays at 326.6, 333.0 and 1378.1 keV have been assigned to de-excite this level. The two last γ-rays have also been observed in coincidence with neutrons. Only a broad limit of $(0-4)^+$ can be set for the J^π value of this level on the basis of its decay characteristics. The $l_p = 1$ value from (^{3}He, d) reaction indicates a $J^\pi = 0^+, 1^+, 2^+$ value, while a $J^\pi = (0)^+$ has been assigned to this level in the (^{3}He, p) reaction [18]). However, in the latter-mentioned studies the 1377.6 keV level was not resolved from the doublet at 1352.7 and 1353.7 keV. Furthermore, in the angular distribution of the deuterons populating the 1380 keV state [5]) an $l_p = 3$ value cannot completely be excluded. For these reasons no further limit than $(0-4)^+$ can be placed for the J^π value of this level.

The 1418.6 keV *level.* A level of approximately this energy has been reported in the (p, n) reaction study [9]), and a $J^\pi = (3^+, 4^+, 5^+)$ has been assigned for a level observed at 1410 keV from the (d, α) reaction [7]). In the present work, this level has been assigned on the evidence of the 1044.4 keV γ-ray that was observed in coincidence with the 321.1 keV γ-ray. No other de-excitation mode of this level was observed. This limited information for its decay mode is not contradictory with the $J^{\pi} = (3^+, 4^+, 5^+)$ value that has been assigned to this level from the (d, α) reaction study [7]).

The 1435.3 keV *level.* This level has been observed in the (p, nγ), the (p, n) and the (^{4}He, nγ) reaction studies [6, 9, 10]). A level of 1451±15 keV was reported from the (^{3}He, d) study [5]) to have $l_p = 1$, which would require a $J^{\pi} = 0^+, 1^+, 2^+$ value for this level. In this work the 1453.3 keV γ-ray was assigned, on the basis of good energy agreement, to de-excite this level and populate the ground state. The 1453.3 keV γ-ray was further observed in coincidence with neutrons. The limited information for its decay mode is not contradictory with the $J^{\pi} = 0^+, 1^+, 2^+$ value assigned to this level from the (^{3}He, d) reaction study [5]).

The 1523.5 keV *level.* This level has been observed in the (p, γ), (p, n) and (^{4}He, nγ) reaction studies [8-10]). We have observed only one γ-ray at 1411.6 keV to de-excite this level. This γ-ray has been observed in coincidence with neutrons and with the 111.9 keV γ-ray. From this limited information no definite J^{π} assignments are possible.

The 1524.9 keV *level.* This level has been previously observed in the (^{4}He, nγ) reaction study [10]). In the present work two γ-rays at 1158.8 and 1524.6 keV have been assigned to de-excite this level. Both have been observed in coincidence with neutron pulses and the 1158.8 keV γ-ray has been seen in coincidence with the 365.9 keV γ-ray.

The 1549.6 keV *level.* A level at 1547±5 keV has been previously observed in the (p, n) reaction study [9]). In this work two γ-rays at 473.5 and 663.5 keV have been assigned to de-excite this level. The 473.5 keV γ-ray is rather weak to be seen in the nγ coincidence with spectra. The 663.5 keV γ-ray, however, has been observed in coincidence with neutron pulses and with the 774.5 keV γ-ray.

The 1555.4 keV *level.* A level at 1552 keV excitation has been observed in the (d, α) reaction and a $J^{\pi} = (1^+, 2^+, 3^+)$ has been assigned [7]). However, the four closely spaced levels at 1523.5, 1524.9, 1549.7 and 1555.4 keV that have been assigned in the present work were not resolved in the (d, α) reaction study. Three γ-rays at 504.8, 1189.4 and 1555.4 keV have been assigned to de-excite this level. The 1189.4 keV γ-ray is rather weak to be observed in the nγ coincidence spectra. The 504.8 and 1555.4 keV γ-rays were observed in coincidence with neutron pulses and the 504.8 keV γ-ray was seen also in coincidence with the 1050.9 keV γ-ray.

The 1606.4 keV *level.* This level has been observed in the (p, n) and the (^{4}He, nγ) reaction studies [9, 10]). An $l_p = (1)$ has been suggested for this level in the (^{3}He, d) reaction [5]), although this assignment seems uncertain. We have observed three γ-rays at 1148.5, 1494.7 and 1606.3 keV to de-excite this level. The 1148.5 and 1494.7 keV γ-rays have been observed in coincidence with neutrons and with the 432.9 and 111.9 keV γ-rays respectively. The 1606.3 keV transition to the ground state is rather weak to be observed in the nγ coincidence spectra. The fact that this level decays only to levels with J^{π} value of 2^{+}, 3^{+} and 4^{+} below is utilized to limit its J^{π} assignment to 2^{+}, 3^{+} or 4^{+}.

The 1730.4 keV *level.* This level has been observed in the (p, γ) and (p, n) reaction studies [8, 9]. In the present work three γ-rays at 1356.1, 1364.4 and 1730.5 keV have been assigned to de-excite this level. The 1356.1 and 1364.4 keV transitions have been observed in coincidence with neutron pulses and the 1364.4 keV γ-ray has been seen in coincidence with the 365.9 keV γ-ray. The 1730.5 keV transition to the ground state is rather weak to be seen in the nγ coincidence spectra.

The 1740.6 keV *level.* This level has been observed in the (p, γ) reaction [8]. A level at 1734 keV excitation has been observed in the (p, n) reaction [9]. A level at 1743 ± 20 keV has been reported from the (^{3}He, d) reaction [5] to have $l_p = 1$ which would require a J^{π} value of 0^{+}, 1^{+} or 2^{+} for this level. However, it is rather impossible to certainly associate this value with any of the three closely spaced levels at 1730.4, 1740.6 and 1749.6 keV excitation. In this work the 1628.7 keV γ-ray was observed in coincidence with neutrons and with the 111.9 keV γ-ray and was assigned to de-excite this level.

The 1749.6 keV *level.* A level at 1745 keV excitation has been observed in the (p, n) reaction study [9]. Three γ-rays at 863.3, 1696.9 and 1749.4 keV have been assigned to de-excite this level. These three γ-rays have been seen in coincidence with neutrons and the 863.3 keV γ-ray has been observed in coincidence with the 774.5 keV γ-ray. The fact that this level decays to levels with J^{π} values of 2^{+} and 4^{+} below is utilized to limit its J^{π} assignment to 2^{+}, 3^{+} or 4^{+}.

The 1757.5 keV *level.* This level has not been previously reported. Two γ-rays at 707.2 and 1645.2 keV have been assigned to de-excite this level. Both have been seen in coincidence with neutron pulses and the 1645.2 keV γ-rays has been observed in coincidence with the 111.9 keV γ-ray.

The 1866.1 keV *level.* A level at 1864 keV has been observed in the (p, n) reaction [9]. A level at 1870 keV was reported from the (^{3}He, d) study [5] to have a J^{π} value of 1^{+} or 2^{+}. In the (d, α) reaction [7] a level that has been observed at 1880 keV was assigned a J^{π} value of 1^{+}, 2^{+} or 3^{+}. Four γ-rays at 979.9, 1408.1, 1813.3 and 1869.0 keV have been assigned in this work to de-excite this level. The two 1408.1 and 1866.0 keV γ-rays have been observed in coincidence with neutrons. All these four γ-rays have been assigned on the basis of proper energy differences. On the evidence of the $l_p = 1$ from the (^{3}He, d) reaction [5] only the values $J^{\pi} = 0^{+}$, 1^{+} or 2^{+} are possible for this level. The fact that this level decays to a level with $J^{\pi} = 4^{+}$ below is used to limit its J^{π} assignment to 2^{+}.

5. Discussion

The present results are generally in good agreement with previous reaction studies, while in some cases previously reported levels were shown to be unresolved

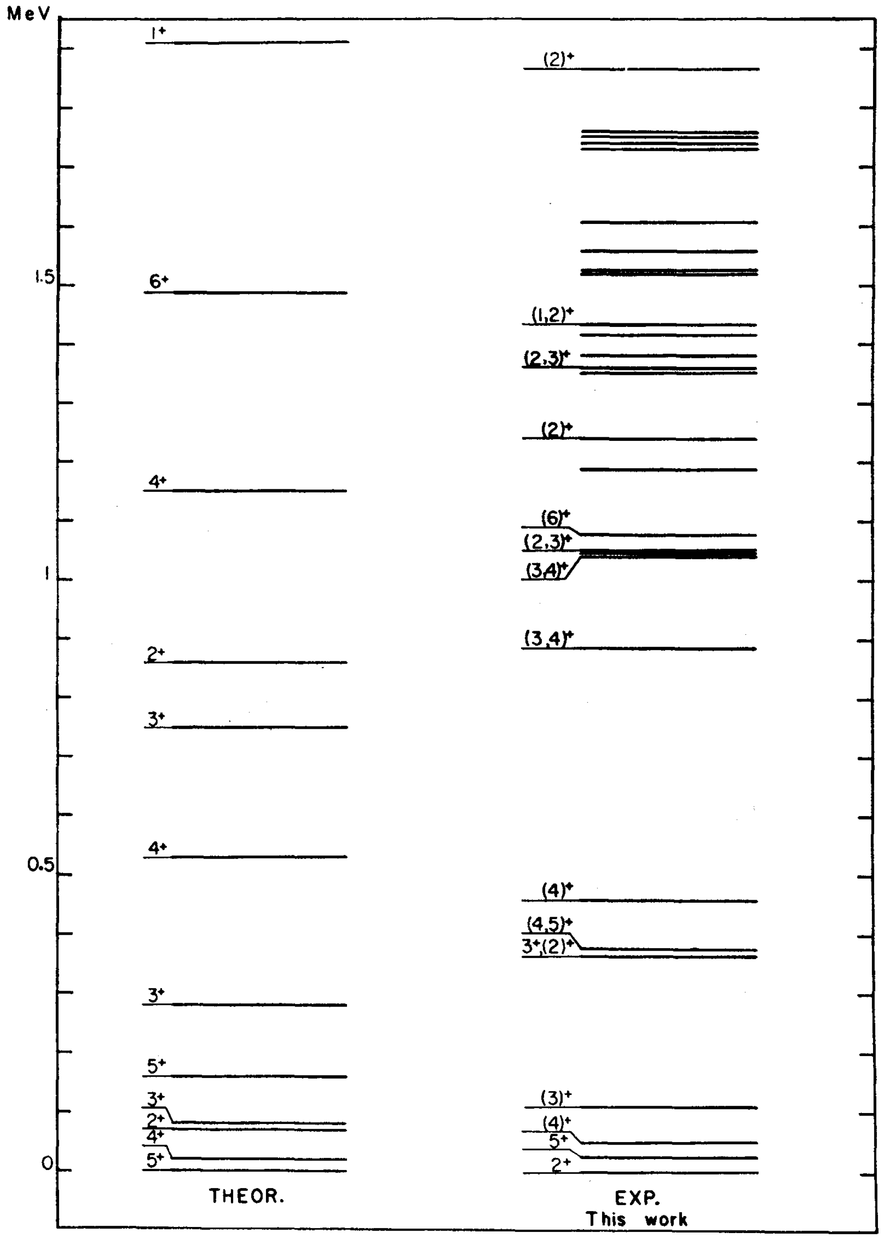

Fig. 8. Comparison of the experimental level sequence in ^{58}Co with the calculations of Vervier [20]. The agreement is only qualitative.

multiplets. From the summary of table 4 it is seen that the level energies reported by Robertson *et al.* [10]) are systematically lower by ≈ 0.5 keV from our results. The (^{4}He, nγ) reaction is expected to populate many states with broad variety of J^π values. Since most of the levels established in this work were seen to de-excite by more than one γ-ray cascade, level energies of good accuracy were obtained. The levels at 1044.4, 1418.6, 1549.7, 1555.4, 1730.4, 1740.6, 1749.6, 1757.6 and 1866.1 keV were not reported by Robertson *et al.* [10]) in their (^{4}He, nγ) study, while they reported levels at 1424.0 and 1928.5 keV which are not consistent with our results. Although definite J^π assignments were made for a number of levels in ^{58}Co, for many other levels only a range of J^π values remains. This fact permits only a limited utilization of these data for determining the nature of the configurations required to describe the low-lying levels in this nucleus.

Vervier [20]) has calculated the energy-level sequence in ^{58}Co assuming $1f_{\frac{7}{2}}^{-1}$ configuration for the proton hole and $2p_{\frac{3}{2}}$, $2p_{\frac{1}{2}}$ and $1f_{\frac{5}{2}}$ for the neutron orbits and considering only seniority-one states for the neutrons. The matrix elements for the n-n interaction were obtained from direct fitting of the levels of known configuration for neighboring nuclei without making any phenomenological assumption about the form of the interaction [21]). For the p-n residual interaction a zero-range potential of the form $V_p = [V_0 + V_1(\boldsymbol{\sigma}_p \cdot \boldsymbol{\sigma}_n)]\, \delta(\boldsymbol{r}_p - \boldsymbol{r}_n)$ was assumed. This calculation has been only in a qualitative agreement with the experimental results. A comparison of the present results with the calculated levels of Vervier [20]) is shown in fig. 8. More recently the matrix elements for the p-n residual interaction for nuclei in the ^{58}Co region have been calculated without any phenomenological assumption about the form of the interaction [22]). The utilization of these matrix elements may improve the calculation of the ^{58}Co levels, since the zero-range force does not seem to describe successfully the p-n residual interaction which might even be non-local. As is suggested by Vervier [20]) the short-comings of the ^{58}Co calculations are probably due also to the neglect of seniority-mixing in the neutron orbits. Thus a more complete calculation taking the seniority-three states into account would probably reproduce the spectrum of the ^{58}Co nucleus better. Furthermore, however, there exists the distinct possibility of neutrons occupying the $g_{\frac{9}{2}}$ orbit and this should be taken into account in future calculations. Those configurations which contain one $g_{\frac{9}{2}}$ neutron may have relatively low excitation energy. Configurations containing an even number of $g_{\frac{9}{2}}$ neutrons lie higher but they can contribute to the redistribution of the spacing of the other levels when they are considered in the interaction matrix.

We wish to thank Mr. John Hood and the personnel of the Washington University cyclotron for their assistance with the measurements. The cooperation of the staff of the Washington University computing facilities is gratefully acknowledged. One of us (A.C.X.) wishes to thank Dr. E. J. Hoffman for some fruitful discussions.

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