EXPERIMENTAL EVIDENCE FOR LOW LYING INTRUDER STATES IN ^{54}Mn

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Abstract :

High spin states in ^{54}Mn were populated in the ^{52}Cr(α, pnγ) reaction. Using angular distribution, linear polarization and γ-γ coincidence measurements, the following unambiguous spin and parity assignements were obtained : E_x, J^π ; 1073 keV, 6^+ ; 1784 keV, 7^+ ; 1925 keV, 7^+ ; 2857 keV, 8^+ and 3244, $(9)^+$. In addition a new level was observed at an excitation energy of 3939 keV. The experimental data show evidence for low lying intruder states as predicted by a recent shell model calculation.

NUCLEAR REACTIONS ^{52}Cr(α, pnγ)^{54}Mn, E_α = 33 MeV ; measured γγ(θ) coin, angular distributions, linear polarizations. ^{54}Mn ; deduced J, π, δ, γ branching ratios. Enriched targets. Comparison with shell model calculations.

1. Introduction

The configurations of low lying high spin states in nuclei near closed shells are expected to be rather pure. Several attempts have been made to observe such states in ^{54}Mn (Poletti et al 1974, Alenius et al 1975, Beale et al 1976 and Nathan et al 1977), but until now no unambiguous spin-parities higher than 5^+ have been assigned to excited levels. This fact hampers a straightforward comparison between experiment and a recent calculation made by Johnstone and Benson (1977). These authors calculated excitation energies of states belonging to various n_1 particule-n_2 hole (n_1 p-n_2h) configurations relative to the ^{56}Ni core. In particular they predicted that the first 6^+ state which they associated with the 1073 keV level, is an intruder state having a 2p-4h configuration. The present work was initiated in order to identify unambiguously the high spin states and to determine their decay properties. The results confirmed the classification of states given by Johnstone and Benson (1977).

2. Experimental method and data analysis

A 33 MeV α-beam, delivered by the Strasbourg MP tandem Van de Graaff, struck the target and was stopped in a Faraday cup three meters away. The target consisted of a 10 mg/cm^2 pellet of Cr_2O_3(enriched to 95 % in ^{52}Cr) sandwiched between two thin mylar foils. Several γ-ray techniques were used for studying the ^{54}Mn levels. Angular distributions were performed by detecting γ-rays at 5 angles (90°, 70°, 55°, 45° and 30° relative to the beam direction) with a 100 cm^3 Ge(Li) detector placed at 20 cm from the target. The relative efficiency curve of the detector was obtained using the lines from ^{56}Co and ^{152}Eu radioactive sources. Its resolution (FWHM) was 2.3 keV for a 1.33 MeV γ-ray. The γ-ray linear polarization (F. Beck et al. 1976) was simultaneously measured with a three Ge(Li) Compton polarimeter positioned at - 90^{o}. The polarisation sensitivity was determined by comparing calculated and measured polarizations of γ-rays emitted in (p, p') reactions on ^{12}C, ^{19}F, ^{24}Mg, ^{28}Si, ^{56}Fe and $^{107,109}Ag$ at the 7 MV Van de Graaff accelerator as well as known E2 transitions observed in the (α, 2n) reactions on ^{50}Ti, ^{52}Cr and ^{54}Fe at the MP tandem accelerator (Haas et al. 1978). In order to establish the level scheme and to obtain the directional correlation of γ-rays emitted from the oriented nuclear states (D.C.O. method : J.A. Grau et al (1974)) a γ-γ coincidence measurement was also performed. The two Ge(Li) counters were positioned at 35^{o} and 90^{o} in the reaction plane and placed at 9 cm from the target. D.C.O. ratios were deduced from the data by using the relative γ-γ coincidence efficiencies measured in a 90^{o}-90^{o} configuration of the Ge(Li) detectors. Known lines from the $^{48}Ca(\alpha, 2n)^{50}Ti$ reaction (Haas et al. 1978) and from a ^{152}Eu source were used to cover the whole energy range of interest.

A simultaneous χ^2 fit was made to the angular distribution coefficients A_2 and A_4, the linear polarization $p = [(N_{\perp} - N_{//})]/[(N_{\perp} + N_{//})Q]$ and D.C.O. ratios R (35^{o}, 90^{o}). It determines, on the basis of the 0.1 % confidence level the angular momentum change ΔJ, the mixing ratio δ (Rose and Brink 1967), the electric and/or magnetic character of each transition and the attenuation parameter α_2 for the nuclear alignement. The α_2 and α_4 coefficients are related since in the present analysis a gaussian distribution has been assumed for the magnetic substate population (G.A.P. Engelbertink et al 1977). The estimates of errors associated with the mixing ratios δ were obtained at a χ^2 value corresponding to one standard deviation from the normalised χ^2_{min}.

Due to the target structure no attempt has been made to determine lifetime values. However Doppler shifts have been observed for γ-rays corresponding to the 2857 ⟶ 1073, 3244 ⟶ 1784 and 3939 ⟶ 2157 keV transitions. Consequently an upper limit of 10 ps can be set for each initial level. This limit as well as lifetime values for other levels (see table 3) exclude the presence of M2, E3 or M3 transitions on the basis of unrealistic enhancement.

3. Results

Excited levels and their decay modes, deduced from the present experiment, are shown in fig. 1. Apart from the 3939 keV level which has not been reported prior to this work, the present decay scheme is in agreement with the one proposed by Alenius et al (1975). A summary of the present experimental data is given in table 1. The spin, parity and mixing ratio values deduced from the χ^2 analysis are presented in table 2. Since spin and parity for the 156 and 368 keV levels have already been determined in previous work, the analysis was limited to the determination of the mixing ratio for the 156 and 212 keV transitions. The present value for the 156 keV transition $\delta = 0.12 \pm 0.05$ is to be compared with the one determined by Ogawa and Taketani (1972) $|\delta| < 0.1$ who assumed a compound nucleus reaction mechanism to analyse their angular distributions.

The properties of all the other observed levels for which no rigourous spin-parity assignments have previously be en reported, will be given in detail below.

3.1. The 1073 keV level

As shown in fig. 2, the χ^2 analysis yields a unique J^π value, namely 6^+.

This is in agreement with the $\ell_n = 3$ transfer to this level observed in the (d, t) reaction on ^{55}Mn, $J^\pi = 5/2^-$ (Taylor and Cameron 1976).

3.2. The 1784 keV level

The existence of a doublet at this excitation energy has been shown by Alenius et al (1975). The decay of the level observed in the present work indicates that it is the same level as the one excited in the ^{51}V(^{6}Li, p2n), ^{51}V(α, n) and ^{48}Ca(^{11}B, 5n) reactions (Poletti et al 1974, Alenius et al 1975, Nathan et al 1977). Both realistic transition strengths for the γ-ray issued from this level and the χ^2 analysis limit J^π to 5^+ or 7^+. As it will be seen later the 7^+ value is the only one compatible with the γ-decay of the 2857 keV level to this level.

3.3. The 1925 keV level

As in the case of the 1784 keV level the analysis of the γ decaying the 1925 keV level leaves only the possibility 5^+ and 7^+ and the γ-decay of the 2857 keV level excludes 5^+.

3.4. The 2857 keV level

This level was found to decay 48 ± 10 % to the 1073 keV level, 22 ± 6 % to the 1784 keV level and 30 ± 5 % to the 1925 keV level. The angular distribution and the linear polarization for the 2857 ⟶ 1073 keV transition associated with several D.C.O. ratios (see table 1) reject all possible spin-parities except $J^\pi = 8^+$. As a $\Delta J = 3$ solution would yield unrealistic transition strengths for the other γ branches, $J^\pi = 5^+$ is excluded for both the 1784 and 1925 keV level.

3.5. The 3244 keV level

The branching ratios for this level could not be obtained since the 3244 ⟶ 1784 keV transition is obscured by a background transition corresponding to the β decay of ^{40}K. The analysis of the 3244 ⟶ 2857 keV

γ-transition limits J^{π} to 7^+ or 9^+. The γ-ray excitation function measured by Alenius et al (1975), along with the arguments outlined by Taras and Haas (1975), support 9^+. However such an assignment could depend on the details of the reaction mechanism involved, therefore the spin value 9 is indicated in parenthesis in fig.1.

3.6. The 3939 keV level

This level, which decays to the 2857 keV and 1925 keV levels, was weakly excited in the present reaction and no branching ratios could be measured. In accordance with usual transition strengths the spin parity assignments for the 3939 keV level are limited to 6^+, $7^{\pm}$, $8^{\pm}$, 9^+.

4. Conclusion

Unambiguous spin assignements for a number of levels in ^{54}Mn have been obtained in the present work. Several of these levels have already been associated by Johnstone and Benson (1977) with 1p-3h states (1784 keV, 7^+ ; 3244 keV, 9^+) or with 2p-4h states (1073 keV, 6^+ ; 1925 keV, 7^+). Their classification was based on spectroscopic factors and on γ-decay branches (calculated M1 and E2 transition strengths between states of different configurations being hindered). This identification is corroborate by the experimental transition strengths reported in table 3 and furthermore confirm the configurational purety foreseen by Johnstone and Benson (1977). Note for example for the 1784 keV level, the predicted lifetime of 1.2 ps is in good agreement with the experimental result (Kudoyarov et al. 1976). However opposed to those levels, a rather strong mixing of both kind of configurations seems to happen in the wave function of the 2857 keV 8^+ level. Theoretically, the 8^+ states of the 1p-3h and 2p-4h configurations are predicted at roughly the same excitation energy and therefore configurational mixing for the 2857 keV level is not surprising. This mixing could also explain the gamma branch from the 3244 keV to the 2857 keV level. Finally, the 3939 keV level could be the 9^+ member of the 2p-4h $K^\pi = 6^+$ band since it decays mainly to the 7_2^+ 2p-4h state and its excitation energy corresponds to the one predicted by the J(J + 1) rule.

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Table 1 : Experimental data

E_i(keV)	E_f(keV)	A_2[a]	A_4[a]	p	Transitions[b] used to determine D.C.O. ratios	R[d]
156.3[c]	0	-0.357(8)	0.000(20)			
368.3[c]	156	-0.253(8)	0.000(40)	-0.33(2)	368 → 156 → 0	1.17 (5)
1073.2[c]	368	-0.269(10)	0.010(30)	-0.29(3)	1073 → 368 → 156	1.00 (3)
					1073 → 368 (→) 156 → 0	1.13 (3)
1783.5[c]	368	0.36 (4)	-0.10(6)	0.55(9)	1784 → 368 → 156	1.84 (12)
					1784 → 368 (→) 156 → 0	2.18 (17)
1925.2[c]	1073	-0.64 (6)	-0.03(5)	-0.03(5)	1925 → 1073 — 368	0.46 (7)
					1925 → 1073 (→) 368 → 156	0.66 (10)
					1925 → 1073 (→ 368 →) 156 → 0	0.56 (9)
2856.5 (3)	1073	0.41 (6)	-0.24(8)	0.63 (16)	2857 → 1073 → 368	1.49 (15)
					2857 → 1073 (→) 368 → 156	2.03 (18)
					2857 → 1073 (→ 368 →) 156 → 0	2.24 (18)
	1784	-0.56 (20)	0.00(20)	-0.03(18)		
	1925			0.01 (8)		
3244.2 (5)	1784	-	-	-	3244 → 1784 → 368	1.26 (17)
					3244 → 1784 (→) 368 → 156	2.23 (19)
					3244 → 1784 (→ 368 →) 156 → 0	2.35 (23)
	2857	-0.23 (4)	0.00 (6)	-0.51(16)	3244 → 2857 → 1073	0.69 (15)
					3244 → 2857 → 1925	1.34 (20)
3939.9 (6)	2857	-0.6 (3)	-	-0.13(18)		
	1925				3939 → 1926 → 1073	2.50 (80)

a) the finite solid angle attenuation factors are negligeable

b) unobserved transitions are in parenthesis

c) energy values from Nathan et al (1977)

d) These values do not include correction for the finite solid angle [$Q_2(90^o) = 0.93$; $Q_4(90^o) = 0.78$; $Q_2(35^o) = 0.95$; $Q_4(35^o) = 0.84$]. The solid angle corrections are however taken into account in the χ^2 analysis .

Table 2: Results of unnormalized χ^2 fits

E_i(keV)	E_f(keV)	J_i^π	J_f^π	δ	χ^2_{min}	degrees of freedom
156	0	4^+	3^+	0.12 (5)	0.5	1
368	156	5^+	4^+	0.00(2)	0.5	1
1073	368	6^+	5^+	0.02 (2)	0.6	2
1784	368	3^+	5^+	0.12 (5)	8.0	2
		5^+	5^+	- 0.18 (27)	8.1	2
		7^+	5^+	0.00 (5)	0.4	2
		4^-	5^+	0.40 (12)	8.4	2
		7^-	5^+	> 11	9.6	2
1925	1073	5^+	6^+	0.40 (18)	4.8	2
		7^+	6^+	0.40 (15)	2.4	2
		5^-	6^+	0.6 (3)	2.0	2
		7^-	6^+	0.47 (25)	4.0	2
2857	1073	8^+	6^+	0.02 (5)	1.4	2
3244	2857	7^+	8^+	0.00 (10)	9.0	2
		9^+	8^+	0.00 (10)	5.2	2

Table 3 : Transition strengths in ^{54}Mn (W.u.)

E_i(keV)	E_f(keV)	J_i^π	J_f^π	BR (%) [a]	τ (ps)	B(E2)	B(M1)
156	0	4^+	3^+	1.0	227 (63) [b]	45 (40)	0.037 (11)
368	156	5^+	4^+	99	10.4(16) [c]	< 5.2	0.32 (7)
	0	5^+	3^+	< 1		< 10	
1073	368	6^+	5^+	99	292 (50) [c]	$< 2.6\ 10^{-3}$	$3.1\ (5)\ 10^{-4}$
	156	6^+	4^+	< 1		$< 4.3\ 10^{-3}$	
1784	1073	7^+	6^+	< 5	$1.2^{+1.3}_{-0.4}$ [d]		$< 6.3\ 10^{-3}$
	368	7^+	5^+	95		$9.4^{+6.6}_{-4.9}$	
1925	1073	7^+	6^+	95	$1.18^{+1.36}_{-0.44}$ [e]	$16.6^{+28.1}_{-13.3}$	$0.36^{+0.26}_{-0.21}$
	368	7^+	5^+	[5]		[0.32 ± 0.18]	
2857	1925	8^+	7^+	25	$2^{d)} < \tau < 10^{f)}$	< 12	$< 5 \times 10^{-3}$
	1784	8^+	7^+	16		< 3.8	$< 2 \times 10^{-3}$
	1073	8^+	6^+	59		$0.2 < B(E2) < 1.1$	

a) Branching ratios from Alenius et al. (1975)

b) from Nathan et al. 1977

c) from Poletti et al. 1974

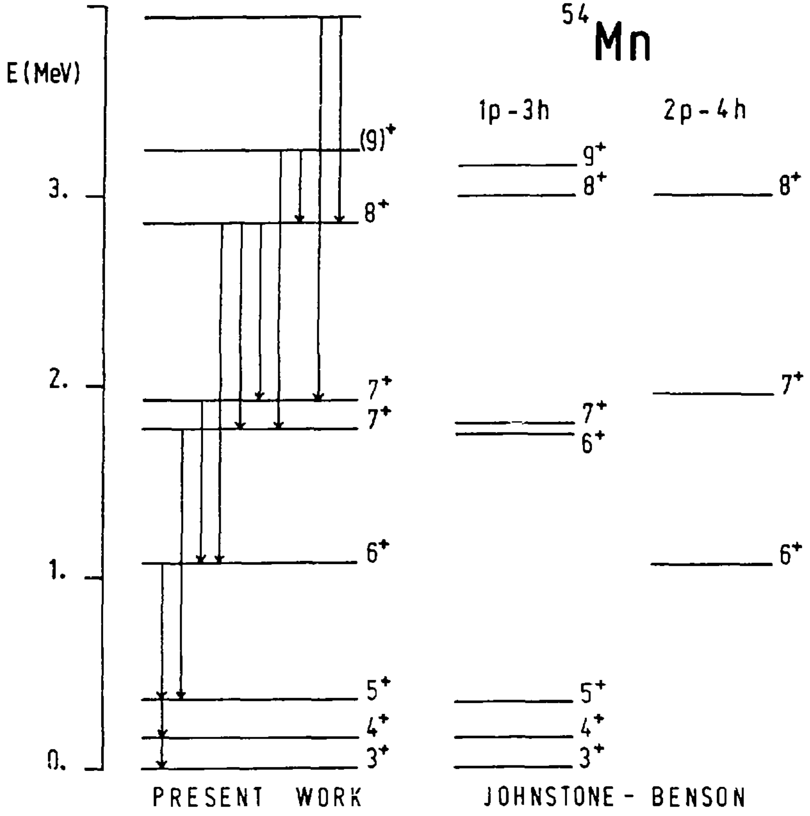
d) from Kudoyarov et al. 1976

e) from Buhl et al. 1977

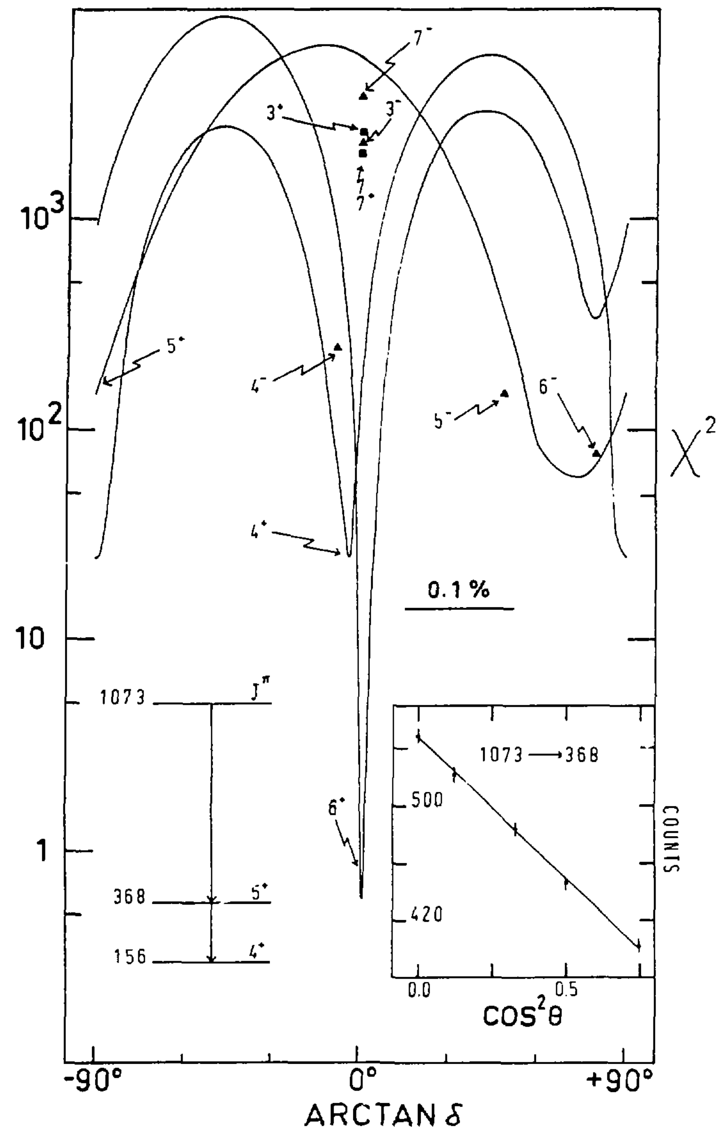
f) present work

Fig. 1 : Comparison between the experimental levels and the results of shell model calculations. Only the γ-branches observed in the present work are indicated.

Fig. 2 : The χ^2 analysis of the angular distribution, linear polarization, D.C.O. ratio , R = 1.00 ± 0.03, for the 1073 ⟶ 368 keV transition. Triangles and squares indicate the minimum of the χ^2 function for the corresponding spin and parity hypotheses. The angular distribution is shown in the insert.



^{54}Mn
E (MeV)
3.
2.
1.
0.
(9)$^+$
8$^+$
7$^+$
7$^+$
6$^+$
5$^+$
4$^+$
3$^+$
1p - 3h
9$^+$
8$^+$
7$^+$
6$^+$
5$^+$
4$^+$
3$^+$
2p - 4h
8$^+$
7$^+$
6$^+$
PRESENT WORK
JOHNSTONE - BENSON



7⁻
3⁺
3⁻
7⁺
10³
10²
10
1
5⁺
4⁻
4⁺
5⁻
6⁻
6⁺
0.1 %
χ²
1073
J^π
368
5⁺
156
4⁺
1073 ⟶ 368
500
420
COUNTS
0.0
0.5
COS²θ
-90°
0°
+90°
ARCTAN δ

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