High-spin γ -ray spectroscopy in ^{52}Mn

M. Axiotis,^{1,2} S. M. Lenzi,³ N. Mărginean,^{1,4} D. R. Napoli,¹ C. A. Ur,^{3,4} F. Brandolini,³ E. Farnea,³ A. Gadea,¹ A. Algora,⁵ G. de Angelis,¹ D. Bazzacco,³ P. G. Bizzeti,⁶ A. Bizzeti-Sona,⁶ P. von Brentano,⁷ J. A. Cameron,⁸ A. Dewald,⁷ H. Grawe,⁹ C. A. Kalfas,² S. Lunardi,³ T. Martínez,¹ C. T. Papadopoulos,¹⁰ Zs. Podolyák,¹¹ C. Rossi Alvarez,³ J. Sanchez-Solano,¹² D. Tonev,^{7,13} and R. Vlastou¹⁴

¹*INFN Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy*

²*Institute of Nuclear Physics, NCSR Demokritos, GR-15310 Athens, Greece*

³*Dipartimento di Fisica dell'Università and INFN Sezione di Padova, I-35131 Padova, Italy*

⁴*National Institute of Physics and Nuclear Engineering, RO-76900 Bucharest, Romania*

⁵*IFIC, CSIC-University Valencia, Apartado Oficial 22085, E-46071 Valencia, Spain*

⁶*Dipartimento di Fisica dell'Università and INFN, Sezione di Firenze, I-50019 Firenze, Italy*

⁷*Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*

⁸*Tandem Accelerator Laboratory, McMaster University, Hamilton, Ontario, L8S 4K1, Canada*

⁹*Gesellschaft für Schwerionenforschung mbH, D-64291 Darmstadt, Germany*

¹⁰*National Technical University of Athens, GR-15780 Athens, Greece*

¹¹*Department of Physics, University of Surrey, Guildford, GU2 7XH, UK*

¹²*Departamento de Física Teórica C-XI, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*

¹³*Institute for Nuclear Research and Nuclear Energy, BAS, 1784 Sofia, Bulgaria*

¹⁴*National Technological University of Athens, GR-15780 Athens, Greece*

(Received 5 March 2007; published 3 July 2007)

The electromagnetic decay properties of high-spin states in ^{52}Mn have been studied through various experiments with the GASP and EUROBALL arrays plus the ISIS light charged-particle detector and the Neutron Wall. From γ - γ particles coincidence measurements, spins, and parities of these states and branching ratios of their decay γ rays have been determined. Using the Doppler-shift attenuation method the mean life of some states have been established. These results are compared with large-scale shell-model calculations in the full fp shell.

DOI: [10.1103/PhysRevC.76.014303](https://doi.org/10.1103/PhysRevC.76.014303)

PACS number(s): 21.10.Hw, 21.10.Tg, 21.60.Cs, 27.40.+z

I. INTRODUCTION

Nuclei near the $N = Z$ line, in the $1f_{7/2}$ shell, constitute a privileged benchmark where several nuclear properties can be studied in great detail. This is due to recent experimental developments that have allowed spectroscopic studies of these nuclei at high spin. Near the center of the shell, collective features such as rotational bands have been observed in several nuclei [1–3] up to the band termination. These structures coexist with more spherical structures in some cases. When approaching the neutron or proton closed shells, single-particle behavior shows up, which can give rise to high-spin isomeric states [4,5]. In parallel to the experimental developments, important improvements have been made in shell-model calculations that are able to describe, in the full fp -shell valence space, the different properties of $1f_{7/2}$ -shell nuclei, including rotational phenomena, with very good accuracy [6]. Recently, these investigations have been extended to isospin symmetry breaking studies, which have allowed the understanding of specific nuclear structure phenomena [7–9].

The study of odd-odd nuclei is very challenging because they are particularly sensitive to the proton-neutron interaction. In odd-odd $N = Z$ nuclei, $T = 0$ and $T = 1$ states coexist at low spin. Rotational positive-parity bands have been observed near the middle of the shell, in ^{46}V and ^{50}Mn . They are well described with the shell model taking into account the whole pf shell [10–12]. Negative-parity structures have been also observed in both nuclei. The rotational band

observed in ^{46}V to the band terminating 17^- state has been reproduced with shell-model calculations in the full pf space, allowing for one hole excitation in the $d_{3/2}$ shell. In the heavier ^{50}Mn , the negative-parity structure cannot be reproduced by these calculations and the inclusion of the upper sdg shell seems to be necessary, which is not feasible with the current shell-model capabilities. For the odd-odd $N = Z + 2$ nucleus ^{48}V a complete spectroscopic study has been made by Brandolini *et al.* [13], where a precise description has been obtained with shell-model calculations for both positive- and negative-parity states. Very scarce spectroscopic information has been reported, however, beyond band termination in this mass region [14].

In the present work new experimental data on the odd-odd $N = Z + 2$ nucleus ^{52}Mn are presented. High-spin states of both positive- and negative-parity have been observed up to an excitation energy of ~ 16 MeV. Prior to the present work, these studies were limited to the band-terminating 11^+ state at 3836 keV. The description of the experimental techniques and findings are given in Sec. II. The experimental results are discussed in the framework of the shell model in Sec. III and the conclusions are presented in Sec. IV.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

The results presented in this article for the ^{52}Mn nucleus were extracted from three different experiments. The first

of them (EBN) was performed with the EUROBALL spectrometer, which was composed of 15 Cluster and 26 Clover HPGe detectors, equipped with BGO Compton suppression shields. In this experiment the EUROBALL spectrometer was combined with the 4π charged-particle detector ISIS [15], consisting of 40 (ΔE , E) Si telescopes, and the Neutron Wall [16], composed of 15 threefold segmented neutron detector units and 1 fivefold, which covered a solid angle of 1π . The reaction used was $^{28}\text{Si}(^{28}\text{Si}, 3pn)$ at 110 MeV beam energy. A ^{28}Si target of $850 \mu\text{g}/\text{cm}^2$ (enriched to $>99.9\%$) evaporated on a $15\text{-mg}/\text{cm}^2$ gold backing was used. Data were recorded when at least two γ rays in the Ge detectors and a neutron in the Neutron Wall were detected in coincidence, or when at least three γ rays in the Ge detectors and a hit (either from a γ ray or from a neutron) in the Neutron Wall were in coincidence. We also examined data obtained in two other experiments performed with the 4π GASP gamma array [17], which consists of 40 Compton-suppressed large volume HPGe detectors with a multiplicity filter of 80 BGO crystals, along with the 4π charged-particle detector ISIS. The reactions used were $^{24}\text{Mg}(^{32}\text{S}, 3pn)$ at 130 MeV bombarding energy and $^{28}\text{Si}(^{28}\text{Si}, 3pn)$ at 115 MeV beam energy. In the first (GASP-I) case the target was self-supported with a thickness of $400 \mu\text{g}/\text{cm}^2$, whereas in the second (GASP-II) a $\sim 800 \mu\text{g}/\text{cm}^2$ ^{28}Si target (enriched to $>99.9\%$) evaporated on a $13 \text{ mg}/\text{cm}^2$ gold backing was used. In both cases events were recorded when at least two Ge detectors and two elements of the multiplicity filter fired in coincidence.

The above mentioned experiments were performed at the XTU Tandem accelerator of the Legnaro National Laboratory. The energy calibration and the efficiency correction were performed using ^{56}Co , ^{133}Ba , and ^{152}Eu sources.

A. The level scheme

For the analysis of the EBN data a γ - γ - γ coincidence cube and γ - γ coincidence matrices were constructed, with and without conditions on the charged particles and neutrons. In the upper part of Fig. 1 a spectrum of ^{52}Mn γ rays obtained in coincidence with neutrons and the 870-keV ($7_1^+ \rightarrow 6^+$) transition is shown. With these data the positive-parity levels of ^{52}Mn have been extended up to the 15^+ state at 9.9 MeV. A negative-parity structure was observed for the first time. The high-spin states, having very short lifetimes, decayed in flight inside the target backing producing for the resulting transitions very broad lines in the spectra. Cleaner spectra for these lines were obtained from the GASP-I data. In this case, in fact, recoiling ions move in the vacuum and the Doppler shift of the emitted γ rays can be accounted for. The lower panel of Fig. 1 shows a GASP-I spectrum gated at the 870-keV γ transition and in coincidence with two protons.

From this analysis the level scheme of ^{52}Mn shown in Fig. 2 was deduced. A total of 25 new levels and 59 new γ transitions have been added to the previously known level scheme [18]. We have also observed two transitions that we were not able to place in the level scheme: a transition of 2421 keV that seems to decay to the 7_1^+ state and a transition of 3004 keV that decays probably to the 10_1^+ state.

FIG. 1. Spectra obtained by applying a gate at the 870-keV transition to the ground state. In the upper panel a spectrum from the EBN data in coincidence with neutrons is shown, whereas in the lower panel a spectrum from the GASP-I experiment is presented, in coincidence with two protons.

The intensities shown in the level scheme (see also Table I) have been deduced from the thin-target (GASP-I) experiment, so as to avoid errors arising from the broad line shapes of the thick target experiments. Spins and parities of the states in Fig. 2 have been determined by angular distribution and polarization analysis, as described below.

B. Angular distribution, polarization, and lifetime measurements

The 40 Ge detectors of GASP are distributed in seven rings, at 34° (six detectors), 60° (six detectors), 72° (four detectors), 90° (eight detectors), 108° (four detectors), 120° (six detectors), and 146° (six detectors) with respect to the beam axis. To study the angular distributions seven γ - γ -coincidence matrices were produced, having on the first axis the γ rays detected in one ring and on the second, the ones detected in the entire array. Making gates on the second axis, the angular distributions of most of the transitions were obtained. These distributions are practically unaffected by the coincidence requirement, due to the approximate spherical symmetry of the array. For this analysis data of the thin-target experiment were used. Where possible, the angular distributions obtained in the EBN experiment were compared with the GASP data and were found in good agreement. The deduced spin values and mixing ratio of the γ rays are shown in Fig. 2 and Table I.

TABLE I. Spectroscopy information on ^{52}Mn from the present work: Level energy and spin, γ -ray energy and final spin, relative intensity, branching ratio (experimental and theoretical), angular distribution parameters A(2) and A(4), multipole character, mixing ratio, and polarization asymmetry of the transitions.

$E_x(\text{keV})$	I_i	$E_\gamma(\text{keV})$	I_f	Intensity ^a	Branching ratio		A(2)	A(4)	Character	δ	Asymmetry ($\times 10^{-2}$)
					Exp. ^b	Theory					
0	6^+										
870	7_1^+	870	6^+		100.00	100.00	-0.41(3)	0.06(6)	$M1+E2$	-0.26(9)	-5.80(43)
2285	8_1^+	1415	7_1^+	58.5(15)	88.4(23)	88.82	-0.53(2)	0.02(1)	$M1+E2$	-0.49(8)	-1.55(57)
		2285	6^+		11.6(10)	11.18	0.26(10)	-0.05(12)	$E2$		1.2(24)
2710	7_2^+	1840	7_1^+	1.45(18)	27.3(33)	12.75					
		2710	6^+		72.7(45)	87.25					
2907	9_1^+	622	8_1^+	49.3(15)	47.0(12)	37.83	-0.37(2)	0.00(5)	$M1+E2$	-0.23(4)	-6.23(61)
		2037	7_1^+	36.9(10)	53.0(15)	62.17	0.21(4)	-0.06(6)	$E2$		4.44(76)
3602	8_2^+	695	9_1^+	0.85(18)	1.51(10)	2.38	-0.37(15)	0.00(6)	$M1+E2$	+0.31(17)	
		892	7_2^+	1.63(41)	0.83(9)	0.16					
		2732	7_1^+	0.33(6)	3.11(23)	0.16					
		3602	6^+		94.5(27)	97.30	0.17(10)	-0.08(16)	$E2$		
3836	11_1^+	929	9_1^+	61.8(16)	100.00	100.00	0.21(1)	-0.05(2)	$E2$		6.81(52)
3891	8_3^+	984	9_1^+		21.3(10)	31.22	-0.55(11)	0.01(22)	$M1+E2$	+0.66(26)	
		1181	7_2^+		39.5(12)	12.42					
		1606	8_1^+	1.40(24)	22.1(11)	21.66					
		3021	7_1^+	1.92(17)	17.0(11)	34.71					
4161	10_1^+	325	11_1^+	1.54(21)	13.7(20)	3.39	-0.21(5)	0.00(9)	$M1+E2$	+0.06(10)	-2.7(67)
		1254	9_1^+	12.3(10)	65.5(34)	83.89	-0.54(6)	0.02(8)	$M1+E2$	-0.44(18)	
		1876	8_1^+	2.74(21)	20.8(30)	12.72					
4198	(9_2^+)	3328	7_1^+		100.00	100.00					
4679	9^-	788	8_3^+	2.32(43)	8.78(23)		-0.54(11)	0.02(17)	$E1+E2$	-0.50(68)	
		1077	8_2^+	2.78(22)	72.2(43)						13.9(76)
		1772	9_1^+		4.09(22)						
		2394	8_1^+	0.95(14)	6.57(41)						
		3809	7_1^+	1.01(15)	1.20(16)						
		4679	6^+		7.20(27)						
5051	(10_2^+)	853	(9_2^+)	0.86(25)		47.79					
		890	10_1^+			52.21					
5412	(10_3^+)	3127	8_1^+	1.36(18)	100.00	100.00					
5856	11_2^+	1695	10_1^+	4.80(36)	26.0(18)	33.25	-0.29(9)	0.00(12)	$M1+E2$	-0.13(11)	
		2020	11_1^+	8.93(47)	60.7(26)	57.44	0.17(11)	-0.01(16)	$M1+E2$	-0.33(66)	
		2949	9_1^+	1.99(19)	13.3(14)	9.31					
6060	11^-	1381	9^-	3.85(30)	100.00		0.25(12)	0.00(17)	$E2$		13.5(50)
6483	(11_3^+)	1071	(10_3^+)	0.93(24)	24.1(64)	34.00					
		2647	11_1^+	1.68(12)	75.9(84)	66.00					
7466	12_1^+	983	(11_3^+)			14.00	-0.55(18)	0.01(6)	$M1+E2$	-0.38(4)	
		1610	11_2^+			60.96					
		2415	(10_2^+)	1.74(22)		9.21					
		3630	11_1^+	2.87(19)		15.82					
7700	(12_2^+)	3539	10_1^+	2.12(21)		0.46					
		3864	11_1^+	1.49(21)		99.54					
8151	13_1^+	451	(12_2^+)	0.41(10)		0.36					
		685	12_1^+	2.17(30)	1.25(46)	21.87	-0.40(16)	0.01(28)	$M1+E2$	-0.24(52)	
		2295	11_2^+	7.16(27)	13.9(42)	41.63					0.9(33)

TABLE I. (*Continued.*)

$E_x(\text{keV})$	I_i	$E_\gamma(\text{keV})$	I_f	Intensity ^a	Branching ratio		A(2)	A(4)	Character	δ	Asymmetry ($\times 10^{-2}$)
					Exp. ^b	Theory					
		4315	11_1^+	14.3(3)	84.9(12)	36.13					
8383	(13_2^+)	4547	11_1^+	4.99(17)	100.00	100.00					
8581	(13_1^-)	2521	11^-	2.54(14)	77.0(30)						
		4745	11_1^+	0.77(8)	23.0(19)						
8786	(13_3^+)	1320	12_1^+	0.95(20)	100.00	100.00					
8893	14_1^+	510	(13_2^+)	1.44(10)	17.9(36)	0.00					
		742	13_1^+	21.5(4)	82.1(23)	100.00	-0.27(3)	0.00(6)	$M1+E2$	-0.10(48)	-8.1(12)
9371	13_3^-	3311	11^-								
		5535	11_1^+	0.32(7)							
9905	15^+	1012	14_1^+	14.2(8)		99.77					-4.8(17)
		1522	(13_2^+)	3.19(31)		0.23					
10177	(14_1^-)	1596	(13_1^-)	1.50(29)							
		2026	13_1^+								
11132	(16^+)	1227	15^+		100.00	100.00					
11186	(14_2^-)	1815	(13_3^-)		100.00						
11278	(14_3^-)	1907	(13_3^-)	2.03(23)	100.00						
12010	(15_1^-)	1833	(14_1^-)		100.00						
12061	(17^+)	929	(16^+)			64.25					
		2156	15^+	4.03(23)		35.75	0.24(7)	0.01(11)	$E2$		
13616	(15_2^-)	2338	(14_3^-)	1.50(15)							
		2430	(14_2^-)	0.46(23)							
15569	(16^-)	1953	(15_2^-)	1.38(19)	100.00						

^aThe intensity is obtained by gating on the transitions to the ground state in the GASP-I data. For these lines no intensities can be given. There are also some transitions for which, either because of the low intensity or for that they were seen in other experiment, it is not possible to give the intensities.

^bThe branching ratios were obtained by gating above the transitions. Whenever making the gate was not possible the branching ratio is missing.

For the parity determination the polarization method was used. For this purpose two γ - γ matrices were produced. The first matrix included γ rays scattered perpendicularly to the beam direction in the Clover detectors placed near 90° , in coincidence with the γ rays detected in the rest of the array, whereas the second one included the γ rays that were scattered parallel to the beam versus the entire γ array. The asymmetry of the Compton scattering is given by $A = N_\perp - N_\parallel / N_\perp + N_\parallel$. From these matrices the asymmetry of the Compton scattering was calculated. Knowing that for stretched transitions, a positive asymmetry is associated to an electric multipole, whereas a negative asymmetry to a magnetic one, the character of the lines was determined. All the information derived from this analysis is given in Table I.

To estimate the lifetimes of the states the Doppler shift attenuation method has been used. For this purpose data from the GASP-II experiment were sorted in seven γ - γ -coincidence matrices, each corresponding to the coincidence of the γ rays at any detector of the seven rings with those at all other detectors. The spectra taken by putting a gate on the 929-keV $11_1^+ \rightarrow 9_1^+$ transition were analyzed with the LINESHAPE [19] code, taking into account the feeding from higher lying states. The deduced lifetimes are reported in Table II. The low statistics

of the transitions from the negative-parity states did not allow a lifetime analysis for this part of the level scheme. However, making a gate on the 870-keV γ transition to the ground state we have observed that the 1077-keV transition from the 9^- state was observed without Doppler broadening, leading to the conclusion that the 9^- state has a lifetime greater than 1.1 ps, which is the time needed for the recoil to be stopped in the backing.

TABLE II. The lifetimes deduced in the present experiment.

$E_x(\text{keV})$	$E_\gamma(\text{keV})$	I_i	$\tau(\text{ps})$
4161	325	10_1^+	0.17(5)
4679		9^-	>1.10
8786	1320	13_3^+	0.15(5)
8893	742	14_1^+	0.60(10)
9905	1012	15_1^+	0.10(1)
12061	2156	(17_1^+)	0.11(3)

FIG. 2. The ^{52}Mn level scheme as obtained in the present work.

III. DISCUSSION

Three main structures can be distinguished in the level scheme of ^{52}Mn (see Fig. 2): the ground-state band, that terminates at the 11_1^+ state at 3836-keV excitation energy, a high-spin positive-parity structure and a negative-parity one. These structures have been analyzed in the framework of the spherical shell model.

A. Positive-parity states

To describe these states, calculations have been performed in the full fp shell using the code ANTOINE [20]. The single particle energies have been taken from the experimental spectrum of ^{41}Ca . Four different effective interactions (KB3 [21], KB3G [22], FPD6 [23], and GXPF1 [24]) have been used to calculate the energy levels of the ground-state band. The results are shown in Fig. 3. From this figure, it can be deduced that the GXPF1 interaction gives the best description of the data. However, when extending the calculations to nonyrast or higher spin states, these calculations underestimate the level energies by 300–500 keV. It is the KB3G interaction that gives an overall better description of the data, as shown in Fig. 4. We have therefore adopted the KB3G interaction for the shell-model calculations in the following discussion. In addition to the energy levels, where theory and experiment compare well, the transition probabilities for the decay transitions have been

calculated and the corresponding branching ratios were found in good agreement with the data (see Table I).

To put in evidence the different characteristics of the two positive-parity structures—at low and high-spin—the fractional occupation numbers for the different orbitals in the fp shell can be studied. The calculated values for the yrast states, including the 11_2^+ level, are displayed in

10^+ 4472	10^+ 4539	10^+ 4258	10^+ 4161	10^+ 4315
11^+ 4136	11^+ 4418	11^+ 3935	11^+ 3836	11^+ 4065
9^+ 3067	9^+ 3226	9^+ 2878	9^+ 2907	9^+ 3004
8^+ 2554	8^+ 2530	8^+ 2293	8^+ 2285	8^+ 2454
7^+ 873	7^+ 947	7^+ 818	7^+ 870	7^+ 873
6^+ 0	6^+ 0	6^+ 0	6^+ 0	6^+ 0
KB3	FPD6	GXPF1	Exp.	KB3G

FIG. 3. Comparison between the calculations using different effective interactions and the experimental level energies of the ground-state band in ^{52}Mn .

FIG. 4. Comparison between the calculated and the experimental deduced energies of the positive-parity energy levels in ^{52}Mn .

Fig. 5. In the upper panel, the occupation numbers for the $f_{7/2}$ shell for protons and neutrons are shown. It is clear from the figure that the angular momentum is increasing up to the 11_1^+ state mostly due to proton alignment in the $f_{7/2}$ shell, with a stable $f_{7/2}$ neutron-hole configuration. In the bottom panel only the neutron occupations in the other orbitals of the main shell are shown, as those for the protons are small and quite constant. An abrupt change of configuration is observed at the 11_2^+ state where a neutron is excited from the $f_{7/2}$ to the upper orbitals. This structure, with only six neutrons in the $f_{7/2}$ orbital, continues up to the 16^+ state. This is a fully aligned

state where, in the $f_{7/2}$ shell, the five protons are coupled to the maximum spin $J_\pi = 15/2$ and the two neutron holes to $J_v = 6$, whereas the odd neutron is in the $f_{5/2}$ orbital. To further increase the spin to $J^\pi = 17^+$, another neutron has to be excited to the upper fp orbits.

Lately, high-spin states in the nucleus ^{51}Mn have been reported [25,26]. To explain the yrast states above the $17/2^-$ level, where a pair of neutrons is aligned to the maximum value of $J_v = 6$, the alignment of five protons in the $f_{7/2}$ orbital up to $J_\pi = 15/2$ is addressed, where it reaches the fully aligned state $27/2^-$. This behavior is very similar to the one observed here for the ground-state band in ^{52}Mn , where the maximum spin is $J = 11$ with the odd neutron in the $f_{7/2}$ orbital ($J_v = 7/2$) coupled to the fully aligned $J_\pi = 15/2$ spin of the protons. The relevant part of the two level schemes are compared in the left part of Fig. 6 and in fact they look very similar. To get a better insight into this feature, we have calculated the expectation value of the operator $A_i = [(a_i^\dagger a_i^\dagger)^{J=6} (a_i a_i)^{J=6}]^0$, where i stands for neutrons or protons. This operator “counts” the number of nucleon pairs aligned to $J = 6$. By computing the difference between the expectation values of neutrons and protons for each state, one can get a “picture” of which fluid is aligning as a function of the spin. The results for both nuclei are compared in the right part of Fig. 6. In the case of ^{51}Mn for the low-spin states the alignment of the neutrons and the protons is comparable, giving small contributions to $A_v - A_\pi$. The abrupt rise of the curve at the $17/2^-$ state is caused by the alignment of a neutron pair to $J = 6$. With the neutrons blocked in this configuration the increase of the spin can be generated only by the alignment of the protons (excluding excitations to upper orbitals), as happens for the ground-state band in ^{52}Mn . The similarity between the two curves, for the states in question, is remarkable.

For the high-spin structure in ^{52}Mn (starting with the 11_2^+ up to 17^+) the agreement between experiment and theory is

FIG. 5. Fractional occupation number for the yrast band of ^{52}Mn .

FIG. 6. Comparison of the decay pattern and the alignments between ^{51}Mn and ^{52}Mn (see text).

very good, apart for the 17^+ , whose energy is overestimated. This discrepancy could indicate that such a high-spin state involves excitations to higher shells, but this seems to be ruled out by the short lifetime of this state.

B. Negative-parity states

For the negative-parity band, shell-model calculations have been performed, allowing one particle-hole excitation from the $d_{3/2}$ shell and up to three nucleons to be excited from the $f_{7/2}$ orbital to the higher fp ones. The results were not

found in agreement with the experimental data. This leads us to believe that the configuration of the negative bandhead (9^-) corresponds to the coupling of an octupole vibration to the ground state, as observed in other neighboring nuclei (^{50}Mn [12] and ^{52}Fe [4]). In fact, in Fig. 7 the similarity of the excitation energy of the negative-parity bandhead of the above mentioned nuclei is shown. This could also explain the competition of the octupole transition of 4679 keV to the dipole ones in the decay of the 9^- state. Unfortunately, it is not feasible to perform shell-model calculations that take into account excitations to the $g_{9/2}$ shell.

IV. CONCLUSIONS

In this work, a full spectroscopic analysis for the odd-odd nucleus ^{52}Mn has been carried out, achieving to extend the level scheme considerably above the band termination. The positive-parity part of the level scheme has been compared with full fp shell-model calculations, using several interactions and found in overall good agreement. In particular the interactions that produce better results are the KB3G and the GXPF1, the former being able to describe the whole positive-parity level scheme and the latter up to the ground-state band termination. In addition, a negative-parity structure has been observed for the first time. The description of this structure was not possible in the context of shell model, because taking into account the $g_{9/2}$ shell seems necessary, which for the time being is not feasible. The bandhead of this structure is interpreted as an octupole vibration coupled to the ground state.

ACKNOWLEDGMENTS

The authors thank the technical staff of the LNL accelerator division for their support during the course of the experiments. M.A. acknowledges support by the EC under the contracts TMR/LSF: ERBFMGECT 980110—Access to Large Scale Facilities and HPRI-CT-1999-00083.

FIG. 7. Comparison of the negative-parity bandheads of ^{52}Fe , ^{52}Mn , and ^{50}Mn .

- [1] S. M. Lenzi, D. R. Napoli, A. Gadea, M. A. Cardona, D. Hojman, M. A. Nagarajan, C. R. Alvarez, N. H. Medina, G. de Angelis, D. Bazzacco *et al.*, *Z. Phys. A* **354**, 117 (1996).
- [2] J. A. Cameron, J. Jonkman, C. E. Svensson, M. Gupta, G. Hackman, D. Hyde, S. M. Mullins, J. L. Rodriguez, J. C. Waddington, A. Galindo-Uribarri *et al.*, *Phys. Lett.* **B387**, 266 (1996).
- [3] S. M. Lenzi, C. A. Ur, D. R. Napoli, M. A. Nagarajan, D. Bazzacco, D. M. Brink, M. A. Cardona, G. de Angelis, M. D. Poli, A. Gadea *et al.*, *Phys. Rev. C* **56**, 1313 (1997).
- [4] C. A. Ur, D. Bucurescu, S. M. Lenzi, G. Martinez-Pinedo, D. R. Napoli, D. Bazzacco, F. Brandolini, D. M. Brink, J. A. Cameron, E. Caurier *et al.*, *Phys. Rev. C* **58**, 3163 (1998).
- [5] A. Gadea, S. M. Lenzi, D. R. Napoli, M. Axiotis, C. A. Ur, G. Martinez-Pinedo, M. Gorska, E. Roeckl, E. Caurier, F. Nowacki *et al.*, *Phys. Lett.* **B619**, 88 (2005).
- [6] E. Caurier, J. L. Egido, G. Martinez-Pinedo, A. Poves, J. Retamosa, L. M. Robledo, and A. P. Zuker, *Phys. Rev. Lett.* **75**, 2466 (1995).
- [7] A. P. Zuker, S. M. Lenzi, G. Martinez-Pinedo, and A. Poves, *Phys. Rev. Lett.* **89**, 142502 (2002).
- [8] A. Gadea, S. Lenzi, S. Lunardi, N. Marginean, A. P. Zuker, G. de Angelis, M. Axiotis, T. Martinez, D. R. Napoli, E. Farnea *et al.*, *Phys. Rev. Lett.* **97**, 152501 (2006).
- [9] M. A. Bentley, M. J. T. C. Chandler, J. Brown, M. P. Carpenter, C. Davids, J. Ekman, S. J. Freeman, P. E. Garrett, G. Hammond, R. V. F. Janssens *et al.*, *Phys. Rev. Lett.* **97**, 132501 (2006).
- [10] S. M. Lenzi, D. R. Napoli, C. A. Ur, D. Bazzacco, F. Brandolini, J. A. Cameron, E. Caurier, G. de Angelis, M. D. Poli, E. Farnea *et al.*, *Phys. Rev. C* **60**, 021303(R) (1999).
- [11] C. D. O'Leary, M. A. Bentley, D. E. Appelbe, R. A. Bark, D. M. Cullen, S. Erturk, A. Maj, J. A. Sheikh, and D. D. Warner, *Phys. Lett.* **B459**, 73 (1999).
- [12] C. E. Svensson, S. M. Lenzi, D. R. Napoli, A. Poves, C. A. Ur, D. Bazzacco, F. Brandolini, J. A. Cameron, G. de Angelis, A. Gadea *et al.*, *Phys. Rev. C* **58**, R2621 (1998).
- [13] F. Brandolini, N. Marginean, S. Hankonen, N. H. Medina, R. V. Ribas, J. Sanchez-Solano, S. M. Lenzi, S. Lunardi, D. R. Napoli, A. Poves *et al.*, *Phys. Rev. C* **66**, 024304 (2002).
- [14] J. Ekman, D. Rudolph, C. Andreoiu, C. Fahlander, M. N. Mineva, M. A. Bentley, S. J. Williams, R. Charity, E. Ideguchi, W. Reviol *et al.*, *Phys. Rev. C* **70**, 014306 (2004).
- [15] E. Farnea, G. de Angelis, M. D. Poli, D. D. Acuna, A. Gadea, D. R. Napoli, P. Spolaore, A. Buscemi, R. Zanon, R. Isocrate *et al.*, *Nucl. Instrum. Methods A* **400**, 87 (1997).
- [16] O. Skeppstedt, H. A. Rothand, L. Lindstrom, R. Wadsworth, I. Hibbert, N. Kelsall, D. Jenkins, H. Grawe, M. Gorska, M. Moszynski *et al.*, *Nucl. Instrum. Methods A* **421**, 531 (1999).
- [17] C. Rossi Alvarez, *Nucl. Phys. News* **3**, 3 (1993).
- [18] H. Junde, *Nucl. Data Sheets* **90**, 1 (2000).
- [19] J. C. Wells and N. R. Johnson, Report No. ORNL-6689, p. 44 (1991).
- [20] E. Caurier, Code ANTOINE, Strasbourg, 1989; E. Caurier and F. Nowacki, *Acta Phys. Pol.* **30**, 705 (1999).
- [21] A. Poves and A. P. Zuker, *Phys. Rep.* **70**, 235 (1981).
- [22] A. Poves, J. Sanchez-Solano, E. Caurier, and F. Nowacki, *Nucl. Phys.* **A694**, 157 (2001).
- [23] W. A. Richter, M. J. V. der Merwe, R. E. Julies, and B. A. Brown, *Nucl. Phys.* **A523**, 325 (1991).
- [24] M. Honma, T. Otsuka, B. A. Brown, and T. Mizusaki, *Phys. Rev. C* **69**, 034335 (2004).
- [25] J. Ekman, D. Rudolph, C. Fahlander, R. J. Charity, W. Reviol, D. G. Sarantites, V. Tomov, R. M. Clark, M. Cromaz, P. Fallon *et al.*, *Eur. Phys. J. A* **9**, 13 (2000).
- [26] M. A. Bentley, S. J. Williams, D. T. Joss, C. D. O'Leary, A. M. Bruce, J. A. Cameron, M. P. Carpenter, P. Fallon, L. Frankland, W. Gelletly *et al.*, *Phys. Rev. C* **62**, 051303(R) (2000).