Eur Phys J. A **8**, 153–155 (2000)

The European Physical Journal A

Short note

Gamma-ray spectroscopy of $^{57}_{25}Mn_{32}$ and $^{58}_{25}Mn_{33}$

D.E. Appelbe[1,a], R.A.E. Austin[1], G.C. Ball[2], J.A. Cameron[1], B. Djerroud[1], T.E. Drake[3], S. Flibotte[1], C.D. O'Leary[4], A. Melarangi[4], C.E. Svensson[5], J.C. Waddington[1], and D. Ward[5]

[1] Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada
[2] Triumf, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada
[3] Physics Department, University of Toronto, Toronto, Canada
[4] Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool L69 7ZE, UK
[5] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Received: 10 April 2000
Communicated by D. Schwalm

Abstract. The decays of $^{57}_{25}Mn_{32}$ and $^{58}_{25}Mn_{33}$ have been studied with the 8π Spectrometer following the reaction $^{48}Ca(^{13}C,pxn)^{60-x}Mn$ at a beam energy of 40 MeV. The level schemes of these two nuclei have been extended, and the multipolarities of the observed transitions have been determined.

PACS. 21.10.Pc Single-particle levels and strength functions – 23.20.En Angular Distribution and correlation measurements 23.20.Lv Gamma Transitions and level energies – 27.40.+z $39 \leq A \leq 58$

The only stable isotope of manganese ($Z = 25$) is $^{55}Mn_{30}$, which lies three proton holes and two neutron particles away from the doubly magic $^{56}_{28}Ni_{28}$. As such, it does not exhibit any evidence for collective nuclear rotation. Rather, the observed γ decay follows a path typical of a "shell-model" nucleus. The nuclei $^{57}_{25}Mn_{32}$ and $^{58}_{25}Mn_{33}$ have been studied by several experimental techniques such as heavy-ion fusion-evaporation reactions [1], β decay [2], and transfer reactions such as (t,^{3}He) [3]. These studies have identified states in ^{57}Mn to $E^* = 5.17$ MeV [4], and states in ^{58}Mn to $E^* = 3.72$ MeV. The most recent heavy-ion, fusion-evaporation reaction study of these nuclei was that of Nathen *et al.* [1]. Who identified 11 γ rays in ^{57}Mn, of which 6 were placed unambiguously. In ^{58}Mn a total of 7 γ rays were identified, of which 6 were placed unambiguously. Due to the weak population of these nuclei, Nathen *et al.* were unable to determine the angular distribution coefficients for many of the observed decays.

In this short note we report on the observation of additional γ rays and the determination of angular distribution coefficients for many of the gamma decays associated with these two nuclei.

The reaction $^{48}Ca(^{13}C,pxn)^{60-x}Mn$ was used to populate high-spin states in the nuclei ^{57}Mn and ^{58}Mn. The 40 MeV ^{13}C beam, provided by the 88″ Cyclotron of the Lawrence Berkeley National Laboratory, was incident upon an enriched ^{48}Ca (78%) target. To minimize the oxidation of the calcium, a layer of gold was evaporated on both sides. The target was mounted such that the beam was incident upon $350\mu g/cm^2$ ^{197}Au, $350\mu g/cm^2$ ^{48}Ca and exited through a thin layer of ^{197}Au ($\approx 90\mu g/cm^2$). The resulting γ rays were detected with the 8π Spectrometer [5]. A total of 5.7×10^7 events were recorded in which two or more γ rays were detected in the Compton-suppressed HPGe detectors and at least four elements of the BGO inner ball fired. The main reaction product was ^{58}Fe (3n). The nuclei ^{57}Mn (p3n) and ^{58}Mn (p2n) were populated with 8% and 15% of the 3n channel, respectively.

These data were sorted offline into a symmetric E_γ-E_γ coincidence matrix for analysis with the program "escl8r" [6]. An asymmetric matrix to allow the multipolarity of the observed transitions to be determined was also sorted, allowing the DCO ratio,

$$R_{\mathrm{DCO}} = \frac{I_{\gamma_1(\pm37°),\gamma_2(\pm79°)}}{I_{\gamma_1(\pm79°),\gamma_2(\pm37°)}}, \qquad (1)$$

to be determined. With this method, transitions (γ_1) for which $\Delta J = 2$ yielded a ratio of 1.0, while those with $\Delta J = 1$ gave the value 0.55, when the gating transition (γ_2), was a stretched quadrupole ($\Delta J = 2$). When the gating transition utilized was a stretched dipole ($\Delta J = 1$) the resultant R_{DCO} ratios for a stretched dipole and stretched quadrupole were 1.0 and 0.5, respectively. Four additional asymmetric matrices were sorted, one for each ring (θ=±37°, ±79°) of HPGe detectors of the 8π. In these matrices γ rays detected at any angle were incremented

[a] e-mail: dea@physics.mcmaster.ca

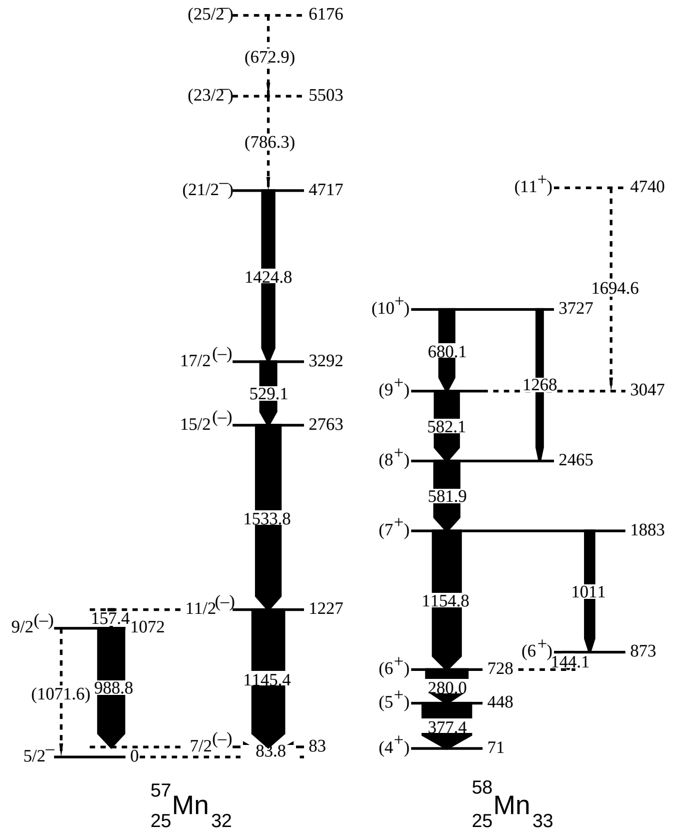

Fig. 1. The level schemes for ^{57}Mn (left) and ^{58}Mn (right) as determined from this experiment. The energies of the excited levels and the γ-ray transition energies are given in keV. The widths of the arrows connecting levels are proportional to the relative intensity of the observed transitions. Tentative transitions are shown by dashed arrows. Levels with their spin/parity assignments in parentheses are uncertain.

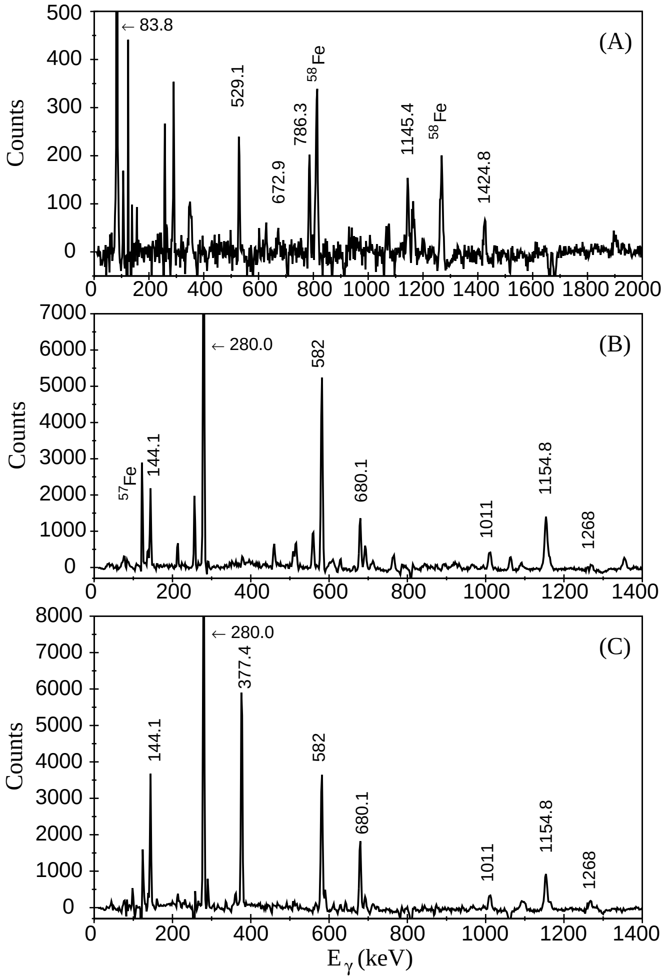

Fig. 2. Coincidence spectra obtained by setting gates on transitions in ^{57}Mn (A) and ^{58}Mn (B-C). (A) Obtained by setting a single gate on the 1533.8-keV transition. (B) Obtained by setting a gate on the 377.4-keV transition. (C) Obtained by setting a gate on the 582-keV transition.

in x, while those detected at a specific angle θ were incremented in y. These additional matrices allow the angular coefficient A_2/A_0 [7] to be determined from a polynomial fit to the relation

$$W(\theta) = A_0 \left(1 + \frac{A_2}{A_0} P_2 \cos(\theta)\right) , \qquad (2)$$

where P_2 is a Legendre polynomial, A_0 and A_2 are dimensionless variables that can be varied to provide the best fit to the data.

The level schemes for both nuclei, as determined in this experiment are presented in fig. 1, while representative spectra can be seen in fig. 2. The experimentally determined properties (energy, relative intensity, R_{DCO}, A_2/A_0) for ^{57}Mn are presented in table 1, while those for ^{58}Mn are presented in table 2.

As was observed by Nathen *et al* [1] the nucleus ^{57}Mn was populated with a much lower fraction of the total fusion cross-section than that of ^{58}Mn, making spectroscopy of this nucleus more difficult. The level scheme presented in fig. 1 for ^{57}Mn is similar to that in fig. 6 of ref. [1]. The placement of the 1072-, 989- and 157-keV transitions is confirmed here. The angular distribution measurements determined here are in good agreement with the tentative assignments made in ref. [1].

Notable differences between this work and the work of Nathen *et al.* [1] are: a) The 786.3- and 672.9-keV transitions, unplaced in ref. [1], have been determined to form part of the main cascade. b) No direct evidence for the 1.07 MeV level was reported in ref. [1], this level has been populated in this work, with the 157- and 988.8 keV transitions being observed. In addition it has been possible to extract the R_{DCO} and A_2/A_0 ratios for several transitions. It is suggested that the spins of some of the levels assigned in ref. [1] should be altered, given the assignment of the 1424.8-keV transition as a quadrupole transition.

It has been possible to add 4 new γ-ray transitions to the decay scheme of ^{58}Mn when compared with that determined by Nathen *et al.* The ground state of ^{58}Mn is believed to be 1^+, with a low-lying 65s isomeric (4^+) state

Table 1. The transition energy, relative intensity (normalized to the 83.8-keV transition), R_{DCO} and A_2/A_0 for transitions observed in ^{57}Mn. Those spin/parity assignments that have not been determined by either this work, or that of previous authors are shown in parentheses.

E_γ (keV)	I_γ	R_{DCO}	A_2/A_0	$J_i^\pi \rightarrow J_f^\pi$
83.8 (4)	100 (10)	1.25 (6)^a	0.11 (4)	$\frac{7}{2}^{(-)} \rightarrow \frac{5}{2}^{(-)}$
157.4 (4)	10.5 (9)	1.3 (1)^b	–	$\frac{11}{2}^{(-)} \rightarrow \frac{9}{2}^{(-)}$
529.1 (3)^c	31.5 (20)	1.19 (6)^b	–	$\frac{17}{2}^{(-)} \rightarrow \frac{15}{2}^{(-)}$
672.9 (4)	8.8 (10)	–	–	$(\frac{25}{2}^-) \rightarrow (\frac{23}{2}^-)$
786.3 (5)	21.8 (20)	–	–	$(\frac{23}{2}^-) \rightarrow (\frac{21}{2}^-)$
988.8 (4)^c	53 (4)	1.1 (1)^b	–	$\frac{9}{2}^{(-)} \rightarrow \frac{7}{2}^{(-)}$
1071.6 (10)	2.0 (20)	–	–	$\frac{9}{2}^{(-)} \rightarrow \frac{5}{2}^{(-)}$
1145.4 (3)	65 (9)	0.86 (3)^b	0.29 (3)	$\frac{11}{2}^{(-)} \rightarrow \frac{7}{2}^{(-)}$
1424.8 (4)	23.8 (18)	1.3 (1)^b	–	$(\frac{21}{2}^-) \rightarrow \frac{17}{2}^{(-)}$
1533.8 (10)	50 (3)	0.82 (5)^b	0.43 (8)	$\frac{15}{2}^{(-)} \rightarrow \frac{11}{2}^{(-)}$

^{a} Gated by the 1145-keV transition.
^{b} Gated by the 83-keV transition.
^{c} The ratio A_2/A_0 is not distinguishable from 0.

Table 2. As for table 1, but for ^{58}Mn. The intensities of transitions are normalized to the 377-keV transition.

E_γ (keV)	I_γ	R_{DCO}	A_2/A_0	$J_i^\pi \rightarrow J_f^\pi$
144.1 (3)	19.4 (14)	0.67 (5)^a	$-^d$	$(6^+) \rightarrow (6^+)$
280.0 (3)	85 (5)	1.02 (4)^b	−0.10 (3)	$(6^+) \rightarrow (5^+)$
377.4 (3)	100 (9)	1.41 (9)^b	−0.45 (3)	$(5^+) \rightarrow (4^+)$
581.9 (7)	51 (4)	0.99 (4)^c	−0.22 (5)	$(8^+) \rightarrow (7^+)$
582.1 (6)	49 (5)	–	–	$(9^+) \rightarrow (8^+)$
680.1 (3)	30.1 (21)	1.01 (6)^c	−0.3 (1)	$(10^+) \rightarrow (9^+)$
1011.0 (4)	18.4 (15)	0.80 (9)^b	−0.2 (1)	$(7^+) \rightarrow (6^+)$
1154.8 (4)	57 (4)	1.05 (5)^c	−0.3 (1)	$(7^+) \rightarrow (6^+)$
1268 (2)	12 (4)	0.82 (6)^c	–	$(10^+) \rightarrow (8^+)$
1694.6 (8)	5 (2)	–	–	$(11^+) \rightarrow (9^+)$

^{a} Gated by the 377-keV transition.
^{b} Gated by the 144-keV transition.
^{c} Gated by the 581-keV transition.
^{d} Not distinguishable from zero.

at $E^* = 71$ keV. In the study of Nathen *et al.*, no evidence for a 71-keV transition was observed due to an electronic cut-off. In this work such a transition (unless it is the decay from an isomeric state) should be observable (c.f. the 83.8 keV transition in ^{57}Mn). No evidence for such a transition has been observed. This is not surprising if the 71-keV transition is an M3, given its expected transition rate. The assignment of this state as a 65s isomer is in agreement with the non-observation of the 71-keV transition. This being the case, we have adopted a spin of (4^+) for the 71-keV level [8][1]. In the previous γ ray spectroscopy of ^{58}Mn [1] the 1154.8-keV transition was assigned as a stretched quadrupole. The angular distribution analysis presented here indicates that the 1154.8-keV transition is in fact a dipole. Such an assignment is not inconsistent with the lifetime measurements reported in ref. [1]. With the exception of the 1268- and 1695-keV transitions, the observed γ rays assigned to ^{58}Mn are all dipoles. The 1268-keV transition is assumed to be a stretched quadrupole as it allows a bypass of the 680.1- and 582.1-keV transitions. The 1694.6 keV transition has a weak intensity, thus its multipolarity cannot be ascertained. The placement of this transition is tentative given its weak intensity. The 0.87-MeV level is assigned as $J^\pi = (6^+)$ from intensity arguments. Both the 1011-keV transition that feeds this level and the 144-keV transition that decays from this level have large errors on their A_2/A_0 measurements, thus are not useful in determining the spin and parity of the 0.87-MeV level. The assignment of the 1154.8-keV transition as a dipole suggests that either of the 1011- or the 144-keV transitions have $\Delta J = 0$. As the decay of the 1.88-MeV state is predominantly via the 1154.8-keV transition, it is unlikely that the 0.87-MeV state has the same spin as the 1.88-MeV state.

In conclusion, we have reinvestigated the high-spin gamma decays of the nuclei ^{57}Mn and ^{58}Mn. Angular correlation coefficients for the majority of the observed decays have been determined. It is hoped that this work will provide an insight into a region of the nuclear chart in which additional study, both theoretical and experimental is required.

[1] The spins of both this level and the ground-state are uncertain. The ground state having a spin of either 1 or 0.

We would like to thank the crew of the 88″ cyclotron for providing the high quality beam, J. Greene (Argonne National Laboratory) for manufacturing our targets, and D.C. Radford for his analysis software [6]. This work has been supported by the Natural Sciences and Engineering Research Council of Canada, the U.S. D.O.E. under contract No. DE-AC03-76SF00098, one of us (A.M.) acknowledges the support of the United Kingdom Engineering and Physical Sciences Council.

References

1. A.M. Nathen, J.W. Olness, E.K. Warburton, J.B. McGrory, Phys. Rev. C **17**, 1008 (1978).
2. U. Bosch *et al.*, Nucl. Phys. A **447**, 89 (1988).
3. F. Ajzenberg-Selove, R.E. Brown, E.R. Flynn, J.W. Sunier, Phys. Rev. C **31**, 777 (1985).
4. M.R. Bhat, Nucl. Data. Sheets, **85**, 415 (1998).
5. J.P. Martin *et al.*, Nucl. Instrum. Meth. Phys. Res. A **257** 301 (1987).
6. D.C. Radford, Nucl. Instrumn. Meth. Phys. Res. **A 361**, 267 (1995).
7. K.S. Krane, R.M. Steffen and R.M. Wheeler, Nuclear Data Tables **11**, 351 (1973).
8. M.R. Bhat, Nucl. Data. Sheets, **80**, 789 (1997).