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States of ^{54}V and ^{58}Mn†

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The ^{54}Cr$(t,{}^3$He$)^{54}$V and ^{58}Fe$(t,{}^3$He$)^{58}$Mn reactions have been used to study the masses and the low-lying excited states of ^{54}V and ^{58}Mn, using 23 MeV tritons and a quadrupole-dipole-dipole-dipole spectrometer. The mass excess of ^{54}V is $-49\,891(15)$ keV. At least 19 excited states of ^{54}V with $E_x < 2.5$ MeV have been observed. The mass excess of ^{58}Mn is $-55\,832(30)$ keV, assuming that an (unresolved) isomeric state exists at $E_x = 30 \pm 10$ keV. β decay evidence from other work, together with these results, suggests that these two states have $J^\pi = 3^+$ and 0^+. Sixteen other states of ^{58}Mn have been observed with $E_x < 1.9$ MeV.

[NUCLEAR REACTIONS ^{54}Cr$(t,{}^3$He$)$, ^{58}Fe$(t,{}^3$He$)$, $E=23.0$ MeV; measured (θ). ^{54}V, ^{58}Mn deduced levels. New masses of ^{54}V and ^{58}Mn.]

I. INTRODUCTION

The decay of ^{54}V has been studied by Ward, Pile, and Kuroda[1] who found that $Q_{\beta^-} = 7.0 \pm 0.1$ MeV and that its half-life is 43 ± 3 sec. ^{54}V decays to high spin states of ^{54}Cr: No decay is observed to ^{54}Cr*(0, 0.83) with $J^\pi = 0^+, 2^+$. This is consistent with $J^\pi = 5^+$ for ^{54}V$_{\text{g.s.}}$ which is suggested on the basis of systematics.[1]

In the compilation of Wapstra and Bos[2] the mass excess of ^{58}Mn is given as $-56\,210 \pm 100$ keV, which leads to $Q_{\beta^-} = 5940 \pm 100$ keV. Three recent experiments[3-5] have studied the β decay of ^{58}Mn. Ward, Pile, and Kuroda[3] report that two activities are involved in the decay: One of these has $\tau_{1/2} = 3.0 \pm 0.1$ sec and $E_{\beta^-} = 6.1 \pm 0.3$ MeV; the other has $\tau_{1/2} = 65.3 \pm 0.7$ sec (see Ref. 4) and $E_{\beta^-} = 6.1 \pm 0.2$ MeV (Ref. 3), 5.9 ± 0.1 MeV (Ref. 4). The shorter-lived state decays 100% to the ground state of ^{58}Fe ($J^\pi = 0^+$) with a $\log ft = 5.0$. This suggests[3] that the 3-sec ^{58}Mn state has $J^\pi = 0^+$ or 1^+. The most complete study of the decay of the 65-sec state is that by Tirsell, Multhauf, and Raman[5]: They report that this ^{58}Mn state decays very strongly to ^{58}Fe*(2.134) ($J^\pi = 3^+$). The nature of the decay to this and to other states of ^{58}Fe leads Tirsell *et al.*[5] to conclude that the 65-sec state of ^{58}Mn probably has $J^\pi = 3^+$ but that a 4^+ assignment cannot be excluded. The previous evidence thus suggests two closely spaced states of ^{58}Mn with $J^\pi = 0^+$ or 1^+ ($\tau_{1/2} = 3$ sec) and with $J^\pi = 3^+$ or 4^+ ($\tau_{1/2} = 65$ sec): It is not clear which of these is the ground state.[6] Kocher and Auble[6] regard the assignment of the 3-sec activity to ^{58}Mn as uncertain.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The present experiment uses the $(t,{}^3$He$)$ reaction to measure the masses and to observe the low-lying excited states of ^{54}V and ^{58}Mn. The reactions were studied using a 23-MeV triton beam from the LASL three-stage Van de Graaff facility and a magnetic spectrometer of the quadrupole-dipole-dipole-dipole (Q3D) type which uses a focal plane detector system involving a 1-m long helix detector with 0.8-mm spatial resolution.[7]

The self-supporting ^{54}Cr target, enriched[8] to 94.35% ^{54}Cr (also 3.26% ^{52}Cr), was 120 μg/cm^2 thick and was oriented at 30° to the incident triton beam. Data were taken at three angles, $\theta_{\text{lab}} = 25°$, 30°, 35°, and two values of the magnetic field ($B = 5.353$ and 5.139 kG). Runs were also made with an enriched ^{24}Mg target under identical conditions to calibrate[9] the channel number versus the energy of the outgoing ^{3}He ions. The self-supporting ^{58}Fe target was enriched[8] to 82.48% ^{58}Fe (15.57% ^{56}Fe, 1.48% ^{57}Fe, and 0.46% ^{54}Fe). It had a thickness of 100 μg/cm^2 and was oriented at 30° to the incident triton beam. Again data were taken at the three angles, $\theta_{\text{lab}} = 25°$, 30°, 35°. For calibration and contaminant subtraction, runs with enriched ^{24}Mg, ^{56}Fe, and ^{57}Fe targets were made under identical conditions.

A. States of ^{54}V

Figure 1 shows spectra obtained at $\theta_{\text{lab}} = 25°$, at $B = 5.353$ and 5.139 kG. The numbered groups correspond to states in ^{54}V: See Table I. With the ex-

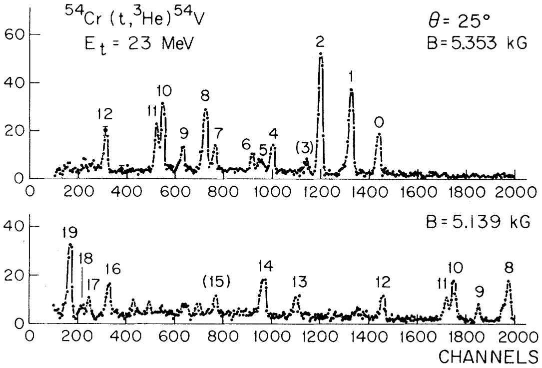

FIG. 1. Spectra of the ^{3}He ions from the ^{54}Cr(t, ^{3}He)^{54}V reaction at $E_t = 23.0$ MeV, $\theta_{\text{lab}} = 25°$, $B = 5.353$ and 5.139 kG. The ordinate shows the average number of counts recorded in a 5-channel bin. The abscissa shows the channel number. The numbered groups are due to states in ^{54}V: See Table I.

ception of group 5 the widths of the observed groups (full width at half maximum ≃25 keV) are consistent with the involvement of single states. However, states ≲20 keV apart would not be resolved, nor would we resolve states which are weakly populated and which are located in the near vicinity (≲40 keV) of strong groups.

Group 0 corresponds to the ground state of ^{54}V.

TABLE I. Energy levels of ^{54}V.

Group No.[a]	E_x in ^{54}V (keV)	$\frac{d\sigma}{d\Omega}$[b] (μb/sr)
0	0[c]	2.0
1	111 ± 8	3.9
2	238 ± 8	4.9
3	(291 ± 10)	
4	442 ± 10	1.4 ± 0.5
5	495 ± 10	
6	532 ± 10	
7	694 ± 10	0.9 ± 0.4
8	739 ± 10	2.4 ± 0.9
9	840 ± 15	
10	930 ± 15	1.9 ± 0.7
11	960 ± 15	1.4 ± 0.8
12	1200 ± 10	1.6
13	1533 ± 15	
14	1662 ± 15	2.1 ± 0.9
15	1852 ± 10	
d		
16	2309 ± 10	1.4
17	2390 ± 15	
18	2425 ± 15	
19	2477 ± 10	2.8

[a] See Fig. 1.

[b] $\theta_{\text{lab}} = 25°$; ±30% except where shown otherwise.

[c] Q_0 measured in this experiment is −7023 ± 15 keV.

[d] There is weak evidence in two runs for states at $E_x = 1.92$, 1.98, and 2.13 MeV.

We find $Q_0 = -7023 \pm 15$ keV which leads to an atomic mass excess of −49 891 ± 15 keV (based on the Wapstra-Bos masses[2] for ^{54}Cr, t, and ^{3}He). The mass of ^{54}V is then 53.946 440(16) amu and $Q_{\beta^-} = 7042 \pm 15$ keV. This value for Q_{β^-} is in agreement with the value 7.0 ± 0.1 MeV determined by Ward *et al.*[1] and substantially reduces the error in the mass value.

In deciding on the location of the energy levels of ^{54}V we have to consider the possibility that some of the structure might be due to the ^{52}Cr(t, ^{3}He)^{52}V reaction since ^{52}Cr was a 3.26% component of the target. Fortunately the mass and the energy levels of ^{52}V are well known: $Q_0 = -3958 \pm 2.7$ keV (Ref. 2) and the level density of ^{52}V is very high.[10] Figure 1 covers approximately the range $2.5 < E_x < 4.2$ MeV in ^{52}V, yet we do not observe any evidence for individual groups for channels 300→500 and 1500→2000 at $B = 5.353$ kG, regions in which ^{52}V states would be expected to appear if very strongly populated. We conclude therefore that none of the numbered groups are due to ^{52}V: The unnumbered groups at channels 500, 650, and 700 ($B = 5.139$ kG) are weak enough so that they might be due to particularly intensely populated states (or unresolved groups of states) in ^{52}V. A general rule of thumb that one might take is to consider the strongest populated state in ^{54}V, the state at $E_x = 238$ keV (group 2) which has a differential cross section of 4.9 μb/sr at 25°. If the most intense state in ^{52}V were populated with the same cross section, it would appear (taking into account the relative amounts of ^{52}Cr and ^{54}Cr in the target) as a group with an intensity of 40 counts above background, spread over some 30–40 channels, i.e., it could not be distinguished from background. Thus the background presumably reflects the contribution of the ^{52}Cr (t, ^{3}He)^{52}V reaction and the groups we observe are due to states in ^{54}V.

The differential cross sections we have observed for the states of ^{54}V are appreciably smaller than those for the ^{34}S(t, ^{3}He)^{34}P reaction[9] (highest differential cross section observed in that reaction was 94 μb/sr) and in the ^{62}Ni(t, ^{3}He)^{62}Co reaction.[11] This is not surprising for two reasons: (a) The Q value for the reaction to ^{54}V$_{\text{g.s.}}$ is 1.7 MeV more negative than Q_0 for ^{34}P$_{\text{g.s.}}$ and ^{62}Co$_{\text{g.s.}}$; (b) the ΔJ between the target nucleus and the ground state of ^{54}V, for instance, is very large: $0^+ \rightarrow (5^+)$.

B. States of ^{58}Mn

Figure 2 shows spectra taken at $\theta_{\text{lab}} = 25°$ and 35°. The groups labeled 0→16 correspond to states of ^{58}Mn: See Table II. The other structures are due to states in ^{56}Mn and ^{57}Mn from the ^{56}Fe and ^{57}Fe in the target.

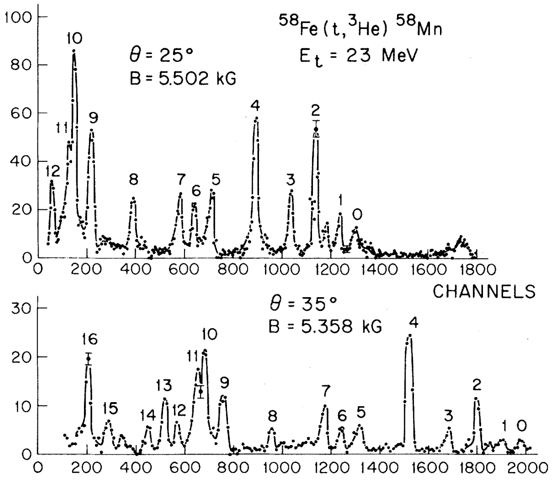

FIG. 2. Spectra of the ^{3}He ions from the ^{58}Fe(t, ^{3}He)^{58}Mn reaction at $E_t = 23.0$ MeV and at $\theta = 25°$ ($B = 5.502$ kG) and 35° ($B = 5.358$ kG). The ordinate shows the average number of counts recorded in a 5-channel bin ($\theta = 25°$) or in a 10-channel bin ($\theta = 35°$). The abscissas show the channel number. The numbered groups are due to states in ^{58}Mn: See Table II.

The highest energy ^{3}He group which can be attributed to the ^{58}Fe(t, ^{3}He)^{58}Mn reaction is that at channel 1300 in the 25° spectrum: It corresponds to $Q = -6318 \pm 15$ keV but its width is appreciably greater than that of other observed groups in this reaction (full width at half maximum ≃ 50 keV, rather than ~30 keV). We suggest therefore that group 0 is due to two unresolved states with a separation of 30 ± 10 keV, and we adopt $Q_{\text{g.s.}} = -6300 \pm 30$ keV. Then the mass excess of ^{58}Mn is $-55\,832 \pm 30$ keV, the mass is 57.94006(3) amu, and the E_{β^-} (max) (to ^{58}Fe$_{\text{g.s.}}$) is 6320 ± 30 keV. This E_{β^-} is ~380 keV greater than the value previously used (see Introduction) whose error was estimated to be 100 keV. It should be noted that if the earlier value of the mass of ^{58}Mn were used to calculate the ground state location, the ground state group should occur at channel 1650 in the 25° spectrum. No evidence is seen for such a state in the three runs which were made with the same value of the magnetic field ($B = 5.502$ kG) at $\theta = 25°$, 30°, and 35°. The structure at approximately channel 1750 in Fig. 2 is due to imperfectly subtracted ^{56}Mn and ^{57}Mn groups.

TABLE II. States of ^{58}Mn from ^{58}Fe(t, ^{3}He)^{58}Mn.

Group No.[a]	E_x in ^{58}Mn (keV)	$\frac{d\sigma}{d\Omega}$[b] (μb/sr)
0	0[c]	3.7
1	77 ± 8	2.8
2	174 ± 12	6.4
3	294 ± 10	5.4
4	454 ± 8	11.8
5	665 ± 15	6.4
6	744 ± 8	4.9
7	813 ± 15	6.0
8	1036 ± 15	5.7
9	1250 ± 15	10.6
10	1332 ± 20	17
11	1370 ± 20	
12	1456 ± 20	
13	1515 ± 20[d]	
14	(1595 ± 20)[d]	
15	1776 ± 20[d]	
16	1872 ± 20[d]	

[a] See Fig. 2.

[b] $E_t = 23$ MeV, $\theta_{\text{lab}} = 25°$; values are ±30%.

[c] $Q = -6.318 \pm 0.015$ MeV; this group probably consists of two unresolved groups 30 ± 10 keV apart: see text.

[d] Observed in only one run.

Thus we find $Q_0 = 6.30 \pm 0.03$, and $Q = -6.33 \pm 0.03$ MeV for an isomeric state: One of these presumably corresponds to the state with $\tau_{1/2} = 65.3 \pm 0.7$ sec with $J^\pi = 3^+$ (or 4^+) and the other to the possible state with $\tau_{1/2} = 3.0 \pm 0.1$ sec and $J^\pi = 0^+$ or 1^+. We cannot state which of these two states is the ground state of ^{58}Mn but the spacing of the two states, 30 ± 10 keV, enables us to eliminate the possibility of an $E2$ transition ($1^+ \to 3^+$, or $3^+ \to 1^+$). The lifetime of an $E2$ transition with $E_\gamma = 30 \pm 10$ keV is $\approx 10^{-2}-10^{-3}$ sec.[12] Both $M3$ and $E4$ transitions have sufficiently large lifetimes (10^6-10^8 s and $10^{13}-10^{15}$ sec) so that the direct β decay of the isomeric state can take place. If we assume that the 65-sec state has $J^\pi = 3^+$ (which is the most reasonable value from the β-decay work[5]), then the possible 3-sec state has $J^\pi = 0^+$.

How will the new mass of ^{58}Mn affect the logft values calculated previously?[3, 5]

(a) Assuming the ground state to be the 3^+, 65-sec state, the $\log ft$ value[13] for the predominant transition (75.8%) to ^{58}Fe*(2.134) ($J^\pi = 3^+$) becomes 5.56, rather than 5.5 based on $Q = 4186$ keV instead of $Q = 3966$ keV.[5] The $\log ft$ values to the 2^+ states ^{58}Fe*(3.233, 4.313) (branching ratios 3.2 and 2.25%) change from 6.2 and 5.5 (calculated by Ref. 5) to 6.35 and 5.70, respectively.

(b) Assuming the isomeric state to be the 0^+, 3-sec level at $E_x = 30 \pm 10$ keV, $\log f_0 t = 4.9$ for the only transition observed,[3] that to ^{58}Fe$_{\text{g.s.}}$, as compared with the previous value of 5.

There had been no previous evidence on other states of ^{58}Mn. Table II lists 16 other states of ^{58}Mn with $E_x < 1.9$ MeV observed in this reaction. It should be noted that we observed the region $1.5 < E_x < 1.9$ MeV during only one run (see lower part of Fig. 2) and that we might have missed weakly populated states in that region. All the states we observe are bound, and the widths of all groups, except group 0 which was previously discussed, are consistent with widths of single states. However, states separated by ≲15 keV, or weakly populated states within ~40 keV of the observed groups, would not have been observed.

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