Spin, Hyperfine Structure, and New Magnetic Moment of 21-min Mn^{52m}†

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The hyperfine structure of 21-min Mn^{52m} has been measured by atomic-beam magnetic resonance. The spin is 2, and the magnetic hyperfine constant $|a|$ is 200±4 kc/sec, yielding a magnetic moment $|\mu| = 0.0077(4)$ nm. This unusually small number is in much better agreement with theoretical calculations than the previously reported moment. The value of b is expected to be zero; it was not measured.

I. INTRODUCTION

As part of our program of measuring nuclear spins and moments in the $f_{7/2}$ shell by atomic-beam magnetic resonance, we have measured the hyperfine structure of 21-min Mn^{52m}. The magnetic moment of this isotope has been reported[1] as about 1 nm, while a recent calculation,[2] otherwise successful in predicting moments to 0.2 nm, gives 0.01 nm. The present experiment resolves this discrepancy in favor of the calculated value.

We discuss the previous work in Sec. II and the present experiment in Secs. III and IV. In Sec. V we comment on the results.

II. BACKGROUND

Bauer *et al.*[1] measured the magnetic moments of several manganese isotopes by the method of nuclear alignment in paramagnetic crystals. In most of these measurements the Mn isotope of interest was grown into the crystal. In the case of Mn^{52m} they grew a crystal containing 8-h Fe^{52}, since the half-life of the manganese was too short. Fe^{52} has spin 0 and thus decays to Mn^{52m} (see Fig. 1) with no memory of nuclear alignment. At low temperatures produced by adiabatic demagnetization, the manganese should then line up with an external magnetic field. In its subsequent decay the 1.43-MeV gamma ray will have an angular distribution which is not isotropic. For other manganese isotopes in this crystal the anisotropy was as great as 40%. However, the 2-2-0 angular correlation is not very favorable, and the observed anisotropy was only 3%. This led to a magnetic moment for Mn^{52m} of about 0.8 to 1.0 nm, depending on the nature of the β decay.[1]

McCullen, Bayman, and Zamick (MBZ)[2] have recently reported a calculation which reproduces the observed behavior of spins, moments, ft values and spectroscopic factors quite well over the $1f_{7/2}$ shell. The difference between their calculated nuclear magnetic moments and experimental measurements is typically 0.1–0.2 nm. For Mn^{52m} the calculation gives +0.01 nm, or a difference of about 1 nm. This striking disagreement is not even approached in the sixteen other cases listed. A simple argument (see Sec. V) shows that the observed moment is badly out of line with any theory restricted to the $1f_{7/2}$ shell, and can only be explained by severe configuration mixing. By contrast, the moment of the 6+ ground state of Mn^{52} differs by only 0.03 nm from the calculated value.

An examination of the experimental data[1] which led to this unusual magnetic moment reveals some uncertainties. We therefore decided to make an independent measurement of the Mn^{52m} moment by the atomic-beam magnetic resonance method.

III. THEORY OF THE EXPERIMENT

The hyperfine-structure Hamiltonian for an atom with magnetic dipole and electric quadrupole interactions is[3]

$$\mathcal{H} = ha(\mathbf{I}\cdot\mathbf{J}) + \frac{hb}{2}\frac{3(\mathbf{I}\cdot\mathbf{J})^2+\frac{3}{2}(\mathbf{I}\cdot\mathbf{J})-I(I+1)J(J+1)}{I(2I-1)J(2J-1)} - g_J\mu_0\mathbf{J}\cdot\mathbf{H} - g_I\mu_N\mathbf{I}\cdot\mathbf{H}. \quad (1)$$

For small external fields H, the good quantum numbers are (F, M_F), where $\mathbf{F}=\mathbf{I}+\mathbf{J}$ and M_F is the projection of $\mathbf{F}$ on $\mathbf{H}$. In the limit of very high field H the good

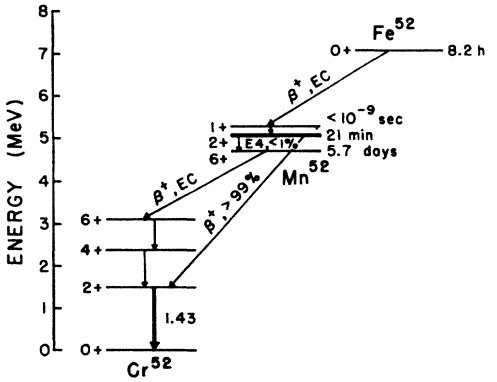

FIG. 1. Decay scheme of Fe^{52} (from Ref. 1).

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[1] R. W. Bauer, M. Deutsch, G. S. Mutchler, and D. G. Simons, Phys. Rev. **120**, 946 (1960).
[2] J. D. McCullen, B. F. Bayman, and L. Zamick, Phys. Rev. **134**, B515 (1964).
[3] N. F. Ramsey, *Molecular Beams* (Oxford University Press, London, 1956). A more detailed discussion is given here.

quantum numbers become (M_I, M_J), the projections of **I** and **J** separately on **H**. In this limit the Hamiltonian becomes

$$\mathcal{H} \cong -g_J\mu_0 H M_J + haM_IM_J + hb\frac{(3M_J^2-J(J+1))(3M_I^2-I(I+1))}{2J(2J-1)2I(2I-1)} - g_I\mu_N H M_I. \quad (2)$$

An atomic-beam magnetic resonance machine deflects atoms by inhomogeneous strong magnetic fields. From the above form of $\mathcal{H}$ it follows that the deflection of an atom is proportional to its value of M_J. The focusing-type machine deflects atoms which have not undergone a change in the sign of M_J to one collector ("beam"), and atoms which have undergone a change in the sign of M_J to another ("flop"). Ordinarily the "flop" signal is small until radio-frequency power is applied at the correct resonance frequency. However, when we attempted to investigate resonances of Mn^{52m} at low magnetic field, we found a gigantic "flop" signal, ten times the usual height, in the absence of any radio frequency and in defiance of all effects to reduce it.

We interpreted this as evidence that the magnetic moment of Mn^{52m} is extremely small. The machine used here was the original Lemonick-Pipkin-Hamilton (LPH) machine,[4] which has a magnetic shield between the "A" and "C" magnets. This shield has a small hole in it through which the beam must pass; as the atom passes through the hole, the magnetic field it experiences is changed by a large percentage in a time of ~ 2 μsec. Thus the atom sees Fourier components in the magnetic field which extend up to ~ 1 Mc/sec. Assuming that the magnetic field changes in magnitude but not in direction, these Fourier components are only capable of exciting hyperfine transitions with $\Delta M_F = 0$. Then transitions must take place between states of different F which are separated in energy by less than ~ 1 Mc/sec. For such states to exist in quantity, the hyperfine constants a and b must be very small. (If $\Delta M_F = 1$ transitions were allowed, this condition would not be necessary. Since no previous experiment on the LPH machine was similarly afflicted, we conclude that $\Delta M_F = 1$ is forbidden.)

Work was resumed on Mn^{52m} when the newer atomic-beam apparatus for short-lived isotopes[5] was available. This machine has no magnetic shield, and the exit end of the "A" magnet is constructed so as to minimize sudden changes in the magnetic field. The fact that the enormous "flop" signal was no longer found supports the above explanation of its occurrence. Since the hyperfine structure would still be difficult to observe at low field, it was decided to observe it at relatively high field instead.

In the Hamiltonian for high field [Eq. (2)] the term in g_JH is dominant. We shall neglect the term in g_IH as being very much smaller than the others. Here $I=2$ and $J=\frac{5}{2}$, so the six Zeeman levels are split up into five hyperfine components each (see Fig. 2). The states with $M_J = \pm\frac{1}{2}$ have energies (note that g_J is negative)

$$E(M_I, \pm\tfrac{1}{2}) = \mp\tfrac{1}{2}g_J\mu_0 H \pm \tfrac{1}{2}haM_I - \tfrac{1}{10}hb(M_I^2-2). \quad (3)$$

The observable transitions obey the selection rules $\Delta M_J = \pm 1$, $\Delta M_I = 0$; thus they are at frequencies

$$\nu(M_I) = (-g_J\mu_0 H/h) + aM_I. \quad (4)$$

The term in b drops out for these transitions; it is expected that b is very small in any case (see Sec. IV). If $b=0$, then the transitions between any pair of adjacent M_J levels will have these frequencies, and it is almost certain that multiple-quantum transitions will also occur with a substantial probability. This simply increases the height of the observed resonances. Therefore we expect to see a group of $(2I+1)$ transitions, five in this case, equally spaced about a center frequency of $(g_J\mu_0 H/h)$ with spacing a.

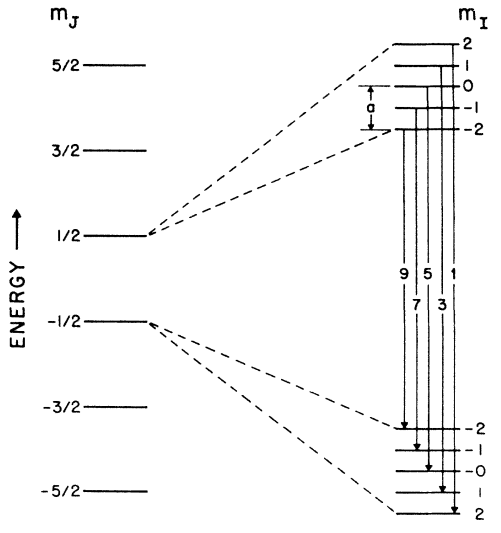

FIG. 2. Energy levels of Mn^{52m} at high field, and the allowed transitions between $M_J = \pm\frac{1}{2}$. The transitions are numbered as in Table I.

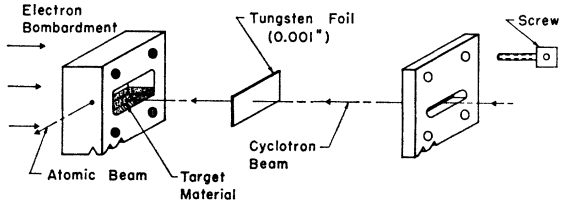

FIG. 3. Molybdenum electron-bombardment oven design.

[4] A. Lemonick, F. M. Pipkin, and D. R. Hamilton, Rev. Sci. Instr. **26**, 1112 (1955).

[5] O. Ames, E. A. Phillips, and S. S. Glickstein, Phys. Rev. **137**, B1157 (1965).

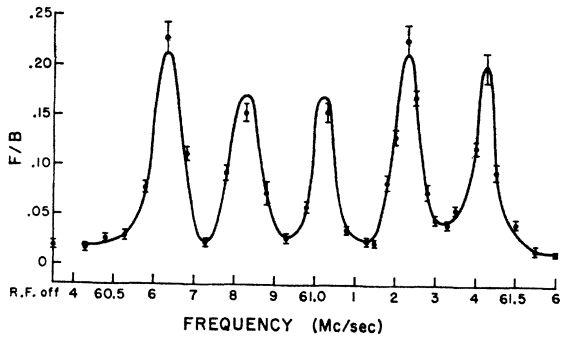

FIG. 4. Observed Mn^{52m} resonances at high field. The points have been adjusted to a K^{39} resonant frequency of 16.873 Mc/sec ($H=21.782$ G). The center peak is calculated to lie at $\nu_0=61.022$ Mc/sec. The point plotted on the F/B axis was taken with the rf off.

IV. DETAILS AND RESULTS

The external beam of the Princeton FM cyclotron was directed into a molybdenum oven which contained natural chromium metal (see Fig. 3). Manganese was produced by the reaction $Cr^{52}(p,n)Mn^{52}$, which was such an efficient source of fast neutrons that it was necessary to improve the shielding of the machine. A beam of 0.150 μA gave a tolerable neutron level and adequate activity. The oven was heated to ~1300°C. by electron bombardment; at this temperature the manganese atoms diffused out of the coarse granules in a time of the order of 5 min, while the chromium seemed not to evaporate appreciably. After being heated, the oven could not be taken apart again, but it lasted for the whole experiment. An autopsy later showed the chromium apparently unchanged, except for some which had recrystallized onto the tungsten window.

The detector assembly was identical to that used for K^{38}.[6] The activity was collected on iron etched in HCl and counted by a pair of thin plastic beta scintillators. The oven was bombarded, and the collectors exposed, for approximately 10 min; then a new probe was inserted and exposed while the first one was being counted.

The accumulation of data was handicapped by the fact that the manganese atom has a very large electronic moment (5 Bohr magnetons), making the resonant frequency unusually sensitive to the field strength in the C magnet. Small shifts in this field, almost unavoidable in an experimental area near so many magnetic disturbances, shifted the resonances by a troublesome amount. For example, turning the cyclotron magnet on would lower the manganese resonant frequency by 2 Mc/sec. The final data of Fig. 4 were taken in one run so as to minimize these problems.

In Fig. 4 we plot the normalized counting rate (defined as flop counts/beam counts) as a function of frequency at about 22 G. There are five and only five lines, proving that the spin of Mn^{52m} is indeed 2. Data from this curve and others like it (Table I) give the values $g_J=-2.0016\pm0.0002$; $|a|=200\pm4$ kc/sec. Comparison with the known hyperfine structure of Mn^{55} (Table II) gives $|\mu|=0.0077$ nm. This appears to be the second smallest moment ever measured; the Uppsala[7] value of 0.0017 for Tl^{198} is the smallest. The value of a is also unusually small.

These small moments are accompanied by very large hyperfine-structure anomalies[8]; a rough calculation

TABLE I. Summary of observational data at magnetic fields between 21.0 and 21.8 G, as reduced by Hyperfine-4A.[a] The last five points correspond to the curve in Fig. 6. Result of least-squares fit: $a=0.2001\pm0.0038$; $\chi^2=2.3$. Comparing isotope: Mn^{55}, ${}^6S_{5/2}$, $I=\frac{5}{2}$, $g_J=-2.00152$, $\mu_I=+3.4678$, $a=72.422$ Mc/sec. Calibrating isotope: K^{39}, ${}^2S_{1/2}$, $I=\frac{3}{2}$, $g_J=-2.00231$, $\mu_I=+0.3914$, $\Delta\nu=461.7197$ Mc/sec.

K^{39} calibration frequency (Mc/sec)	Mn^{52m} frequency (Mc/sec)	Resonance assignment (see Fig. 2)	Residual and probable error (kc/sec)
16.423(6)	59.745(10)	3	+2(22)
16.425(6)	59.555(10)	5	+5(22)
16.427(4)	59.375(30)	7	+19(33)
16.428(3)	59.165(50)	9	+7(51)
16.488(7)	60.140(15)	1	−17(28)
16.499(6)	59.402(10)	9	+9(22)
16.508(3)	60.220(15)	1	−3(18)
16.275(5)	59.070(10)	5	+15(19)
16.283(4)	58.880(10)	7	−1(17)
16.865(6)	60.990(10)	5	−8(22)
16.867(6)	60.795(10)	7	−9(22)
16.869(5)	60.607(8)	9	−3(18)
16.871(4)	61.420(8)	1	+3(15)
16.873(3)	61.232(8)	3	+8(13)

[a] Computer routine based on the Berkeley programs (see Ref. 5).

TABLE II. Measured hyperfine structure of manganese isotopes. If sign is not stated, it is not known.

Isotope	I	a (Mc/sec)	b (Mc/sec)	c (Mc/sec)	μ (nm)	Q (b)	g_J
Mn^{55},[a] stable	$\frac{5}{2}$	72.422(2)	0.013(28)	0.0014(18)	+3.4678[d]	+0.35(5)[d]	−2.00152(5)[f]
Mn^{56},[b] 2.6 h	3	56.3924(23)	0.00(5)	···	[+3.2403(2)][d,e]		−2.0012(1)
Mn^{52m},[c] 21 min	2	0.200(4)	···	···	[0.0077(4)][e]		−2.0016(2)

[a] G. K. Woodgate and J. S. Martin, Proc. Phys. Soc. (London) **A70**, 485 (1957).
[b] W. J. Childs, L. S. Goodman, and L. J. Kieffer, Phys. Rev. **122**, 891 (1961).
[c] Present work.
[d] I. Lindgren, Appendix I in *Perturbed Angular Correlations* (North-Holland Publishing Company, Amsterdam, 1964).
[e] Computed from the Fermi-Segrè formula (see Ref. 3).
[f] L. Goodman (private communication).

[6] E. A. Phillips, O. Ames, and S. S. Glickstein, Phys. Rev. **138**, B773 (1965).
[7] I. Lindgren (private communication).
[8] A. Bohr, Phys. Rev. **81**, 331 (1951).

TABLE III. Nuclei whose wave functions are in principle the same. A negative number of particles indicates holes.

Nucleus number	Protons	Neutrons	Value of β	Example
1	x	y	β_1	$_{21}Sc_{23}^{44}$
2	y	x	$-\beta_1$	$_{23}V_{21}^{44}$ (unknown)
3	$-x$	$-y$	β_1	$_{27}Co_{25}^{52}$ (unknown)
4	$-y$	$-x$	$-\beta_1$	$_{25}Mn_{27}^{52}$

using the MBZ wave functions[2] gives $|\epsilon|\cong 2\frac{1}{2}\%$ for Mn^{52m}. To be safe, we quote $|\mu|=0.0077\pm 0.0004$ nm.

Table II lists the known hyperfine-structure data on isotopes of manganese. We have recently learned[7] that Lindgren's group has obtained a value for a (Mn^{52m}) which agrees well with ours. The value of g_J from our data is in satisfactory agreement with more accurate measurements. No isotope of manganese has yet been found with a nonzero value of b, the quadrupole interaction constant. In fact, the $^6S_{5/2}$ electronic state of manganese is spherically symmetric and has no hyperfine interactions at all in first order; the comparatively small values of a which are observed are due to core polarization.[9] To measure b for Mn^{52m} would require observing the resonances at intermediate field, i.e., less than 1 G; an attempt was made to do this with unsatisfactory results. The data in Table I are consistent with $|b|<2$ Mc/sec.

V. DISCUSSION

The new magnetic moment for Mn^{52m}, ± 0.0077, agrees extremely well with the value of $+0.01$ calculated by McCullen *et al.*[2] It also is satisfying for some more general reasons.[10]

The odd-group model describes the protons outside a closed shell as coupled to a spin I_P with gyromagnetic ratio g_P and the neutrons similarly as coupled to I_N with g_N. Since we restrict these protons and neutrons to the $f_{7/2}$ shell, g_P and g_N are independent of the number of particles. When I_P and I_N couple to I, the resulting gyromagnetic ratio is

$$g=\tfrac{1}{2}(g_P+g_N)+\tfrac{1}{2}(g_P-g_N)\times(I_P(I_P+1)-I_N(I_N+1))/I(I+1). \quad (5)$$

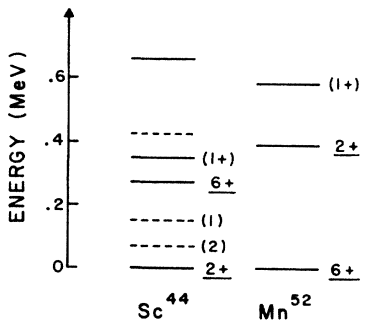

FIG. 5. Energy levels of Mn^{52} and Sc^{44} compared. The dashed states do not seem to be $f_{7/2}$ (Ref. 2).

[9] N. Bessis, H. Lefebvre-Brion, and C. M. Moser, Rev. Mod. Phys. 35, 548 (1963); Phys. Rev. 124, 1124 (1961).

[10] The argument follows that given by D. L. Harris and J. D. McCullen, Phys. Rev. 132, 310 (1963). See also Ref. 2.

TABLE IV. Comparison of magnetic moments of Mn^{52} and Sc^{44}.

	$f_{7/2}$ particles	I	Magnetic moments (nm) μ_{exp}	μ_{calc} (Ref. 2)	$(\mu/I)_{exp}$
Sc^{44}	$1p$, $3n$	6	+3.868(20)[a]	+3.62	+0.645(3)
		2	+2.556(30)[a]	+2.21	+1.278(15)
Mn^{52}	$-3p$, $-1n$	6	3.075[b]	+3.05	(+)0.512
		2	0.0077(4)[c]	+0.01	±0.004(0)
Odd-group model prediction ($I_P=I_N=\frac{7}{2}$)					+0.55
Equation (7) prediction: $(\mu/I)_{Sc}+(\mu/I)_{Mn}=g_P+g_N=$					+1.11
Experimental numbers:		(I=6)			+1.157(4)
		(I=2)			+1.278(15)

[a] Recalculated from data originally reported in Ref. 10.
[b] I. Lindgren (private communication).
[c] This work.

The actual nucleus may not be very well represented by this model; if I_P and I_N are not good quantum numbers, we can still expand the actual nuclear wave function in terms of a set of values of I_P and I_N. On the assumption that the nucleons are restricted to the $f_{7/2}$ shell, this set is complete and the expansion is exact. Then g will be given by a sum of several expressions like Eq. (5); the coefficients of the second term will average to some number β:

$$g=\tfrac{1}{2}(g_P+g_N)+\tfrac{1}{2}(g_P-g_N)\beta. \quad (6)$$

If we now assume charge symmetry of nuclear forces, the magnitude of β is not changed by substituting neutrons for protons or holes for particles. Thus we have four nuclei (see Table III) with the same magnitude of β; the sign of β must change when neutrons and protons are interchanged [see Eq. (5)].

Any model of these nuclei which assumes charge symmetry and restricts the nucleons to the $f_{7/2}$ shell must predict that all four will have the same energy levels and the same magnitude for β. In fact (see Fig. 5) the energy levels of Mn^{52} and its cross conjugate[2] Sc^{44} are similar in that both have low-lying 2+ and 6+ states. If the values of β for these two nuclei are equal and opposite, then

$$g(Sc^{44})+g(Mn^{52})=g_P+g_N=\begin{cases}1.11\ \text{(Schmidt limit)}\\ 1.10\ \text{(MBZ)}^2.\end{cases} \quad (7)$$

Table IV shows the experimental test of this relationship. The agreement is excellent for the 6+ states and very good for the 2+ states, where the individual moments are quite far from the odd-group model values.

As mentioned earlier, a gross violation of these predictions would imply severe admixture of other shells in the wave functions. It is no longer necessary to draw this unhappy conclusion.

ACKNOWLEDGMENTS

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