Nuclear Spin and Magnetic Moment of 2.6-hr Mn^{56}†

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The atomic-beam magnetic-resonance technique has been used to examine the hyperfine structure of 2.6-hr Mn^{56}. The results obtained are $I=3$, $|a|=56.3924\pm0.0023$ Mc/sec, $|b|\leqslant0.050$ Mc/sec, $g_J=2.0012\pm0.0001$, and $\mu_I=+3.2402\pm0.0002$ nm. The value given for the nuclear magnetic dipole moment is deduced from the Fermi-Segrè relation and is therefore subject to correction for a possible hyperfine anomaly.

INTRODUCTION

The ground-state nuclear spins and magnetic moments of the manganese isotopes of mass 53, 54, and 55 were known[1,2] prior to the present investigation, and the magnetic hyperfine interaction constant a had been measured[3] for Mn^{55}. The near equality of the measured moments of Mn^{54} and Mn^{55} indicates that the addition of a neutron to Mn^{54} contributes little to the dipole moment. The purpose of the present work was to extend these results through the odd-odd isotope Mn^{56}.

PRINCIPLE OF THE METHOD

The atomic-beam magnetic-resonance technique, which was used for the measurements, has been fully described by a number of authors.[4,5] Briefly, an atom of the beam is deflected away from a centrally located detector by two strong, inhomogeneous magnetic fields unless a suitable change of state occurs in a homogeneous field between the deflecting fields. With the present arrangement, this change of state must be such that the effective magnetic moment of the atom, at strong field, changes sign but retains its magnitude. The transition is induced by an appropriately oriented rf magnetic field, of the proper resonant frequency, located in the homogeneous field. The frequency ν for resonance, in addition to depending on the homogeneous field H, also depends on the nuclear spin I, the hyperfine interaction constants a and b, the nuclear magnetic moment μ_I, and several electronic parameters. The quantities of interest (in this experiment a, b, I, μ_I, and g_J, the electronic g factor) are deduced from measurements of the resonance frequencies for a number of known intensities of the homogeneous magnetic field.

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1 D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).
2 R. W. Kedzie and C. D. Jeffries, Bull. Am. Phys. Soc. **3**, 415 (1958).
3 G. K. Woodgate and J. S. Martin, Proc. Phys. Soc. (London) **A70**, 485 (1957).
4 J. R. Zacharias, Phys. Rev. **61**, 270 (1942).
5 L. S. Goodman and S. Wexler, Phys. Rev. **99**, 192 (1955).

SOURCE PREPARATION

The sources for the atomic beam were prepared by irradiating stable manganese metal, which consists entirely of Mn^{55}, in a flux of 2×10^{13} neutrons cm^{-2} sec^{-1} for 1–3 hr in the Argonne research reactor CP-5. The large cross section (13.3b) and high abundance (100%) of Mn^{55}, and the short half-life of Mn^{56} (2.6 hr) led easily to a source of adequate activity. To eliminate unnecessary transfers of the sample after removal from the pile, the irradiation was carried out in the graphite oven subsequently used to produce the atomic beam.

EXPERIMENTAL DETAILS

Ovens, and Alignment of the Beam

Because of the relatively low temperature (about 1000°C) required to produce a suitable manganese beam, graphite was found to be a satisfactory material for the oven. In addition, a material which (like graphite) has a small capture cross section for thermal neutrons was needed because of the desirability of irradiating the manganese in the oven.

Since the hot tungsten surface-ionization detector will not detect manganese atoms, some other means of alignment of the beam was necessary. The addition of small amounts of KF or Ga to the oven load prior to irradiation provided atoms in the beam which could be detected and used for alignment. The beam of radioactive Mn^{56} was found to decrease with time when either of these materials was added, but the decrease was found to be less objectionable when Ga was used. The activities induced in the Ga (21-min and 14-hr) were not troublesome if the length of the irradiation was limited to 2–3 hours.

Calibration of the Homogeneous Magnetic Field

The great improvement in the homogeneity of the central field, conventionally referred to as the C field, has been described[6] previously. This change was effected during the course of the present work, and it may be seen in the tables that the uncertainties quoted for resonance frequencies are generally smaller for the later phases of the work.

6 L. S. Goodman, Rev. Sci. Instr. **31**, 1351 (1960).

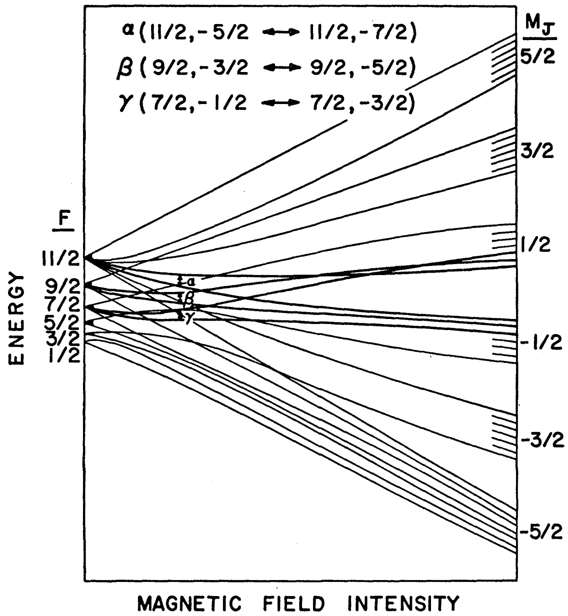

FIG. 1. Schematic hfs diagram for Mn^{56}. Of the 42 levels, only 21 are shown. The three $\Delta F=0$ transitions α, β, and γ are indicated.

The method used for calibration of the field was also improved during the course of collecting the data. Initially, the field was set by observing resonances in either Ga or K, with the hot-wire detector on the center line. With this arrangement, the field could not be measured during Mn^{56} collections, and field drifts between measurements were often troublesome. The use of a separate alkali oven, a separate rf loop, and an off-center hot-wire detector for the calibration beam made it possible to monitor the field continuously while making measurements on the manganese.[7] The magnetic fields at the two loop positions were measured by inducing the same alkali resonance, in turn, in the two loops and noting the resonance frequencies. At no time were field differences greater than 3 milligauss observed.

Detection of the Radioactive Mn^{56}

The radioactive Mn^{56} was detected by allowing the beam to condense on metal collectors which were subsequently removed from the vacuum and counted in a bank of identical, gas-flow Geiger counters. Of a number of collection surfaces tried, the most satisfactory was a clean copper surface at room temperature. The surface was prepared (on steel collectors) by first etching the steel surface, and then momentarily dipping the collector into a dilute solution of $CuSO_4$. The collectors were then kept in alcohol until immediately before insertion into the vacuum system. The present arrangement for removing the collectors from the vacuum for counting is briefly described in a previous publication.[8]

THEORY

The Hamiltonian for description of the energy levels of an atom in an external magnetic field is given[9] by

$$\mathcal{H}=ha\mathbf{I}\cdot\mathbf{J}+hbQ_{\text{op}}+g_J\mu_0H(J_z+\gamma I_z),$$

where a and b are the magnetic-dipole and electric-quadrupole hyperfine-interaction constants, I and J are the nuclear spin and the total electronic angular momentum, respectively, and Q_{op} is the electric-quadrupole operator. The external magnetic field is H, the quantities h and μ_0 are Planck's constant and the Bohr magneton, and g_J is the electronic g factor. The parameter γ denotes the ratio of the nuclear to the electronic g factor, and we adopt the convention $g_I=-\mu_I/I$ and $g_J=-\mu_J/J$. All symbols are defined as in reference 9. Terms of order higher than the electric-quadrupole interaction have been neglected.

The atomic ground state of manganese, ${}^6S_{5/2}$, arises from five $3d$ electrons coupled to zero orbital angular

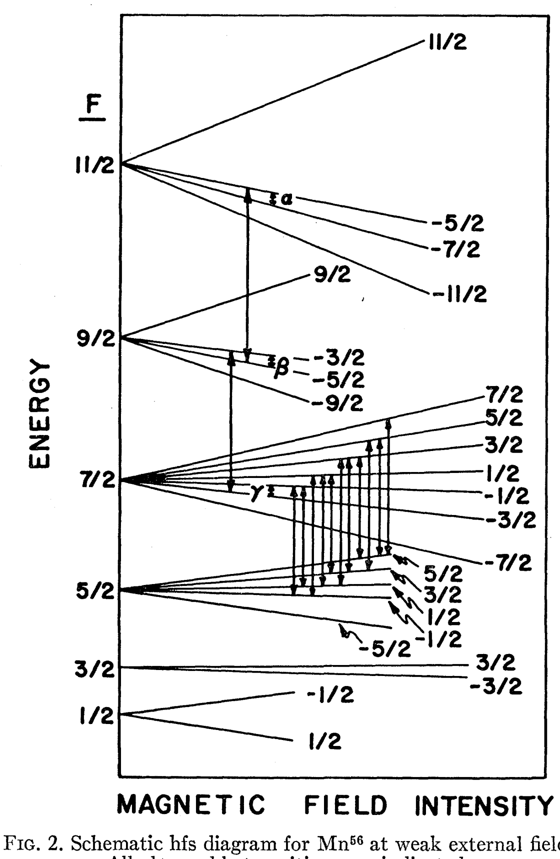

FIG. 2. Schematic hfs diagram for Mn^{56} at weak external field. All observable transitions are indicated.

[7] W. J. Childs, J. A. Dalman, and L. S. Goodman, Argonne National Laboratory Report ANL-6130, March, 1960 (unpublished), p. 32.

[8] W. J. Childs, L. S. Goodman, and L. J. Kieffer, Phys. Rev. **120**, 2138 (1960).

[9] N. F. Ramsey, *Molecular Beams* (Oxford University Press, New York, 1956), p. 272.

TABLE I. Observations of the $\Delta F=0$ transitions in Mn^{56}. All frequencies are in Mc/sec except that in columns 6 and 7 the frequency differences are in kc/sec. The transitions used for field calibration are the $(2, -1 \leftrightarrow 2, -2)$ transition in K^{39} and in $Ga^{69,71}(P_{\frac{1}{2}})$, and the $(4, -3 \leftrightarrow 4, -4)$ transition in Cs^{133}. The theoretical frequencies were calculated by use of the value $|a|=56.3924$ Mc/sec determined from observations of the $\Delta F=\pm1$ transitions. The values used for g_J were chosen to give the closest agreement with the observed frequency at the strongest field ($g_J=2.0012$ for μ_I positive, and $g_J=2.0014$ for μ_I negative). The electronic g factors used for K^{39}, $Ga^{69,71}(P_{\frac{1}{2}})$, and Cs^{133} were 2.002309, 0.665825, and 2.002577, respectively.[a]

H(gauss)	Calibration isotope	Calibration frequency	Mn^{56} transition	Observed Mn^{56} frequency	ν(obs) − ν(calc) $\mu_I>0$	$\mu_I<0$
1.429	K^{39}	1.009	α	1.858±0.025	31	30
			β	1.762±0.030	12	11
			γ	1.612±0.020	8	7
6.131	$Ga^{69,71}(P_{\frac{1}{2}})$	1.426	α	7.957±0.020	12	5
			β	7.648±0.020	−30	−36
			γ	7.100±0.040	−3	−10
10.219	$Ga^{69,71}(P_{\frac{1}{2}})$	2.378	α	13.403±0.040	4	−6
			γ	12.125±0.025	−28	−38
30.656	Cs^{133}	10.815	α	42.580±0.025	−10	−40
			β	42.987±0.007	4	−24
			γ	42.252±0.007	4	−21
91.968	Cs^{133}	32.986	γ	224.428±0.015	3	−3

[a] V. Hughes, in *Recent Research in Molecular Beams*, edited by I. Estermann (Academic Press, Inc., New York, 1959), pp. 87–90.

momentum and to the maximum possible spin. The electronic g factor for manganese was known to be very nearly 2 (the Russell-Saunders value for a pure $^6S_{5/2}$ state) prior to the present research. For pure L-S coupling with no admixing, the nonrelativistic value of both a and b should be 0. In Mn^{55}, however, $a\neq0$, but b is 0 to within experimental error.[3] Since one would expect $a=0$ from the nature of the atomic state, it is difficult to make a theoretical prediction of the relative signs of μ_I and the observed nonzero a.

The nuclear spin $I=3$, found in the present work, couples to $J=5/2$ to yield six zero-field hyperfine levels characterized by $F=11/2$, $9/2$, $7/2$, $5/2$, $3/2$, and $1/2$. For a small value of $|b/a|$, $\Delta F=0$ transitions should be observable in the levels $F=11/2$, $9/2$, and $7/2$. There should also be 13 observable transitions of the type $\Delta F=\pm1$, of which 6 correspond to $\Delta m_F=0$ and 7 to $\Delta m_F=\pm1$. To induce the former, the rf magnetic field must be parallel to the homogeneous field, while for the latter, it must be perpendicular to it. The observable $\Delta F=0$ transitions are indicated on the schematic hfs diagram (Fig. 1). For simplicity, 21 of the 42 levels have been omitted. Figure 2 shows the situation at weak field in more detail.

All transition frequencies required were calculated by the digital computer GEORGE. The calculated frequencies, which are effectively differences between appropriate pairs of eigenvalues of the Hamiltonian, are independent of the sign of a, for a given sign of g_I, if $b=0$. Since b is found to be 0 to within experimental error, no determination of the sign of a was made.[10] It was possible, however, to confirm that the sign of the magnetic dipole moment is positive, as reported previously.[11]

[10] The sign of a could be measured, however, in a more elaborate experiment. See J. G. King and V. Jaccarino, Phys. Rev. **94**, 1610 (1954), or reference 8.

MEASUREMENTS

Measurements on $\Delta F=0$ Transitions

Table I summarizes the results of measurements on the three observable $\Delta F=0$ transitions. The measurements at the lowest field are sufficient to establish that the nuclear spin of Mn^{56} is $I=3$, as reported previously.[12,13]

For convenience, the $\Delta F=0$ transitions corresponding to $F=11/2$, $9/2$, and $7/2$ are labelled α, β, and γ, respectively. The internal consistency of their resonance frequencies establishes that $b\approx0$. If b is assumed to be negligibly small, values for $|a|$ and g_J can be extracted from the data presented. If, for the moment, the data at 91.968 gauss are disregarded, the results $|a|=56.3\pm0.2$ Mc/sec and $g_J=2.001\pm0.002$ are obtained. These values are relatively insensitive to the sign assumed for μ_I.

The dependence of the three frequencies α, β, and γ on magnetic field intensity is shown in Fig. 3.

The half-life of the radioactive decay of atoms collected on resonance was measured several times to be 2.7 ± 0.2 hours, a result in good agreement with the reported[1] half-life of 2.6 hr for the ground state of Mn^{56}.

Sign of the Magnetic Moment

As discussed below, observation of the $\Delta F=\pm1$ transitions led to a more precise value for $|a|$, namely

[11] R. W. Bauer and M. Deutsch, Phys. Rev. **117**, 519 (1960).

[12] W. J. Childs and L. S. Goodman, Bull. Am. Phys. Soc. **1**, 21 (1958).

[13] W. J. Childs, L. S. Goodman, and L. J. Kieffer, Phys. Rev. Letters **1**, 296 (1958).

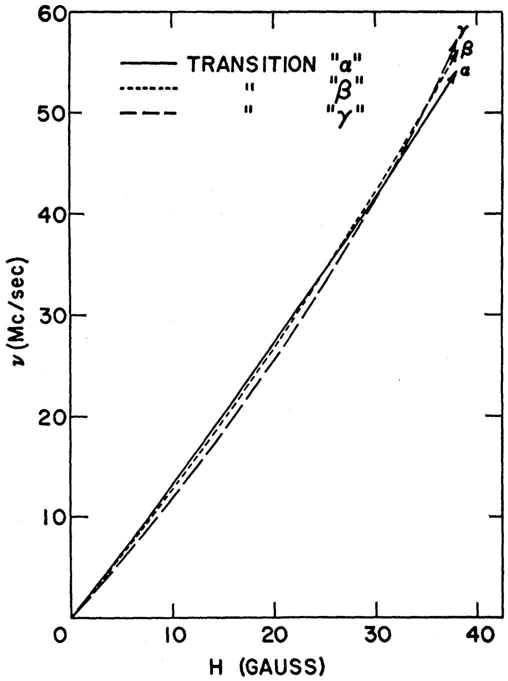

FIG. 3. The magnetic field dependence of the three observable $\Delta F=0$ transitions through 40 gauss. At stronger fields, the resonances are well separated. It should be noted that the order of the resonance frequencies is reversed as the field is increased from 0 to 40 gauss.

$|a|=56.3924\pm0.0023$ Mc/sec. To establish the sign of μ_I, the precise magnitude of a was used, together with the rough value quoted above for g_J, to predict the resonance frequency of transition γ at 91.968 gauss. The transition was observed at this field three times with the result $\nu_\gamma=224.428\pm0.015$ Mc/sec as noted in Table I. In order to account for this result, with the precise value of $|a|$, g_J must have the value 2.0012 ±0.0001 for μ_I positive or 2.0014 ± 0.0001 for μ_I negative, regardless of the sign of a. Columns 6 and 7 of Table I list the differences between the observed resonance frequencies and those calculated for all the observed transitions by use of the precise value for $|a|$, the correct sign for g_I, and the g_J value required to give the best fit at the strongest field. Consideration of the results at the two highest fields (where the greatest sensitivity is found) shows that consistency is possible only if μ_I is positive. This result confirms that the magnetic dipole moment of Mn^{56} is positive as previously reported.[11]

As mentioned above no determination of the sign of a was made.

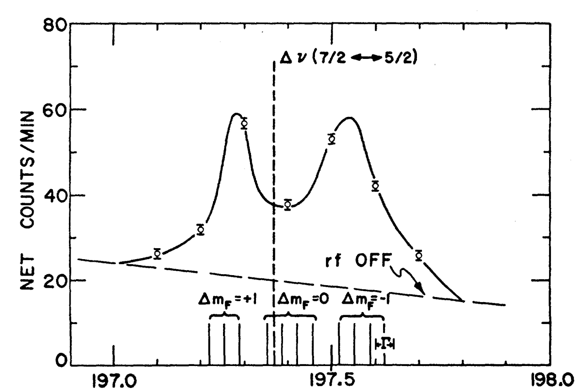

FIG. 4. Appearance of the observable transitions connecting the $F=7/2$ and $F=5/2$ hyperfine levels at 0.15 gauss. The resonance frequency and change in m_F for each of the 11 resonances involved are indicated below the data. It can be seen that the applied dc field shifts some frequencies up from the hyperfine separation and some down. The rf loop used was relatively less efficient in inducing $\Delta m_F=0$ transitions. The beam intensity, with the rf off, was monitored several times during the run as indicated by the sloping, dashed line. The full width at half maximum Γ of the highest frequency component, when observed individually at 1 gauss at reduced rf power, is shown ($\Gamma=39$ kc/sec).

Observation of the $\Delta F=\pm1$, $\Delta m_F=\pm1$ Transitions

As has already been mentioned, the search for $\Delta F=\pm1$ transitions was carried out before the measurements at 91.968 gauss confirmed the reported sign of the magnetic moment. The hyperfine intervals between which observable transitions can be induced were calculated from the value deduced for $|a|$ from measurements on the $\Delta F=0$ transitions at fields up to 30.656 gauss. The results were

$$\Delta\nu(11/2\leftrightarrow 9/2)=309.7\pm1.1 \text{ Mc/sec},$$
$$\Delta\nu(9/2\leftrightarrow 7/2)=253.4\pm0.9 \text{ Mc/sec},$$
$$\Delta\nu(7/2\leftrightarrow 5/2)=197.1\pm0.7 \text{ Mc/sec}.$$

Even for the smallest interval listed, the region to be searched (1.4 Mc/sec) is large compared to the expected resonance width (20–50 kc/sec). There are, however, 11 transitions which can be observed between the $F=7/2$ and $F=5/2$ levels (see Fig. 2). The C field was set at 0.15 gauss where these transitions should be spaced only 35 kc/sec apart so that the span of frequency for which some transition could be induced stretched continuously over about 400 kc/sec. A search under these conditions quickly revealed such a block of transitions (Fig. 4) positioned in such a way as to yield the result $\Delta\nu(7/2\leftrightarrow 5/2)=197.368\pm0.040$ Mc/sec. From this number, it can be shown that if $b=0$ then $|a|=56.391\pm0.011$ Mc/sec, regardless of the sign of either a or μ_I. This result makes possible a more precise estimate of the two larger hyperfine separations.

The field was next set at 1 gauss, where the spacing between adjacent $F=7/2\leftrightarrow 5/2$ transitions is calculated to be 230 kc/sec, and the $(7/2, 7/2\leftrightarrow 5/2, 5/2)$ transition frequency measured. The result, for b assumed to be 0, is $|a|=56.3929\pm0.0023$ Mc/sec.

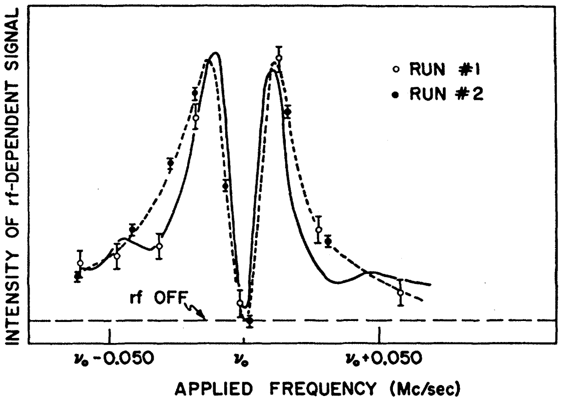

FIG. 5. The appearance of $\Delta F=\pm 1$, $\Delta m_F=0$ transitions. The dashed curve through the experimental points shows the $(9/2,\ -3/2 \leftrightarrow 7/2,\ -3/2)$ transition in Mn^{56}, while the solid curve shows the appearance of the $(2,0 \leftrightarrow 1,0)$ transition in K^{41} observed at the same dc field (0.15 gauss) with the same rf loop. The rf power and frequency were very nearly the same for the two curves. For the Mn^{56}, $\nu_0=253.742$ Mc/sec; and for the K^{41}, $\nu_0=254.014$ Mc/sec.

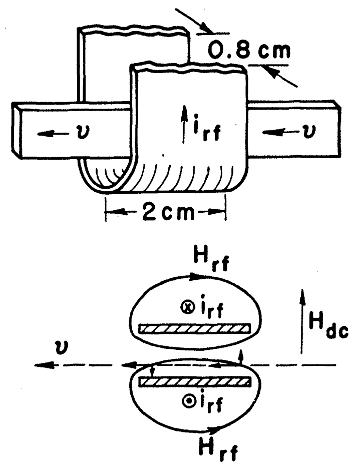

FIG. 6. Schematic views of the rf loop used to induce the transitions shown in Fig. 5. The rectangular atomic beam is shown passing through the loop in the upper half of the figure. In the lower half, the same situation is viewed from above. The dashed line indicates the path of an atom with velocity v as it passes through the loop a little below the symmetry axis. The arrows indicating the directions of rf currents and fields are for a particular instant of time; both oscillate with the rf frequency applied.

Observation of the $\Delta F=\pm 1$, $\Delta m_F=0$ Transitions

To establish more rigorously that $b\approx 0$, it is necessary to measure at least two independent hyperfine spacings. Two of these, $(11/2 \leftrightarrow 9/2)$ and $(9/2 \leftrightarrow 7/2)$, can be observed only through $\Delta m_F=0$ transitions. Both of these intervals have been measured, although in each case the observed line shape exhibited a minimum (rather than the customary maximum) at the central frequency. The symmetry of the line shape on either side of a sharp central minimum was observed for three different shapes of rf loops and was independent of rf power level or the strength of the dc magnetic field. (The detailed shape of the resonance curve is, however, dependent on the level of the rf power and on the geometrical properties of the loop.)

Figure 5 shows a typical line shape obtained with the rf loop of Fig. 6. The dashed curve through the experimental points in Fig. 5 shows the line shape for the $(9/2,\ -3/2 \leftrightarrow 7/2,\ -3/2)$ transition in Mn^{56} as observed at 0.15 gauss. For comparison, the solid line indicates the observed line shape for the $\Delta m_F=0$ transition $(2,0 \leftrightarrow 1,0)$ in K^{41} at the same dc field and at very nearly the same rf power level. The resonance frequencies were, by coincidence, also very nearly the same. The central minimum in the K^{41} curve falls at the reported frequency[14,15] for $\Delta\nu$. In the case of the manganese transition, however, calculations indicate that the frequency is shifted downward 24 kc/sec by the small dc field.

Other investigators[16] have observed central minima in σ transitions induced by a single rf loop. The observed line shape may be tentatively accounted for in the following way. All of the rf loops used could be expected, from their shapes, to introduce the required component of the rf magnetic field parallel to the dc field. (No other component can contribute to the transition probability of $\Delta m_F=0$ transitions.) The loop shown in Fig. 6 is of the type normally used to induce π transitions. Except for atoms that pass through the loop exactly on the center line, a plot of the component of H_{rf} parallel to H_{dc} as a function of distance along the loop axis will show first a component in phase with H_{dc}, and then a component 180° out of phase. It has been shown[17] that such a perturbation should yield a central minimum (as observed), even when averaged over the velocity distribution, if the dc field is sufficiently homogeneous. That this minimum coincides with the resonance frequency, within the precision quoted, is established by the comparison between the frequency of the observed dip and the previously reported[14,15] value of $\Delta\nu$ for K^{41}. This result is also expected theoretically.[17]

All of the measurements on $\Delta F=\pm 1$ transitions are summarized in Table II.

RESULTS

The observed resonance frequencies can be reconciled only with a nuclear spin $I=3$. Evaluation of the eigenvalues of the Hamiltonian, with no external field, together with the measured hyperfine intervals listed in Table II, yields

$$\Delta\nu(11/2 \leftrightarrow 9/2)=(11/2)a+(11/20)b =310.173\pm 0.015 \text{ Mc/sec},$$

$$\Delta\nu(9/2 \leftrightarrow 7/2)=(9/2)a =253.766\pm 0.010 \text{ Mc/sec},$$

$$\Delta\nu(7/2 \leftrightarrow 5/2)=7/2a-(7/25)b =197.375\pm 0.008 \text{ Mc/sec}.$$

[14] P. Kusch, S. Millman, and I. I. Rabi, Phys. Rev. **57**, 765 (1940); S. A. Ochs, R. A. Logan, and P. Kusch, *ibid.* **78**, 184 (1950).

[15] A. L. Bloom and J. B. Carr, Phys. Rev. **119**, 1946 (1960).

[16] For example, G. K. Woodgate and R. W. Hellwarth, Proc. Phys. Soc. (London) **A69**, 588 (1956).

[17] N. F. Ramsey, reference 9, Chap. V.

TABLE II. Observations of the $\Delta F=\pm1$ transitions in Mn^{56}. The $(2, -1 \leftrightarrow 2, -2)$ transition in K^{39} was used for calibration of the magnetic field. The electronic g factor for K was taken to be 2.002309.[a] All frequencies are in Mc/sec.

H (gauss)	Calibration frequency	Mn^{56} transition	Observed Mn^{56} frequency	Mn^{56} hyperfine interval corrected to zero field
0.150	0.105	$(7/2, m \leftrightarrow 5/2, m')$ (11 transitions)	(See Fig. 4)	197.368±0.040
1.000	0.704	$(7/2, 7/2 \leftrightarrow 5/2, 5/2)$	199.088±0.008	197.375±0.008
0.150	0.105	$(9/2, -3/2 \leftrightarrow 7/2, -3/2)$	253.742±0.010	253.766±0.010
0.150	0.105	$(11/2, -5/2 \leftrightarrow 9/2, -5/2)$	310.152±0.015	310.173±0.015

[a] V. Hughes, in *Recent Research in Molecular Beams*, edited by I. Estermann (Academic Press, Inc., New York, 1959), p. 87–90.

The second equation, which is independent of b, yields the result

$$|a|=56.3924\pm0.0023 \text{ Mc/sec.}$$

Comparison of this with the other two equations gives

$$|b|\leqslant 50 \text{ kc/sec.}$$

As mentioned above, the confirmation of the conclusion that

$$\mu_I>0$$

leads to the result

$$g_J=2.0012\pm0.0001.$$

The Fermi-Segrè relation[18] may be conveniently used to evaluate the nuclear magnetic dipole moment from the measured value for $|a|$. Thus we have

$$\mu_I(\mathrm{Mn}^{56})=\frac{a(\mathrm{Mn}^{56})}{a(\mathrm{Mn}^{\lambda})}\frac{I(\mathrm{Mn}^{56})}{I(\mathrm{Mn}^{\lambda})}\mu_I(\mathrm{Mn}^{\lambda}),$$

where λ denotes any other manganese isotope. The only other isotope for which the magnetic hyperfine interaction constant a has been measured[3] is Mn^{55}. On using the value $\mu_I(\mathrm{Mn}^{55})=+3.46766\pm0.00014$ nm,[19] $|a(\mathrm{Mn}^{55})|=72.422\pm0.002$ Mc/sec,[3] and $I(\mathrm{Mn}^{55})=5/2$,[3,19] it is found that

$$\mu_I(\mathrm{Mn}^{56})=+3.2402\pm0.0002 \text{ nm},$$

subject to correction for any hyperfine anomaly.[20]

[18] E. Fermi and E. Segrè, Z. Physik **82**, 729 (1933).
[19] N. F. Ramsey, reference 9, p. 173.
[20] The discrepancy between the present value and the preliminary result published previously (reference 13) is attributed primarily to the assignment of the wrong F to an observed resonance at 30.656 gauss where the three $\Delta F=0$ transitions have very nearly the same frequency (see Fig. 3). Erratic collection efficiencies and field drifts were also sources of confusion prior to the adoption of clean copper collection surfaces and continuous field calibration.

DISCUSSION

The Mn^{56} nucleus contains 25 protons and 31 neutrons, and might be represented as the folding together of the wave functions for two odd-A nuclei, one with $Z=25$ and one with $A-Z=31$. The spins and dipole moments have been measured[1] for Mn^{53} and Mn^{55}, for both of which $Z=25$, and the corresponding quantities have recently been determined[21,22] for Fe^{57} and Fe^{57m}(14 kev), for which $A-Z=31$. Since the spins of Mn^{53} and Mn^{55} are different, it is reasonable to choose Mn^{55} which has more nearly the same number of neutrons as Mn^{56}. If one folds the $(f_{7/2})_{5/2}{}^5$ proton configuration of $\mathrm{Mn}^{55}(I=5/2,\ \mu_I=+3.47$ nm) with the neutron configuration of $\mathrm{Fe}^{57}(I=1/2,\ \mu_I=+0.0903$ nm) or $\mathrm{Fe}^{57m}(I=3/2,\ \mu_I=-0.153$ nm) to form $\mathrm{Mn}^{56}(I=3)$, one obtains for $\mu_I(\mathrm{Mn}^{56})$ the values +3.56 nm or +2.86 nm, respectively. These results are reasonably close to the measured moment of Mn^{56}, +3.24 nm, and are both in error by about the same amount. The difference between the two estimates of μ_I is small because, in the folding process, the neutron configuration contributes very little compared to the proton configuration.

ACKNOWLEDGMENTS

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[21] G. W. Ludwig and H. H. Woodbury, Phys. Rev. **117**, 1286 (1960).
[22] S. S. Hanna, J. Heberle, C. Littlejohn, G. J. Perlow, R. S. Preston, and D. H. Vincent, Phys. Rev. Letters **4**, 177 (1960).