Nuclear-Spin, Hyperfine-Structure, and Magnetic-Moment Investigations on ^{61}Cu, ^{62}Cu, and ^{64}Cu†

BARBARA M. DODSWORTH* AND HOWARD A. SHUGART
Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California

(Received 27 September 1965)

Atomic-beam magnetic-resonance experiments on the $^2S_{1/2}$ ground state of three radioactive copper isotopes, ^{61}Cu, ^{62}Cu, and ^{64}Cu, are described. The results are summarized in the following table. The spins of ^{61}Cu and of ^{64}Cu had been measured previously but are included in parentheses for completeness.

Isotope	$T_{1/2}$	Spin	Hyperfine structure (Mc/sec)	Magnetic moment (nm)
^{61}Cu	3.3 h	($\frac{3}{2}$)	$\Delta\nu(2\rightarrow1)=+11225(200)$	$\mu_{\text{uncorr.}}=+2.13(4)$
^{62}Cu	9.9 min	1		
^{64}Cu	12.8 h	(1)	$\Delta\nu(\frac{3}{2}\rightarrow\frac{1}{2})=-1282.140(8)$	$\mu_{\text{uncorr.}}=-0.216(2)$
$g_J(\text{Cu})=-2.00228(2)$				

The nuclear magnetic moments are calculated from the Fermi-Segrè formula by using known constants of ^{63}Cu and ^{65}Cu. A 1% error is quoted on the ^{64}Cu moment to bracket a possible hyperfine-structure anomaly.

THE radioactive isotopes of copper have been the subject of investigation in this laboratory over a number of years. Previously, preliminary reports of this work have appeared only in abstract form, with author credit being given to the various individuals who helped with the several experiments.[1–5] In this paper a general review and description of all of the work is given. As background to the results quoted here, a short history of previous work should be given. The spin of ^{61}Cu (Ref. 1) was found to be $I=\frac{3}{2}$, and a preliminary hyperfine-structure separation $\Delta\nu=+11\,200(400)$ Mc/sec was announced in Ref. 2. For 9.9-min ^{62}Cu the spin value $I=1$ was reported in Ref. 3. Before work began in this laboratory on ^{64}Cu, the spin ($I=1$) and hyperfine structure $\Delta\nu=\pm1278(20)$ Mc/sec were known.[6] Also Stroke[7] and co-workers at Princeton, in unpublished work, had improved the $\Delta\nu$ to a precision of ±0.7 Mc/sec; however, the sign of the magnetic moment was still undetermined. The electronic g_J factor for the $^2S_{1/2}$ state of copper had been measured by Ting and Lew[8] as $-2.0025(10)$. The ^{64}Cu constants described here were previously reported in abstract form.[5]

† This research was supported by the U. S. Air Force Office of Scientific Research and the U. S. Atomic Energy Commission.
* Present address: New York University, New York, New York.
[1] W. A. Nierenberg, H. A. Shugart, and H. B. Silsbee, Bull. Am. Phys. Soc. **2**, 200 (1957); J. B. Reynolds, R. L. Christensen, D. R. Hamilton, W. M. Hooke, and H. H. Stroke, Phys. Rev. **109**, 465 (1958).
[2] B. M. Dodsworth, V. J. Ehlers, W. B. Ewbank, F. R. Petersen, and H. A. Shugart, Bull. Am. Phys. Soc. **4**, 353 (1959).
[3] B. M. Dodsworth, V. J. Ehlers, W. B. Ewbank, F. R. Petersen, and H. A. Shugart, Bull. Am. Phys. Soc. **4**, 452 (1959).
[4] B. M. Dodsworth (Ph.D. thesis), Lawrence Radiation Laboratory Report UCRL-10780, 1963 (unpublished).
[5] B. M. Dodsworth and H. A. Shugart, Bull. Am. Phys. Soc. **9**, 451 (1964).
[6] A. Lemonick and F. M. Pipkin, Phys. Rev. **95**, 1356 (1954).
[7] H. H. Stroke (private communication).
[8] Y. Ting and H. Lew, Phys. Rev. **105**, 581 (1957).

THEORY OF THE EXPERIMENTS

The energy Hamiltonian describing a free Cu atom in the $^2S_{1/2}$ electronic ground state is

$$\mathcal{H}=ha\mathbf{I}\cdot\mathbf{J}-g_J\mu_0\mathbf{J}\cdot\mathbf{H}-g_I\mu_0\mathbf{I}\cdot\mathbf{H}\,, \qquad (1)$$

where a is the hyperfine-structure dipole-interaction constant, I is the nuclear spin, J is the electronic spin, the g factors are given by $g_J=\mu_J/J\mu_0$, $g_I=\mu_I/I\mu_0$, μ_0 is the magnitude of the Bohr magneton, and $\mathbf{H}$ is the externally applied magnetic field. For copper, for which $J=\frac{1}{2}$, the energy levels of this Hamiltonian are given by the Breit-Rabi formula,[9]

$$W(F,m_F)=\frac{-h\Delta\nu}{2(2I+1)}-g_I\mu_0m_FH+(F-I)h\Delta\nu\left(1+\frac{4m_Fx}{2I+1}+x^2\right)^{1/2}, \qquad (2)$$

in which $h\Delta\nu$ is the zero-field hyperfine-structure separation between the states $F=I+\frac{1}{2}$ and $F=I-\frac{1}{2}$, and $x=(g_I-g_J)\mu_0H/h\Delta\nu$. The $\Delta\nu$ is related to the interaction constant a by

$$\Delta\nu=a(I+\tfrac{1}{2})\,. \qquad (3)$$

In an atomic beam flop-in apparatus, the "standard transition" ($F=I+\frac{1}{2}$, $m_F=-I+\frac{1}{2}\leftrightarrow F=I+\frac{1}{2}$, $m_F=-I-\frac{1}{2}$) is frequently used for calibration purposes with stable alkali isotopes which can be detected by surface ionization on a hot tungsten wire. This transition is also used to determine the nuclear spin and preliminary values of $\Delta\nu$ in the unknown isotope, since the low-field frequency is given by

$$\nu\approx\nu_0+(2I/\Delta\nu)\nu_0^2\,, \qquad (4)$$

[9] G. Breit and I. I. Rabi, Phys. Rev. **38**, 2082 (1931).

TABLE I. ^{61}Cu data.[a]

Calibration isotope and frequency for ^{87}Rb (Mc/sec)	H (G)	^{61}Cu frequency (Mc/sec)	Residual frequency (positive g_I) (kc/sec)
40.870(50)	57.39(7)	40.636(30)	+38
72.055(50)	99.85(7)	71.138(120)	−69
80.725(50)	111.46(7)	79.694(60)	+33
91.707(30)	126.05(4)	90.351(50)	+14
111.800(30)	152.41(4)	109.749(60)	−74
130.150(150)	176.12(19)	127.506(60)	+89
179.950(100)	238.76(12)	174.779(80)	−31
	$\Delta\nu=11\,225(117)$	$\mu_I=+2.13(4)$	$\chi^2=1.4$ (7 points)
[For an incorrect negative-moment assumption	$\Delta\nu=-12\,077(136)$	$\mu_I=-2.29$	$\chi^2=4.4$]

[a] All resonances consist of the standard flop-in transition. Calibration and comparison information is contained in middle section of Table II.

where

$$\nu_0=-g_J\mu_0H/h(2I+1).$$

At low enough fields, where the second term of Eq. (4) may be neglected, the spin may be ascertained from a knowledge of ν, H, g_J, and universal constants. On the other hand, at higher magnetic fields the second term provides an estimate of $\Delta\nu$. Ultimately, various parameters in the Hamiltonian are fitted to the experimental observations by least-squares techniques.

When the experimental data are not precise enough to yield accurate values of μ_I (or g_I) directly from the Hamiltonian, the magnetic moment may be calculated from the Fermi-Segrè relation

$$a_1/a_2\approx g_{I1}/g_{I2}, \tag{5}$$

where 1 and 2 refer to isotopes of the same element. The hyperfine-structure anomaly is a measure of the deviation from equality in Eq. (5). For most elements the anomaly is less than 1%, so this value is taken as the limit of accuracy in the magnetic moment computations.

The main features of the apparatus used in this work are described by Hobson *et al.*[10] Calibration techniques, collection, and normalization procedures followed closely those described by Ewbank *et al.*[11]

^{61}Cu EXPERIMENT

^{61}Cu (3.3 h) was produced at the Berkeley 60-in. cyclotron by the ^{59}Co$(\alpha,2n)^{61}$Cu reaction, with 34-MeV α particles. A chemical separation of the copper from the 4-mil cobalt target was begun shortly after removal of the target from the cyclotron. The foil was dissolved in 12 N HNO_3 with approximately 20 mg of stable copper carrier. The resulting solution was boiled to dryness and the residue redissolved in 3 N HCl, from which the copper was selectively precipitated from the cobalt by H_2S. The CuS precipitate was dissolved in a few drops of concentrated HCl and the copper metal electroplated out of the solution.

A series of resonances of the "standard transition" ($F=2$, $m_F=-1\leftrightarrow F=2$, $m_F=-2$) were taken at fields up to 239 G. A typical resonance is shown in Fig. 1. The radioactive beam atoms were collected on sulfur-coated buttons which were counted in sodium iodide crystal scintillation counters. A least-squares fit to all the data was performed, with first a positive and then a negative value of g_I assumed. The case with a positive value for g_I gave the best fit to the data, as shown in Table I, and resulted in $\Delta\nu=11\,225(200)$ Mc/sec. The error is taken as twice the standard deviation resulting from the least-squares analysis. From the Fermi-Segrè formula and constants for the stable Cu isotopes,[8,12] the uncorrected magnetic moment of ^{61}Cu is calculated to be μ_I(uncorr)$=+2.13(4)$ nm.

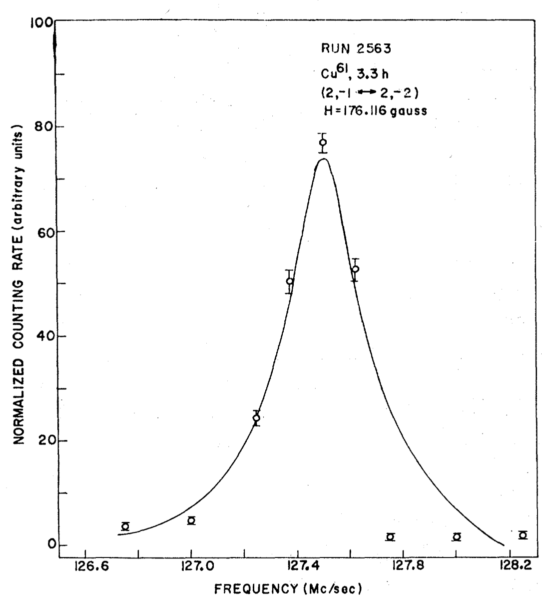

FIG. 1. A ^{61}Cu resonance of the standard transition $(2,-1\leftrightarrow 2,-2)$.

[10] J. P. Hobson, J. C. Hubbs, W. A. Nierenberg, H. B. Silsbee, and R. J. Sunderland, Phys. Rev. **104**, 101 (1956).
[11] W. B. Ewbank, L. L. Marino, W. A. Nierenberg, H. A. Shugart, and H. B. Silsbee, Phys. Rev. **120**, 1406 (1960).

[12] H. L. Cox and D. Williams, Bull. Am. Phys. Soc. **2**, 30 (1957); R. E. Sheriffs and D. Williams, Phys. Rev. **82**, 651 (1951); R. V. Pound, *ibid.* **73**, 523 (1948).

The nuclear spins of all the measured odd-A isotopes of copper are $\frac{3}{2}$, which is explained on the simple shell-model picture by assigning the 29th proton to the $p_{3/2}$ shell. The magnetic moment of ^{61}Cu lies within the Schmidt limits for a $p_{3/2}$ proton, and extends the monotonic decrease in the uncorrected magnetic moments from $+2.38$ for ^{65}Cu and $+2.22$ for ^{63}Cu to $+2.13(4)$ for ^{61}Cu.

^{62}Cu EXPERIMENT

^{62}Cu (9.9 min) was produced as a daughter isotope from the β^+ decay of 9.3-h ^{62}Zn. The zinc was made by the ^{60}Ni$(\alpha,2n)^{62}$Zn reaction by bombarding 10-mil natural nickel with 40-MeV α particles. Simultaneously, some ^{61}Cu (3.3 h) is formed from several reactions, but this isotope is isolated in the first precipitation of copper from the nickel-zinc solution. A portion of the ^{61}Cu is subsequently added to each later precipitation to provide a long-lived component in the beam for normalization purposes. The chemical procedure for ^{62}Cu was similar to that previously described for ^{61}Cu except that the nickel foil was first dissolved in hot aqua regia. After each copper precipitation the ^{62}Cu activity grows to a maximum in about 45 min. Hence samples were taken at about 60-min intervals. The copper metal from the chemistry could be produced in 10 to 15 min after the precipitation phase. Most of the metal was placed in the atomic beam oven; however, a small portion was deposited on a chemistry button, which was decayed along with the sample collected in the atomic beam apparatus. Because of the short half-life of the isotope, the entire oven load was emptied on one button at a frequency corresponding to a resonance of a particular spin. This spin sample, along with the corresponding chemistry sample, was decayed to determine the ratio of ^{62}Cu to ^{61}Cu activity. If the spin sample contains no resonance, the background on the spin sample should have the same ^{62}Cu/^{61}Cu ratio as the chemistry sample. On the other hand, if the ^{62}Cu undergoes a resonance which is deposited on the spin sample, then the ^{62}Cu/^{61}Cu ratio on the spin sample increases over that on the chemistry sample. Two of the seven runs on ^{62}Cu are shown in Fig. 2. All samples taken at frequencies corresponding to spin 1 gave significant increases in the ^{62}Cu component on the spin sample. Two resonance curves were taken, at 8 and 16 Mc/sec, in an attempt to determine a preliminary value of the magnetic moment. Owing to the lack of higher field data, only a lower limit of 1000 Mc/sec for the $\Delta\nu$ could be established.

It is possible to explain the resulting spin for ^{62}Cu on the basis of the simple shell model. The odd 29th proton is assigned to a $p_{3/2}$ level. The five neutrons beyond the closed shell at 28 are divided by the shell theory between the $2p_{3/2}$ and $1f_{5/2}$ states, which lie close together in energy. Occupation of these two levels depends on the magnitude of the difference in

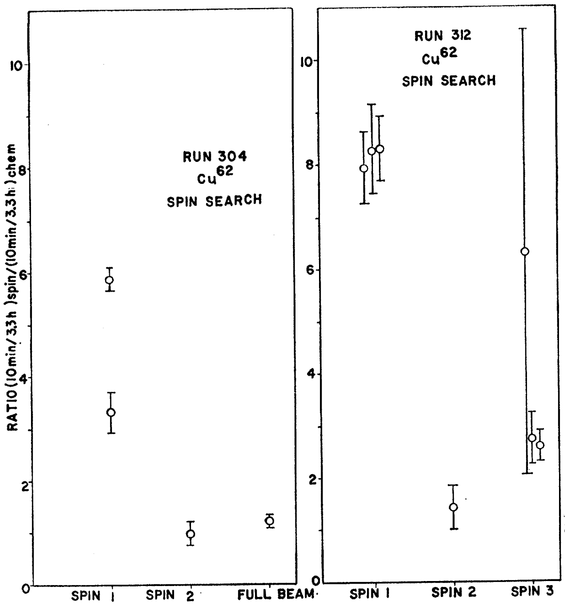

FIG. 2. Two spin searches show the enrichment of ^{62}Cu on the spin-1 samples.

pairing energies $(P_{f_{5/2}}-P_{p_{3/2}})$ relative to the level separation $(E_{f_{5/2}}-E_{p_{3/2}})$.[13] Three possible configurations result for the neutrons: (a) $(p_{3/2})^1(f_{5/2})^4$, (b) $(p_{3/2})^3(f_{5/2})^2$, and (c) $(p_{3/2})^4(f_{5/2})^1$. The Brennan and Bernstein rules[14] for coupling between the odd proton and these neutron configurations yield possible spins of 0 and 3 for configuration (a), spin 2 for configuration (b), and the measured spin 1 for configuration (c).

^{64}Cu EXPERIMENT

^{64}Cu was produced by the ^{63}Cu$(n,\gamma)^{64}$Cu reaction in natural copper at the General Electric reactor at Vallecitos. The resulting activity, which was followed through 8 half-lives, showed a one-component decay of $\approx$12.8 h. Because previous work had identified the spin[6] and approximate hyperfine structure,[6,7] the experiments undertaken here were designed to obtain the sign of the nuclear magnetic moment, as well as improved values of the hyperfine-structure separation and the copper g_J factor. In this endeavor various resonances of the $\Delta F=0$ and $\Delta F=\pm 1$ type were observed at magnetic fields up to 3734 G. Although all resonances were used in the least-squares analysis, particular resonances play a dominant role in determining certain constants in the Hamiltonian, Eq. (1). For example, the hyperfine structure is best established by narrow $\Delta F=\pm 1$ resonances taken at low magnetic fields. A resonance of this type at a field-independent point is

[13] M. G. Mayer and J. Hans D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley & Sons, Inc., New York, 1955).

[14] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).

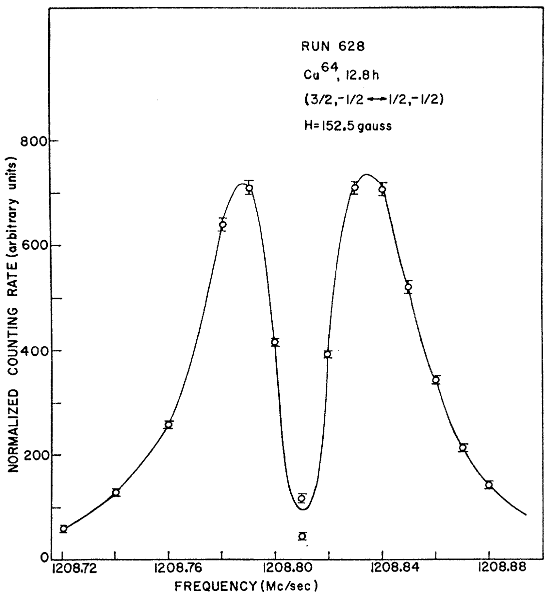

FIG. 3. A $\Delta F=\pm1$ resonance in ^{64}Cu at a field-independent point. The central dip is due to two separated transition regions 90 deg out of phase.

shown in Fig. 3. Because this $\sigma(\Delta m_F=0)$ transition was induced at the two ends of a $\pi(\Delta m_F=\pm1)$ type of hairpin, the pattern is one caused by two separated oscillating rf fields 90 deg out of phase. As another example, the g_J factor and sign of the nuclear magnetic moment are best established by certain resonances at high magnetic fields. A sweep of the $(\frac{3}{2},-\frac{1}{2}\leftrightarrow\frac{1}{2},\frac{1}{2})$, $(\frac{3}{2},\frac{1}{2}\rightarrow\frac{1}{2},-\frac{1}{2})$ doublet at 1100 G showed only one resonant line, even though two were expected. (In labeling resonances the quantum numbers are taken from a diagram for a positive magnetic moment.) The frequency separation of the components of this doublet is often used to determine g_I, and is given by $2\,g_I\mu_0H/h$, which is about 362 kc/sec for ^{64}Cu at 1100 G (see Fig. 4). The absence of one component can be explained as follows: At zero magnetic field (for either a positive or negative sign of the nuclear magnetic moment) both

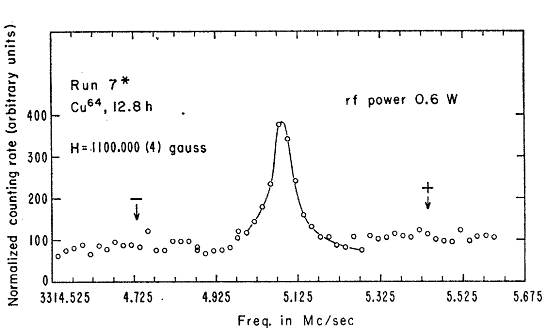

FIG. 4. Only one line of the doublet could be seen at 1100 G. The expected position for the missing line of low transition probability is indicated by the two arrows (one for a positive magnetic moment and the other for a negative magnetic moment).

components of this doublet have the same transition probability. However, as the field is raised the rf perturbation matrix element of one component (A) increases while that for the other component (B) decreases. The decrease in transition probability is explained by the fact that the B component has allowed changes in quantum number $\Delta F=\pm1$, $\Delta m_F=\pm1$ at low fields but has forbidden changes $\Delta m_I=\pm2$, $\Delta m_J=\pm1$ at high fields. Calculations of the shifts in frequency of these transitions for a change in the magnetic moment sign show that the A resonance is shifted only 28 kc/sec while the B resonance is shifted 696 kc/sec. In fact, the B resonance for a positive moment is located 362 kc/sec higher in frequency than the A resonance, and for a negative moment it is 362 kc/sec lower in frequency than the A resonance. Therefore the location of the lower probability transition B in relation to the allowed transition A is a definitive indicator of the sign of the magnetic moment and aids greatly in assigning quantum numbers to the transi-

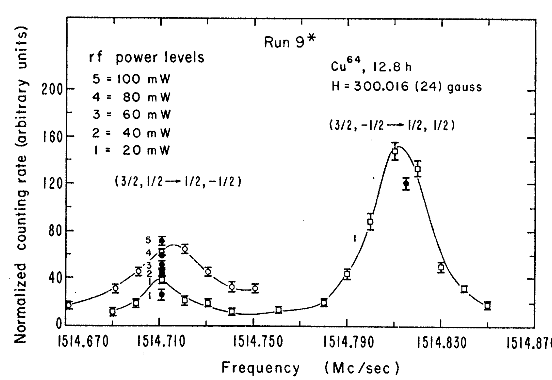

FIG. 5. Both doublet components were observed at 300 G. The position of the low-probability line on the low-frequency side of the other doublet component establishes the magnetic moment as negative. (The quantum number labels are those appropriate to a positive magnetic-moment diagram.)

tions. When the higher frequency component of the doublet has a lower transition probability, the magnetic moment is positive. When the lower frequency component is less intense, the magnetic moment is negative. An attempt to see the resolved, forbidden-component B was finally successful at 300 G, as shown in Fig. 5. This observation demonstrated conclusively that the magnetic moment of ^{64}Cu is negative. This conclusion also results from the over-all least-squares analysis. A collection of data from 24 observations (with quantum labels from a positive moment diagram) and the result of a least-squares analysis of these data appear in Table II. The constants for ^{64}Cu are found to be $\Delta\nu(\frac{3}{2}\rightarrow\frac{1}{2})=-1282.140(8)$ Mc/sec; μ_I(uncorr.) $=-0.216(2)$ nm; $g_J(\text{Cu})=-2.00228(2)$. The errors on $\Delta\nu$ and g_J are taken as twice the standard deviation of the least-squares analysis. The 1% error on

TABLE II. ^{64}Cu data and results.

Isotope	Calibration Frequency (Mc/sec)	Field (G)	^{64}Cu Transition F_1	M_1	F_2	M_2	Frequency (Mc/sec)	^{64}Cu residual frequency (negative magnetic moment) (kc/sec)
^{85}Rb	80.515(40)	152.742(67)	$\frac{3}{2}$	$-\frac{1}{2}$	$\frac{3}{2}$	$-\frac{3}{2}$	177.450(150)	+79
^{39}K	1 088.203(15)	500.028(6)	$\frac{3}{2}$	$-\frac{1}{2}$	$\frac{3}{2}$	$-\frac{3}{2}$	835.750(15)	+8
^{39}K	10 122.973(100)	3 734.410(36)	$\frac{3}{2}$	$-\frac{1}{2}$	$\frac{3}{2}$	$-\frac{3}{2}$	9 646.785(70)	+13
^{39}K	10 123.009(110)	3 734.423(39)	$\frac{3}{2}$	$-\frac{1}{2}$	$\frac{3}{2}$	$-\frac{3}{2}$	9 646.760(70)	−48
^{39}K	10 123.192(100)	3 734.489(36)	$\frac{3}{2}$	$-\frac{1}{2}$	$\frac{3}{2}$	$-\frac{3}{2}$	9 646.950(70)	−40
^{85}Rb	80.478(30)	152.680(51)	$\frac{3}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 208.810(20)	−3
^{85}Rb	80.532(30)	152.771(51)	$\frac{3}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 208.810(20)	−3
^{39}K	3 308.745(10)	1 300.081(4)	$\frac{3}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	3 435.420(40)	−12
^{39}K	0.217(50)	0.309(71)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 282.138(10)	−2
^{39}K	0.217(50)	0.309(71)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 282.140(10)	−0.2
^{39}K	0.217(50)	0.309(71)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 282.137(15)	−3
^{39}K	0.562(20)	0.799(28)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 282.148(10)	+6
^{39}K	0.562(20)	0.799(28)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 282.140(10)	−2
^{39}K	0.562(20)	0.799(28)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 282.139(10)	−3
^{85}Rb	1.509(50)	3.225(107)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 282.223(75)	+54
^{85}Rb	2.291(50)	4.890(106)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 282.226(80)	+20
^{39}K	428.445(50)	250.229(20)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 446.636(20)	−4
^{133}Cs	113.998(10)	300.038(24)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 514.815(10)	+2
^{39}K	1 088.100(25)	499.991(9)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 872.144(15)	+0.4
^{39}K	1 088.100(25)	499.991(9)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1 872.154(15)	+10
^{39}K	2 750.501(10)	1 100.068(4)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	3 315.090(20)	+7
^{39}K	3 308.745(10)	1 300.081(4)	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	3 841.025(20)	−2
^{39}K	428.445(50)	250.229(20)	$\frac{3}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1 446.574(20)	+16
^{133}Cs	113.998(10)	300.038(24)	$\frac{3}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1 514.715(15)	+0.5

Calibration and comparison information:

Isotope	Spin	$g_J(^2S_{1/2})$	$\Delta\nu$ (Mc/sec)	μ_I (uncorr) (nm)
^{39}K	$\frac{3}{2}$	−2.002295(2)	461.719723	+0.3909
^{63}Cu	$\frac{3}{2}$		11 733.83(1)	+2.2206
^{65}Cu	$\frac{3}{2}$		12 568.81(1)	+2.3790
^{85}Rb	$\frac{5}{2}$	−2.002332(2)	3 035.732439	+1.3482
^{87}Rb	$\frac{3}{2}$	−2.002332(2)	6 834.682614	+2.7413
^{133}Cs	$\frac{7}{2}$	−2.002542(2)	9 192.631770	+2.5641

Summary of results:

^{64}Cu $I=1$ $g_J=-2.00228(1)$ $\Delta\nu=-1\,282.140(4)$ $\mu_I=-0.216(2)$ nm $\chi^2=2.5$ (24 points)

(For an incorrect positive-moment assumption: $\chi^2=145$)

netic moment is intended to include a possible hyperfine-structure anomaly.

Coupling the moments of the spin-$\frac{5}{2}$ neutrons of ^{65}Zn or ^{67}Zn to the spin-$\frac{3}{2}$ protons of ^{63}Cu or ^{65}Cu results in a predicted magnetic moment of −0.50 to −0.65 nm for ^{64}Cu. This range of values based on a very simple coupling scheme does not agree well with the experimentally determined value of −0.216 nm.

ACKNOWLEDGMENTS

The authors wish to thank Professor W. A. Nierenberg and Professor H. B. Silsbee for their support in the earliest work on ^{61}Cu, and acknowledge the valuable assistance of Dr. V. J. Ehlers, Dr. W. B. Ewbank, and Dr. F. R. Petersen in the work on ^{62}Cu and the later work on ^{61}Cu.