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NUCLEAR SPIN, HYPERFINE STRUCTURE,
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ON ^{61}Cu , ^{62}Cu , AND ^{64}Cu

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August 5, 1965

Nuclear Spin, Hyperfine Structure, and Magnetic
Moment Investigations on ^{61}Cu , ^{62}Cu , and $^{64}\text{Cu}^*$

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August 5, 1965

ABSTRACT

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 (n. m.)
^{61}Cu	3.3 h	(3/2)	$\Delta\nu(2 \rightarrow 1) = +11\,225(200)$	$\mu_{\text{uncorr}} = +2.13(4)$
^{62}Cu	9.9 m	1		
^{64}Cu	12.8 h	(1)	$\Delta\nu(3/2 \rightarrow 1/2) = -1282.140(8)$	$\mu_{\text{uncorr}} = -.216(2)$
$g_J(\text{Cu}) = -2.00228(2)$				

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 made. The spin of ^{61}Cu (reference 1) was found to be $I = 3/2$, and a preliminary hyperfine structure separation $\Delta\nu = +11200(400)$ Mc/sec was announced in reference 2. For 9.9-min ^{62}Cu the spin value $I = 1$ was reported in reference 3. Before work began in this Laboratory on ^{64}Cu , the spin ($I = 1$) and hyperfine structure $\Delta\nu = \pm 1278(20)$ Mc/sec were known.⁶ Also Stroke⁷ and co-workers at Princeton, in unpublished work, had improved the $\Delta\nu$ to a precision of ± 0.7 Mc/sec; however, the sign of the magnetic moment was still undetermined.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 Lew⁸ as $-2.0025(10)$. The ^{64}Cu constants described here were previously reported in abstract form.⁵

Theory of the Experiments

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

$$\mathcal{H} = h a \vec{I} \cdot \vec{J} - g_J \mu_0 \vec{J} \cdot \vec{H} - g_I \mu_0 \vec{I} \cdot \vec{H}, \quad (1)$$

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 $g_J = \frac{\mu_J}{J\mu_0}$, $g_I = \frac{\mu_I}{I\mu_0}$, μ_0 is the magnitude of the Bohr magneton, and H is the externally applied magnetic field. For copper, for which $J = 1/2$, the energy levels of this Hamiltonian are given by the Breit-Rabi formula,⁹

$$W(F, m_F) = \frac{h\Delta\nu}{2(2I+1)} - g_I \mu_0 m_F H \pm \frac{h\Delta\nu}{2} \left(1 + \frac{4m_F^2}{2I+1} + x^2\right)^{1/2}, \quad (2)$$

in which $h\Delta\nu$ is the zero-field hyperfine-structure separation between the states $F = I + 1/2$ and $F = I - 1/2$, and $x = \frac{(g_I - g_J)\mu_0 H}{h\Delta\nu}$. The $\Delta\nu$ is related to the interaction constant a by

$$\Delta\nu = a(I + 1/2). \quad (3)$$

In an atomic beam flop-in apparatus the "standard transition" ($F = I + 1/2, m_F = -I + 1/2 \leftrightarrow F = I + 1/2, m_F = -I - 1/2$) 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

$$\nu \approx \nu_0 + \frac{2I}{\Delta\nu} \nu_0^2, \quad (4)$$

where

$$\nu_0 = \frac{-g_J \mu_0 H}{h(2I+1)}.$$

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

$$\frac{a_1}{a_2} \approx \frac{g_{I1}}{g_{I2}}, \quad (5)$$

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 contained in reference 10. Calibration techniques, collection, and normalization procedures followed closely those described in reference 11.

^{61}Cu Experiment

^{61}Cu (3.3 h) was produced at the Berkeley 60-inch cyclotron by the $^{59}\text{Co}(\alpha, 2n)^{61}\text{Cu}$ 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 gauss. 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 $\mu_{\text{I}}(\text{uncorr}) = +2.13(4) \text{ nm}$.

The nuclear spins of all the measured odd-A isotopes of copper are 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 m) was produced as a daughter isotope from the β^+ decay of 9.3-h ^{62}Zn . The zinc was made by the $^{60}\text{Ni}(\alpha, 2n)^{62}\text{Zn}$ 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. 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 minutes. 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 $^{62}\text{Cu}/^{61}\text{Cu}$ 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 $^{62}\text{Cu}/^{61}\text{Cu}$ 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 Mc/sec 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 the 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 rules¹⁴ 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 $^{63}\text{Cu}(n, \gamma)^{64}\text{Cu}$ 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 ≈ 12.8 h.

Because previous work had identified the spin⁶ 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 gauss. The hyperfine structure is best established by $\Delta F = \pm 1$ resonances taken at low magnetic fields. A resonance of the $\Delta F = \pm 1$ type at a field-independent point is shown in Fig. 3. Because this σ ($\Delta m_F = 0$) transition was induced at the two ends of a π ($\Delta m_F = \pm 1$) type of hairpin, the pattern is one caused by two separated oscillating rf fields 90 deg out of phase. On the other hand, the g_J factor and sign of the nuclear magnetic moment are best established by certain resonances in high magnetic fields. A sweep of the $(1/2, -1/2 \leftrightarrow 3/2, 1/2)$ $(1/2, 1/2 \leftrightarrow 3/2, -1/2)$ doublet at 1100 gauss showed only one resonance line, even though two were expected (see Fig. 4). The missing line is sensitive to the sign of the nuclear magnetic moment and would occur on opposite sides of the observed line for the two possible assumptions on the magnetic moment sign. It is noticed that the missing line has changes in quantum numbers of $\Delta F = \pm 1, \Delta m_F = \pm 1$ at low fields and $\Delta m_I = \pm 2, \Delta m_J = \pm 1$ at high fields. Selection rules allow this transition at low fields but prevent it at higher fields. In an attempt to understand this behavior, the rf perturbation matrix elements were calculated as a function of magnetic field. As expected, the $(1/2, -1/2 \leftrightarrow 3/2, 1/2)$ transition probability decreased monotonically with field. It was still possible to see the "forbidden" transition at 300 gauss, as shown in Fig. 5. This observation demonstrated conclusively that the magnetic moment of ⁶⁴Cu is negative. A collection of data from 24 observations and the result of a

least-squares analysis of these data appears in Table II. The constants for ^{64}Cu are found to be $\Delta\nu(3/2 \rightarrow 1/2) = -1282.140(8)$ Mc/sec; $\mu_I(\text{uncorr}) = -0.216(2)$ n. m.; $g_J(\text{Cu}) = -2.00228(2)$. The errors on $\Delta\nu$ and g_J are taken as twice the standard deviation of the least-squares analysis. The 1% error on the magnetic moment is intended to include a possible hyperfine-structure anomaly.

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FOOTNOTES AND REFERENCES

- * This research was supported by the U. S. A. F. Office of Scientific Research and the U. S. Atomic Energy Commission.
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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
	$\Delta\nu = 11\,225(117)$	$\mu_I = +2.12(2)$	$\chi^2 = 1.4$ (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.

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

Calibration		^{64}Cu Transition				Frequency (Mc/sec)	^{64}Cu residual frequency (negative magnetic moment) (kc/sec)	
Isotope	Frequency (Mc/sec)	Field (G)	F ₁	M ₁	F ₂			M ₂
^{85}Rb	80.515(40)	152.742(67)	3/2	-1/2	3/2	-3/2	177.450(150)	+79
^{39}K	1 088.203(15)	500.028(6)	3/2	-1/2	3/2	-3/2	835.750(15)	+ 8
^{39}K	10 122.973(100)	3 734.410(36)	3/2	-1/2	3/2	-3/2	9 646.785(70)	+13
^{39}K	10 123.009(110)	3 734.423(39)	3/2	-1/2	3/2	-3/2	9 646.760(70)	-48
^{39}K	10 123.192(100)	3 734.489(36)	3/2	-1/2	3/2	-3/2	9 646.950(70)	-40
^{85}Rb	80.478(30)	152.680(51)	3/2	-1/2	1/2	-1/2	1 208.810(20)	- 3
^{85}Rb	80.532(30)	152.771(51)	3/2	-1/2	1/2	-1/2	1 208.810(20)	- 3
^{39}K	3 308.745(10)	1 300.081(4)	3/2	-1/2	1/2	-1/2	3 435.420(40)	-12
^{39}K	.217(50)	.309(71)	3/2	1/2	1/2	-1/2	1 282.138(10)	- 2
^{39}K	.217(50)	.309(71)	3/2	1/2	1/2	-1/2	1 282.140(10)	- 0.2
^{39}K	.217(50)	.309(71)	3/2	1/2	1/2	-1/2	1 282.137(15)	- 3
^{39}K	.562(20)	.799(28)	3/2	1/2	1/2	-1/2	1 282.148(10)	+ 6
^{39}K	.562(20)	.799(28)	3/2	1/2	1/2	-1/2	1 282.140(10)	- 2
^{39}K	.562(20)	.799(28)	3/2	1/2	1/2	-1/2	1 282.139(10)	- 3.
^{85}Rb	1.509(50)	3.225(107)	3/2	1/2	1/2	-1/2	1 282.223(75)	+54
^{85}Rb	2.291(50)	4.890(106)	3/2	1/2	1/2	-1/2	1 282.226(80)	+20
^{39}K	428.445(50)	250.229(20)	3/2	1/2	1/2	-1/2	1 446.636(20)	- 4
^{133}Cs	113.998(10)	300.038(24)	3/2	1/2	1/2	-1/2	1 514.815(10)	+ 2
^{39}K	1 088.100(25)	499.991(9)	3/2	1/2	1/2	-1/2	1 872.144(15)	+ 0.4
^{39}K	1 088.100(25)	499.991(9)	3/2	1/2	1/2	-1/2	1 872.154(15)	+10
^{39}K	2 750.501(10)	1 100.068(4)	3/2	1/2	1/2	-1/2	3 315.090(20)	+ 7
^{39}K	3 308.745(10)	1 300.081(4)	3/2	1/2	1/2	-1/2	3 841.025(20)	- 2
^{39}K	428.445(50)	250.229(20)	3/2	-1/2	1/2	1/2	1 446.574(20)	+16
^{133}Cs	113.998(10)	300.038(24)	3/2	-1/2	1/2	1/2	1 514.715(15)	+ 0.5

Calibration and comparison information:

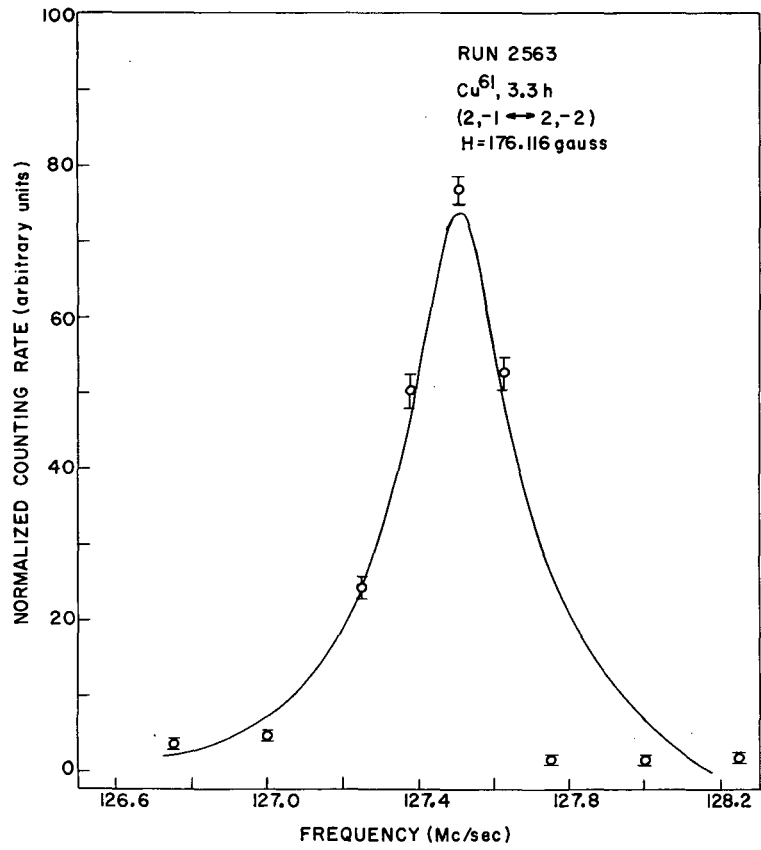
Isotope	Spin	$g_J (^2S_{1/2})$	$\Delta\nu$ (Mc/sec)	μ_{\pm} (uncorr) (nm)
^{39}K	3/2	-2.002295(2)	461.719723	+0.3909
^{63}Cu	3/2		11 733.83(1)	+2.2206
^{65}Cu	3/2		12 568.81(1)	+2.3790
^{85}Rb	5/2	-2.002332(2)	3 035.732439	+1.3482
^{87}Rb	3/2	-2.002332(2)	6 834.682614	+2.7413
^{133}Cs	7/2	-2.002542(2)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

Summary of results:

^{64}Cu $I = 1$ $g_J = -2.00228(4)$ $\Delta\nu = -1 282.140(4)$ $\mu_I = -0.216(2)$ nm $\chi^2 = 2.5$ (24 points)
 (For an incorrect positive-moment assumption: $\chi^2 = 145$)

FIGURE CAPTIONS

- Fig. 1. A ^{61}Cu resonance of the standard transition ($2, -1 \leftrightarrow 2, -2$).
- Fig. 2. Two spin searches show the enrichment of ^{62}Cu on the spin-1 samples.
- Fig. 3. A $\Delta F = \pm 1$ resonance in ^{64}Cu at a field-independent point. The central dip is due to two separated transition regions 90 deg out of phase.
- Fig. 4. Only one line of the doublet could be seen at 1100 gauss. 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).
- Fig. 5. Both doublet components were observed at 300 gauss. The position of the low-probability line on the low-frequency side of the other doublet component establishes the magnetic moment as negative.



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Fig. 1

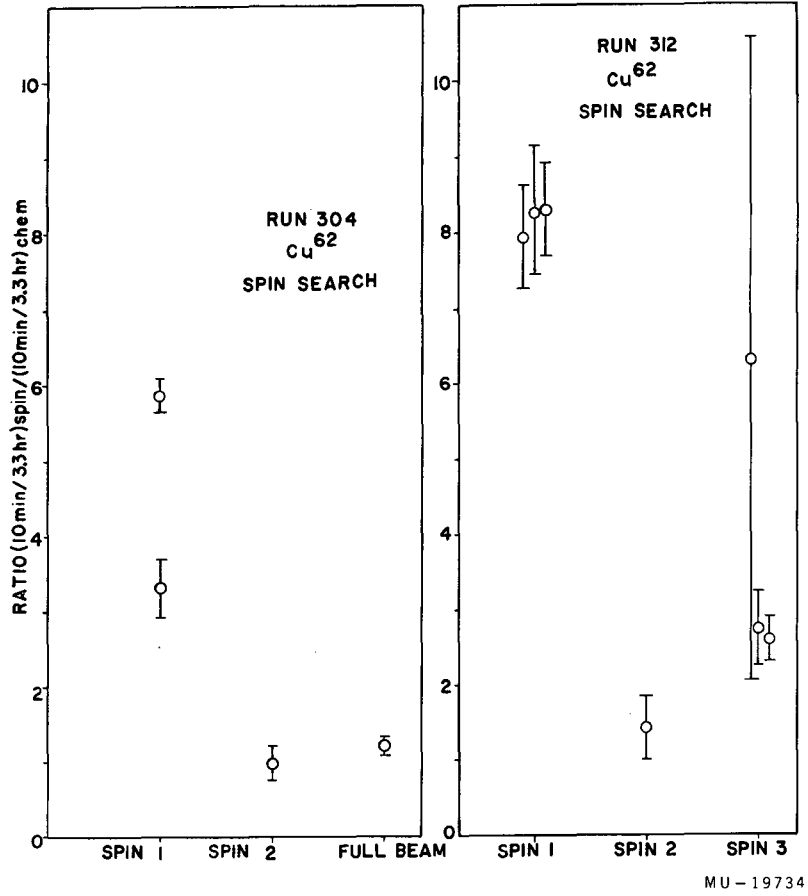
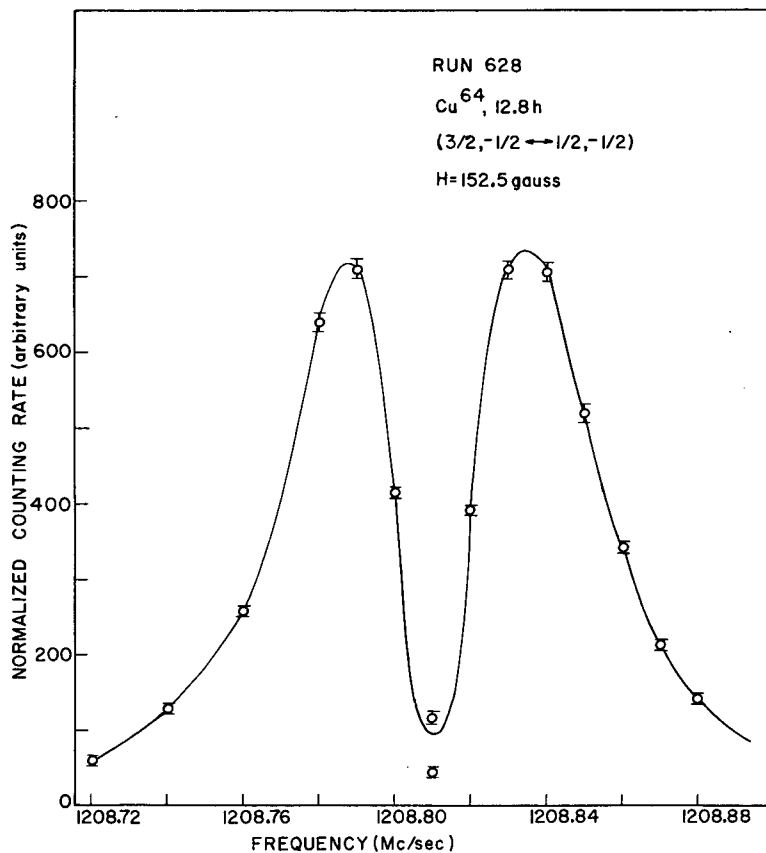
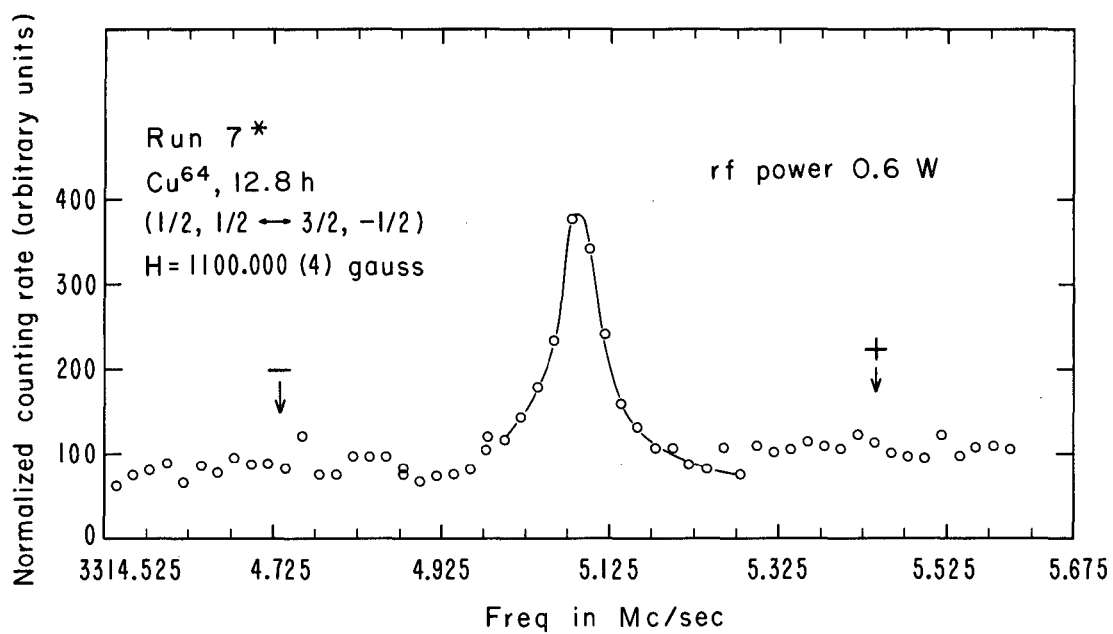


Fig. 2



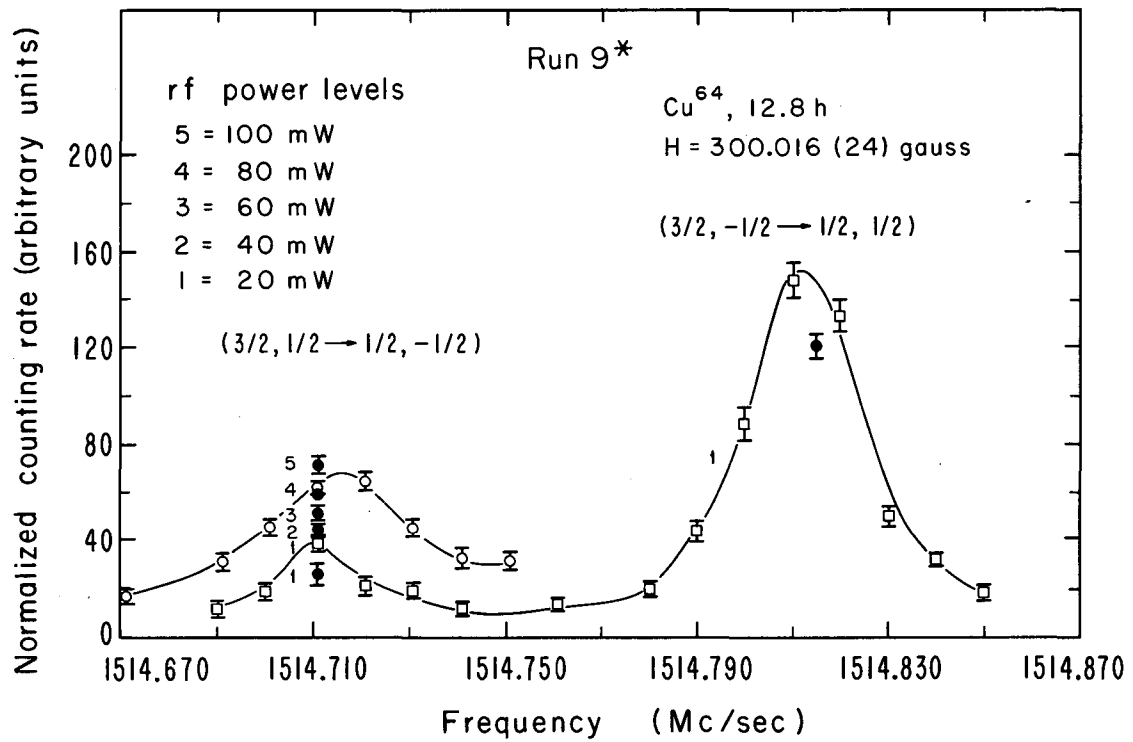
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Fig. 3



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Fig. 4



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Fig. 5

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