Title

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LAWRENCE RADIATION LABORATORY
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DISCLAIMER

NUCLEAR SPINS OF ^{125}Cs AND ^{136}Cs, HYPERFINE STRUCTURE SEPARATION AND NUCLEAR MAGNETIC MOMENT OF ^{125}Cs, ^{127}Cs, AND ^{136}Cs *

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October 1970

ABSTRACT

We have used the atomic beam magnetic resonance method to determine the ground state nuclear spin, the electronic $^2S_{1/2}$ ground state hyperfine structure (hfs) separations, $\Delta\nu$, and the nuclear magnetic moments of 45-min ^{125}Cs and 13-day ^{136}Cs. A more accurate value of the hfs separation of 6.2-hr ^{127}Cs was obtained by combining resonances reported previously with those reported in this work. The collected results are:

Isotope	I	$\Delta\nu(^2S_{1/2})$ (MHz)	$\mu_{I(\text{uncorr})}(\mu_N)$
^{125}Cs	1/2	+ 8,754(40)	+1.40(2)
^{127}Cs	(1/2)← previously measured	+ 9,109(45)	+1.45(2)
^{136}Cs	5	+12,702(28)	+3.68(4)

The errors quoted for the $\Delta\nu$'s are twice the standard deviations of least-square fits to the experimental data. The magnetic dipole moments were obtained from the $\Delta\nu$'s by the Fermi-Segrè formula; an error of ∿1% is taken to include possible hyperfine structure anomalies.

I. INTRODUCTION

Before the present work, the method of atomic beams has furnished the nuclear ground state spins and magnetic moments for a series of ten cesium isotopes with neutron numbers ranging between 72 and 83. Our present measurements extend this series at the neutron-deficient end by adding 45-min ^{125}Cs,[1] and fill a gap in the neutron-rich end with 13-day ^{136}Cs.[2] The latter isotope has 81 neutrons – one less than a closed shell – and 5 protons outside the Z = 50 shell. It should thus be expected that this nucleus is spherical, at least in the ground state, and that the shell model would explain the ground state spin and magnetic moment. Our measurements concur with this picture. The ground state spin of 6.2-hr ^{127}Cs and 31-hr ^{129}Cs[3] is 1/2; this can be understood in terms of a deformed nuclear shape and it was interesting to determine whether or not ^{125}Cs continued the trend.

The production of sufficient quantities of this isotope became possible when the 88-inch cyclotron, with 120-MeV α particles, was built at the Lawrence Radiation Laboratory. In producing ^{125}Cs by (α,6n) on ^{127}I we simultaneously made sufficient quantities of ^{127}Cs to observe resonances for this isotope. We incorporated these resonances with the ones reported previously[3,4] to obtain a better value for its hyperfine structure separation Δν. This paper gives a short review of the experimental procedure and presents the results of the present investigation.

II. THEORY OF THE EXPERIMENT

The Hamiltonian describing the ground state hyperfine structure (hfs) of cesium is given by:

$$\mathcal{H} = ha\underset{\sim}{I}\cdot\underset{\sim}{J} - g_J \mu_B \underset{\sim}{J}\cdot\underset{\sim}{H} - g_I \mu_B \underset{\sim}{I}\cdot\underset{\sim}{H}, \quad (1)$$

where a is the magnetic dipole hfs interaction constant, $\underset{\sim}{I}\hbar$ is the nuclear angular momentum, $\underset{\sim}{J}\hbar$ is the electronic angular momentum, $g_I = \mu_I/I$ and $g_J = \mu_J/J$ are the corresponding g factors, $\underset{\sim}{H}$ is the external magnetic field, h is Planck's constant, and μ_B is the Bohr magneton. The energy levels of Eq. (1) for J = 1/2 are given by the Breit-Rabi formula:

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

where $\Delta\nu = a(I + 1/2)$, $x = (g_I - g_J)(\mu_B/h)H/\Delta\nu$, and $F = I \pm J$.

The theory of operation of an atomic beam apparatus has been described in detail elsewhere[7]; we give only a brief sketch here. Atoms effuse from the slit of an oven at one end of an evacuated chamber and pass through three magnetic fields. The first is strongly inhomogeneous and the atoms suffer deflections due to their magnetic moments. The second magnetic field is homogeneous, and in it transitions are induced among the hfs energy levels by an additional radiofrequency (rf) magnetic field. The third magnetic field is identical to the first. If a transition is induced between a level having $m_J = +1/2$ and one having $m_J = -1/2$, these atoms are deflected by the third magnetic field toward the detector. Those atoms which have not undergone a transition are deflected away from the detector.

For J = 1/2 and for low magnetic fields ($x \ll 1$), the frequency corresponding to the only $\Delta F = 0$ transition satisfying the selection rule of the apparatus ($\Delta m_J = \pm 1$) is given by

$$\nu \approx -g_J H(\frac{\mu_B}{h}) \; / \; (2I + 1). \qquad (3)$$

The spin I is determined by setting the magnetic field to a few gauss and making a discrete frequency search for a resonance. By observing this $\Delta F = 0$ resonance at increasingly higher magnetic fields information is obtained about $\Delta\nu$, as can readily be seen from Eq. (2). Finally, when observation of the $\Delta F = 0$ resonance at high fields has reduced the uncertainty of $\Delta\nu$ to about 1 MHz, a search can be made for a $\Delta F = 1$ transition; this determines $\Delta\nu$ directly.

To a good approximation ($\sim$1%), the hfs interaction constant of any isotope of a given element is proportional to its nuclear g factor. This is expressed by the Fermi-Segrè relation

$$\frac{a(1)}{a(2)} = \frac{g_I(1)}{g_I(2)} \; . \qquad (4)$$

Thus, a measurement of a(1) for isotope (1) yields the nuclear g-factor $g_I(1)$, provided a(1) and $g_I(1)$ have been measured for another isotope, (2), of the same element.

III. EXPERIMENT

We produced ^{125}Cs and ^{127}Cs by the reaction ^{127}I(α,kn)Cs. We chose elemental iodine as target material to insure high yield for the reaction and to expedite the chemical separation of the cesium. To determine the yield as a function of α-particle energy, we bombarded gaseous iodine in a seven-cell target. The α-particles' energies were degraded by aluminum foils that served as partitions between the cells. The results of this study are shown in Fig. 1, which shows a plot of the relative ratios of the resulting activities. In our final target, for production of usable quantities of activity, precautions had to be taken

to prevent interaction between the iodine and the target holder, and to avoid sublimation due to localized heating by the cyclotron beam. The iodine was contained in grooves in a platinum-plated, water-cooled aluminum target. The cover plate had louvers that matched the grooves of the backing plate; a 0.002-in cover foil sealed with a 0.001-in Teflon gasket was used to isolate the target material from the cyclotron chamber. The radioactive cesium was separated from the iodine by washing the target with benzene and a small amount of water containing 15 to 30 mg CsCl carrier. Benzene was chosen for its high solvency for iodine and low latent heat of vaporization. The solution was boiled to dryness, the iodine evaporating in the process. The remaining material was then transferred to a tantalum atomic beam oven, along with calcium metal filings which reduced the CsCl to Cs metal upon heating to about 400°C.

We produced the isotope ^{136}Cs by the reaction $^{136}Xe(p,n)^{136}Cs$, using natural Xe gas in which ^{136}Xe has an abundance of 8.87%. We also used the reaction $^{136}Xe(d,2n)^{136}Cs$. Difficulties with chemical separation precluded the use of other possible reactions[5,6] for the production of this isotope. The incident proton energies were about 20 MeV, while the deuteron energy was about 35 MeV. The pressure (about 2 atmospheres) of the Xe in the target was chosen so that we deposited no more than 15 MeV of the proton energy and 20 MeV of the deuteron energy in the target.

Chemical separation of the Cs from the Xe target was accomplished by pumping the Xe out of the chamber and passing it through water containing a few crops of HCl and 15 to 30 mg CsCl carrier dissolved in it. Upon removing the vacuum connection at the pump, the water was transferred to the target chamber. The washing was repeated four or five times. The resulting solution was then boiled to a few drops which were transferred to an atomic

beam oven and calcium metal filings were added. The chemical separation was performed two weeks after the bombardment to allow the short-lived activities to decay away. The remaining activity was that of ^{131}Cs (9.7 days), ^{132}Cs (6.58 days), and ^{136}Cs (13 days).

After loading the oven into the beam apparatus it was heated by radiation from a nearby hot tungsten wire to a temperature of around 400°C. At this temparature the reaction $Ca + 2CsCl \rightarrow CaCl_2 + 2Cs \uparrow$ occurs readily and the Cs atoms produced leave the oven through a ~0.004-in wide slit to form the atomic beam. After passing through the deflecting magnets and resonance region of the beam apparatus, the radioactive Cs atoms were detected by collecting them on clean sulfur surfaces termed "buttons." Each button or set of buttons was exposed for equal periods of time (usually 5 minutes) and the activity collected was measured by counting decays in well-shielded Geiger counters. As the rf frequency was varied stepwise from button to button, a resonance was detected by an increase in the activity collected.

To eliminate variations in beam intensity which might appear to be resonances (but are not), some normalization scheme had to be utilized to monitor the intensity of the beam. One or more of three different normalization methods were used in this work. First, a hot wire surface ionization detector monitored the ^{133}Cs barrier beam intensity at the position of one of the Stern-Gerlach peaks; second, a small hot wire, masking about 3% of the button placed on the beam center-line ("spin button"), served to monitor the ^{133}Cs resonance (these two signals were recorded on a chart recorder during the exposure times for each set of buttons and were later integrated by cutting and weighing); third, a second button was placed alongside the spin button, and collected simul-

taneously a sample of the radioactive Stern-Gerlach peak. Comparing the side button activity to the ^{133}Cs intensity showed decreases in activity on resonance (flop-out) as expected. Since the spin button activity increases at resonance, the ratio spin-to-side button, in addition to cancelling beam fluctuations, yielded an enhanced resonance when plotted versus rf frequency.

Because the spin of ^{125}Cs turned out to be the same as that of ^{127}Cs and ^{129}Cs, all these isotopes resonated at the same Zeeman frequency in low magnetic fields. A resonance identification therefore depended strongly on careful decay of the buttons and upon good normalization procedures. In the case of ^{136}Cs, the low specific activity produced required that the buttons be counted for times as long as 8 hours and followed in their decay for a month to determine the amount of ^{136}Cs collected.

IV. RESULTS

With the normalization procedure discussed above, the spin of ^{125}Cs was established to be 1/2. With increasing magnetic fields the resonances of ^{125}Cs and ^{127}Cs separated and yielded quantitative information on their respective hfs separations. Operating fields were limited to less than about 300 G due to apparatus limitations. A summary of all data and the results of the least-squares computer fit of the hfs to the data are presented in Table I for ^{125}Cs and in Table II for ^{127}Cs. It can be seen, from Table I, that a positive magnetic moment for ^{125}Cs fits far better than a negative one ($\chi^2 = 0.38$ with positive moment compared to 14.16 for a negative moment). Hence, for ^{125}Cs the hfs separation is $\Delta\nu(^2S_{1/2}) = +8754(40)$ MHz. The error as listed is twice the standard

deviation of the fit. The magnetic moment, uncorrected for diamagnetic shielding, calculated from the $\Delta\nu$ through the use of the Fermi-Segrè formula, is +1.40(2) μ_N. The corrected moment is μ(corr) = +1.41(2). We take the final error on the magnetic moment for all three isotopes to be 1% to include a possible hfs anomaly. The hfs anomalies measured for other Cs isotopes (e.g., ^{131}Cs compared to ^{133}Cs) are of the order of 0.5%.[8] Thus, the assigned error should be realistic.

Our observations for ^{127}Cs are combined with those obtained previously.[3,4] The fit was good for positive nuclear magnetic moment: χ^2 = 0.99 for nine observations, while it equals 19.21 for the negative moment. The results are: $\Delta\nu(^2S_{1/2})$ = +9109(45) MHz, which yields μ(uncorr) = +1.45(2) μ_N and μ(corr) = +1.46(2). Figure 2 shows the resonances of ^{125}Cs and ^{127}Cs at a field of 143 G. Figure 3 is the decay of the buttons corresponding to the ^{125}Cs and ^{127}Cs peaks of Fig. 2, and shows clearly the identification of the isotopes responsible for the signals.

From resonances obtained in the linear Zeeman region, the spin of ^{136}Cs was found to I = 5. For isotope identification, Fig. 4 shows the decay of a resonance button, its normalization button, and a chemistry sample from one of the spin search runs. Subsequent runs performed at progressively higher magnetic fields gave information on the hyperfine structure separation. Ten resonances for this isotope are collected in Table III. As an example of signal strength, resonance sweeps at 161 G are shown in Fig. 5. Fitting the observed resonances, we obtained for the ground state hfs separation $\Delta\nu(^2S_{1/2})$ = +12,702(28) MHz and thus a positive nuclear magnetic moment. The quoted error is twice the standard deviation. The χ^2 of this fit is 2.3, while the χ^2 for the fit assuming negative moment was 281.5. The nuclear magnetic moment obtained from

$\Delta\nu$ is μ(uncorr) = +3.68(4) μ_N, and μ(corr) = +3.70(4).

V. DISCUSSION

The ground state spin of ^{125}Cs and ^{127}Cs cannot be explained easily in terms of the shell model. To obtain a spin 1/2 from five J-J coupled protons, one has to place one of the protons in the $3s_{1/2}$ shell or place all five protons in the $h_{11/2}$ shell. Both of these possibilities are excluded by energy considerations. However, a deformed potential can account for the spin of 1/2.

The possibility of deformed nuclear shapes in the neutron-deficient isotopes in this region was suggested by Mottelson. Experimental observations[9] as well as theoretical calculations[10,11] tend to confirm this picture. Thus, using the model of Mottelson and Nilsson,[12,13] we can explain the spin by placing the odd proton in the 34th level on the prolate side (deformation parameter $\eta \simeq 2$). This assignment gives a nuclear magnetic moment of $\sim 2\ \mu_N$.[14] Kisslinger and Sorensen[15] obtained the ground state spin to be 1/2 through the coupling of a phonon to a spin 5/2 quasi-particle state. The resulting magnetic moment, including corrections for configuration mixing, was 0.45 μ_N. This value can be improved with the appropriate addition of the 5/2 quasi-particle state.

The ^{136}Cs nucleus contains one neutron hole and five protons from the major closed shells of 82 neutrons and 50 protons. Alternatively, the last protons may possibly be in the $1g_{7/2}$ shell, so the configuration would be 3 holes in a closed sub-shell of 58. Because of the proximity to these closed shells, it should not be surprising that the ground state spin and magnetic moment of ^{136}Cs are easily explainable in terms of the shell model. Hence, we used the above configuration and,

by taking a mixture of Wigner and Bartlett forces of zero range, such as those treated by de-Shalit[16] and Schwartz,[17] we find that spin 5 is favored if the spin term contribution is >5%. It should also be pointed out that the spin is in agreement with the Brennan-Bernstein[18] rules and with that proposed by gamma-ray spectroscopy.[19]

With the $(\pi g_{7/2})_{7/2}^{-3}$ and $(\nu d_{3/2})_{3/2}^{-1}$ configuration, we see that, in a single particle shell model picture, the spin 5 implies that the angular momenta of the neutron hole and the odd proton are aligned. Hence, the value of the magnetic moment should be the sum of the magnetic moment of the proton and neutron configurations. Using quenched g-factors for the protons and neutrons we obtain $\mu_{calc} = +3.72\ \mu_N$ in good agreement with experiment.

It is hoped that the nuclear ground state spins and magnetic moments of the cesium isotopes, coupled with information about excited states of these isotopes, will help in the understanding of residual forces and the transitions from a spherical to a deformed nuclear shape.

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Table III. Summary of ^{136}Cs results. (I = 5, J = 1/2, State: $^2S_{1/2}$)

Calibration[b] Isotope	Calibration Freq. (MHz)	Field (G)	Observed[a] Freq. (MHz)	Residual $\nu_{obs} - \nu_{calc}$ (kHz)	
				$g_I > 0$	$g_I < 0$
^{133}Cs	1.185(20)	3.384(57)	0.862(25)	+1.0	-2.6
^{85}Rb	11.108(10)	23.373(21)	5.965(12)	-6.4	-29.3
^{133}Cs	25.359(6)	71.110(17)	18.340(10)	-4.3	-65.1
^{133}Cs	25.655(6)	71.925(17)	18.555(10)	-2.3	-63.7
^{133}Cs	42.776(12)	118.416(32)	30.833(7)	-11.1	-96.8
^{133}Cs	58.835(11)	160.981(29)	42.307(15)	+7.4	-89.4
^{133}Cs	58.837(11)	160.986(29)	42.310(8)	+8.9	-87.6
^{133}Cs	101.182(12)	268.672(30)	72.200(12)	+2.6	-70.6
^{133}Cs	149.872(11)	385.017(25)	106.043(12)	-1.8	+41.4
^{133}Cs	149.876(11)	385.026(25)	106.047(12)	-0.5	+42.6

g_I	A (MHz)	$\Delta\nu$ (MHz)	μ_I (μ_N)	$g_I \times 10^{-4}$	χ^2
Positive	2309.4(2.5)	12702. (14)	+3.68	+4.01	2.30
Negative	2432.3(2.8)	13378. (15)	-3.88	-4.22	281.53

[a] Transitions are between (11/2,-9/2)↔(11/2,-11/2), in the (F, M_F) notation.

[b] For calibration isotope constants see Table I.

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Table II. Summary of ^{127}Cs results. (I = 1/2, J = 1/2, State: $^2S_{1/2}$)

Calibrating Isotope[b]	Calibration Freq. (MHz)	Field (G)	Observed Freq. (MHz)[a]	Residual $\nu_{obs} - \nu_{calc}$ (kHz)	
				$g_I > 0$	$g_I < 0$
^{133}Cs	0.882(6)	2.520(17)	3.259(6)	-1.2	-6.9
^{133}Cs	0.807(6)	2.307(17)	3.228(6)	-2.9	-8.1
^{133}Cs[c]	50.787(75)	139.773(199)	200.020(89)	+83.5	-94.8
^{133}Cs[c]	50.811(75)	139.837(199)	200.119(67)	+89.6	-88.8
^{133}Cs	51.948(12)	142.848(32)	204.450(20)	+20.7	-158.5
^{133}Cs	124.259(20)	324.761(48)	477.430(90)	-40.2	-41.3
^{133}Cs	124.238(20)	324.710(48)	477.379(70)	-13.8	-15.1
^{133}Cs	124.230(20)	324.691(48)	477.340(80)	-23.3	-24.6
^{85}Rb[d]	528.100(80)	649.570(63)	1000.200(600)	+409.9	+18052.3

g_I	$\Delta\nu$ (MHz)	μ_I (μ_N)	$g_I \times 10^{-4}$	χ^2
Positive	9109. (23)	+1.45	+15.8	0.99
Negative	9382. (24)	-1.50	-16.3	19.21

[a] Transitions are between (1,0)↔(1,-1), in the (F, M_F) notation.

[b] For calibration isotope constants see Table I.

[c] Resonances observed by Shugart (Ref. 3).

[d] Resonance observed by Khan (Ref. 4).

Table I. Summary of ^{125}Cs results. (I = 1/2, J = 1/2, State: $^2S_{1/2}$)

^{133}Cs Calibration Frequency (MHz)	Field (G)	Observed [a] Freq. (MHz)	Residual $\nu_{obs} - \nu_{calc}$ (kHz)	
			$g_I > 0$	$g_I < 0$
0.882(6)	2.520(17)	3.259(6)	-1.4	-6.8
0.807(6)	2.307(17)	3.228(6)	-3.1	-8.0
21.318(6)	59.960(17)	84.770(30)	+0.2	-102.7
51.944(12)	142.837(32)	204.628(20)	+29.9	-127.5
117.715(12)	309.033(29)	454.142(17)	-5.6	+30.3

g_I	$\Delta\nu$ (MHz)	μ_I (μ_N)	$g_I \times 10^{-4}$	χ^2
Positive	8754. (19)	+1.40	+15.2	0.38
Negative	9025. (20)	-1.44	-15.7	14.16

	I	g_J	$g_I \times 10^{-4}$	$\Delta\nu$ (MHz)	Transition
^{133}Cs	7/2	-2.002543	3.98994	9192.6317	(4,-3) ↔ (4,-4)
^{85}Rb	5/2	-2.002332	2.93700	3035.7324	(3,-2) ↔ (3,-3)

[a] Transitions are between (1,0)↔(1,-1) in the (F, M_F) notation.

FIGURE CAPTIONS

Fig. 1. Ratios of the different activities resulting from the reaction $^{127}I(\alpha,kn)Cs$ as a function of incident-particle energy. (a) Ratio of the production of ^{125}Cs to ^{127}Cs; (b) ratio of the activity of ^{125}Cs, ^{127}Cs, and ^{129}Cs to a constant background of a long-lived activity (∞) that appeared in the decay of the sample; (c) ratio of the productions of ^{125}Cs and ^{127}Cs to that of ^{129}Cs.

Fig. 2. Resonances of ^{125}Cs and ^{127}Cs.

Fig. 3. Decay analysis of a half beam (mostly fast atoms which are not deflected appreciably by the magnetic field) and of ^{125}Cs and ^{127}Cs resonance buttons, of Fig. 2.

Fig. 4. Decay curves of ^{136}Cs resonance, normalization, and chemistry buttons.

Fig. 5. Resonances of ^{136}Cs.

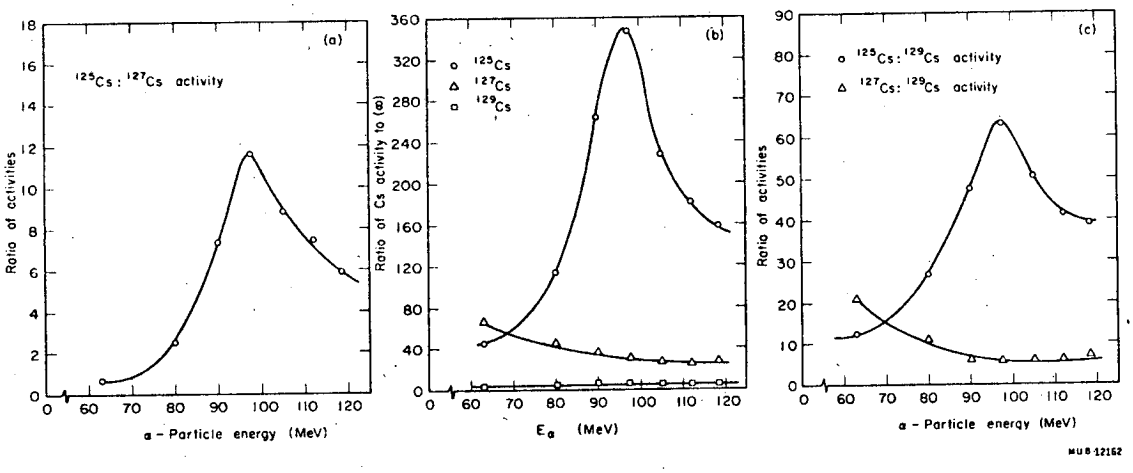
(a)
^{125}Cs : ^{127}Cs activity
Ratio of activities
α - Particle energy (MeV)
(b)
^{125}Cs
^{127}Cs
^{129}Cs
Ratio of Cs activity to (α)
E_α (MeV)
(c)
^{125}Cs : ^{129}Cs activity
^{127}Cs : ^{129}Cs activity
Ratio of activities
α - Particle energy (MeV)
MU8-12162

Fig. 1

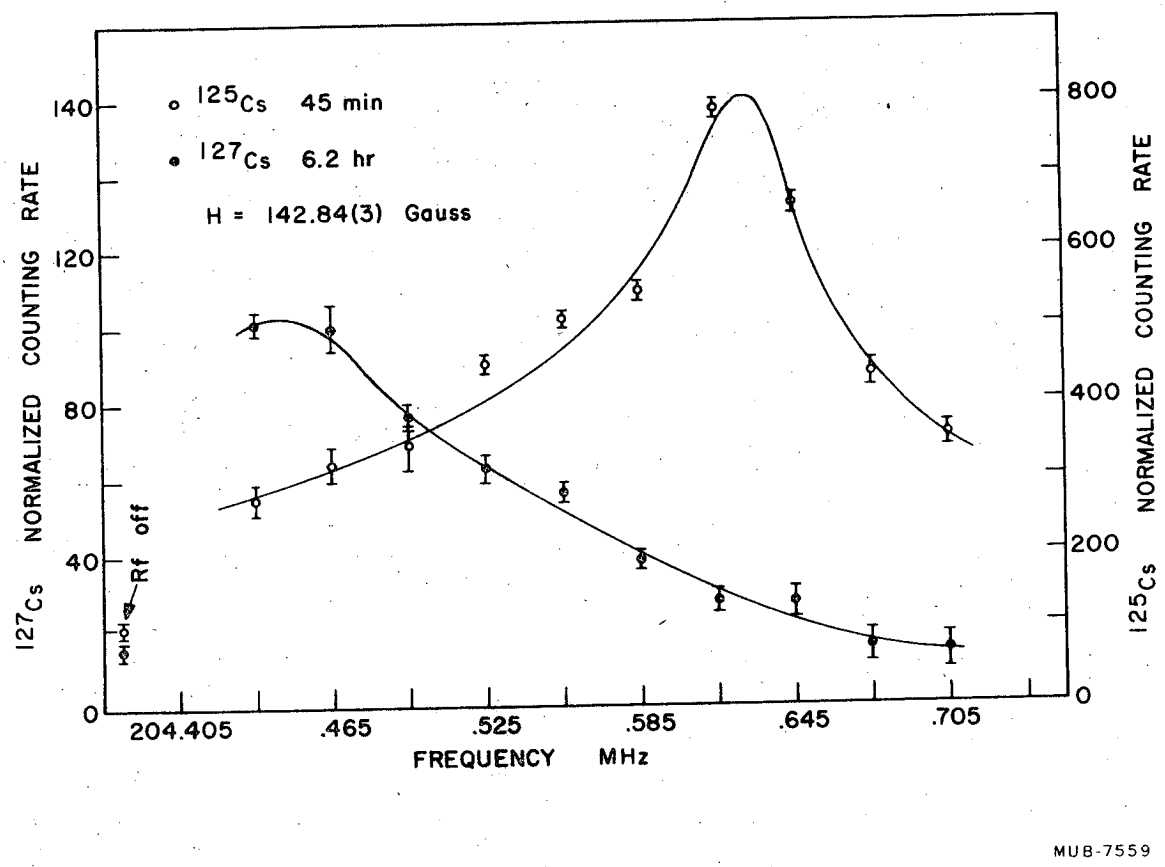
^{125}Cs 45 min
^{127}Cs 6.2 hr
H = 142.84(3) Gauss
^{127}Cs NORMALIZED COUNTING RATE
^{125}Cs NORMALIZED COUNTING RATE
Rf off
140
120
80
40
0
800
600
400
200
0
204.405
.465
.525
.585
.645
.705
FREQUENCY MHz
MUB-7559

Fig. 2

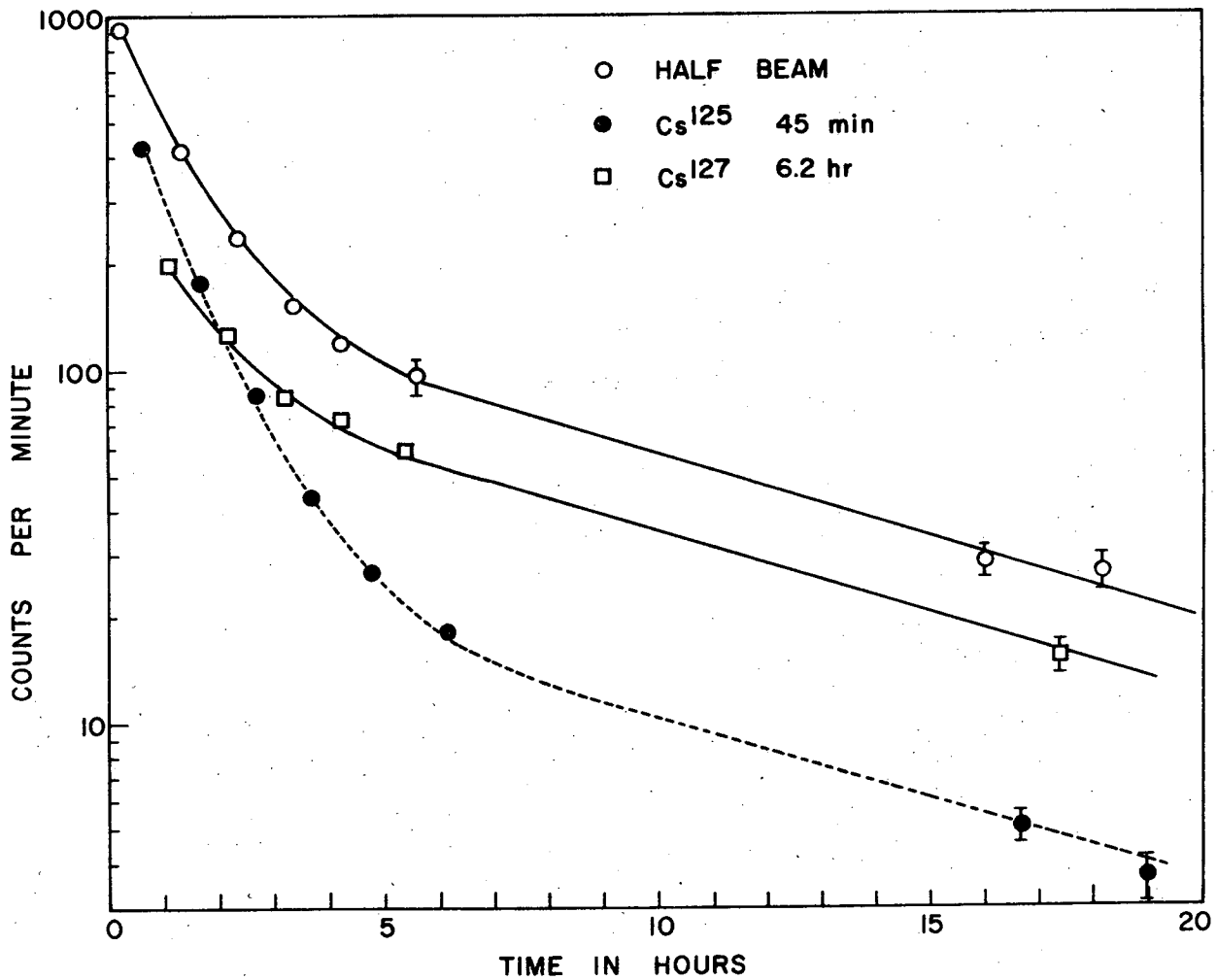
1000
100
10
COUNTS PER MINUTE
HALF BEAM
Cs125 45 min
Cs127 6.2 hr
0
5
10
15
20
TIME IN HOURS
MUB-7558

Fig. 3

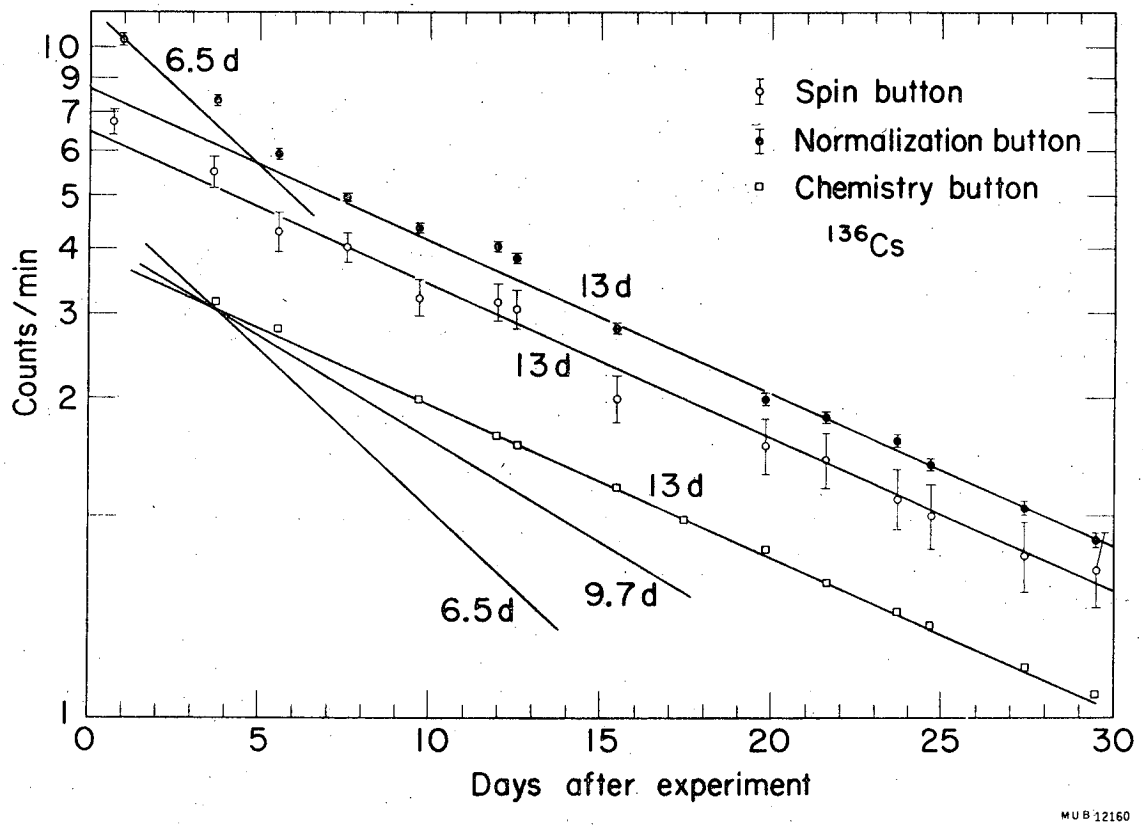
Counts / min
Days after experiment
Spin button
Normalization button
Chemistry button
^{136}Cs
6.5 d
13 d
13 d
13 d
9.7 d
6.5 d
MUB 12160

Fig. 4

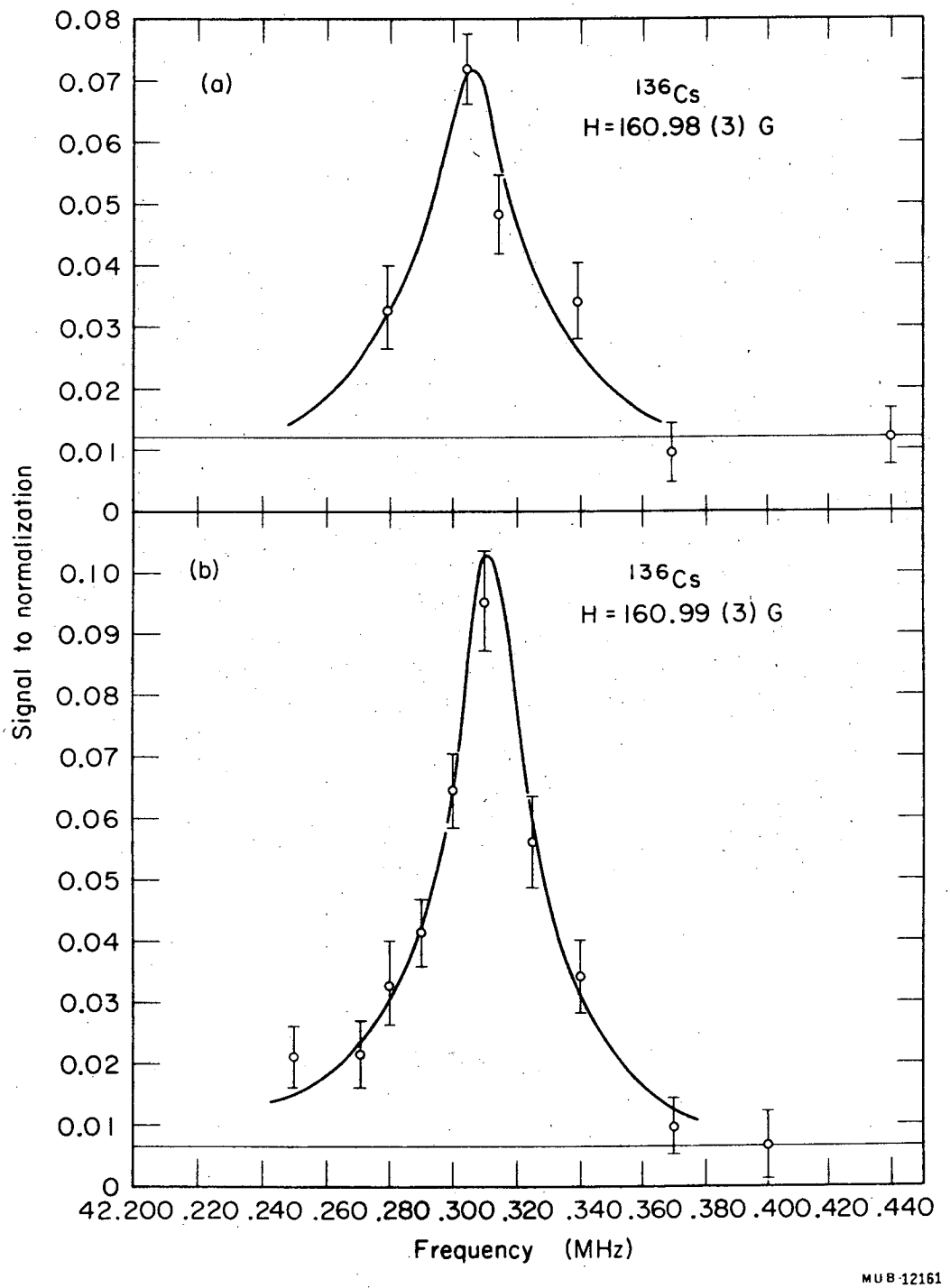
(a)
^{136}Cs
H=160.98 (3) G
(b)
^{136}Cs
H = 160.99 (3) G
Signal to normalization
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
42.200 .220 .240 .260 .280 .300 .320 .340 .360 .380 .400 .420 .440
Frequency (MHz)
MUB-12161

Fig. 5

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