Title

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NUCLEAR MAGNETIC MOMENT, HYPERFINE STRUCTURE, AND HYPERFINE STRUCTURE ANOMALY OF ^{196}Au*

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ABSTRACT

We have measured the hfs separation and nuclear magnetic moment of 6.2-day ^{196}Au. The results we obtain are: $\Delta\nu(^{196}\text{Au}) = 21347.2522(15)$ MHz and $\mu_I(^{196}\text{Au};\ \text{uncorr}) = +0.5823(14)\ \mu_N$. These values give the hfs anomaly with respect to ^{197}Au, $^{196}\Delta^{197} = -8.02(24)\%$. These measurements reconfirm the existence of large hfs anomalies in the gold isotopes. They also show that the ground state nuclear structure of ^{196}Au is similar to that of ^{198}Au.

I. INTRODUCTION

The hfs anomaly ${}^{1}\Delta^{2}$ is defined by

$$(a_1/a_2) = (g_1/g_2)(1 + {}^{1}\Delta^{2}) \quad , \tag{1}$$

where the a's are the hfs interaction constants and the g's are the nuclear g factors for two isotopes of the same element. This quantity, ${}^{1}\Delta^{2}$, depends upon both the distribution of nuclear magnetism and the electronic wave function inside the nucleus. The measurement of hfs anomalies under differing electronic environmental conditions has recently become of interest as a means of separating the contact and non-contact hyperfine fields acting on impurity atoms implanted in ferromagnetic materials.[1,2] This means of separating the different terms of the hfs interaction is most easily effected for those elements, such as gold, whose isotopes have large hfs anomalies.

As a starting point for such an analysis of hyperfine fields, it is useful to have measurements of the hfs anomalies in the free atomic state where, as in the case of the gold isotopes, the electronic ground state is ${}^{2}S_{1/2}$ and hfs splitting is entirely due to the Fermi contact interaction. To determine the hfs anomaly it is necessary to have accurate measurements of the nuclear magnetic moments and hfs interaction constants. Accurate values of the hfs constants and nuclear magnetic moments have been measured previously[3,4] for ^{197}Au, ^{198}Au, and ^{199}Au. This paper describes first a precision atomic-beam magnetic-resonance (ABMR) measurement of the hfs interaction constant and nuclear magnetic moment of 6.2-day ^{196}Au, (I = 2); the nuclear spin and a crude value of the hfs constant and nuclear moment for this isotope were measured several years ago in our laboratory.[5,6] Our results are then used to obtain the hfs anomaly $^{196}\Delta^{197}$. We conclude the paper with a brief discussion of hfs anomalies and nuclear structure for the gold isotopes.

II. EXPERIMENTAL METHOD

The Hamiltonian describing the ground state (J = 1/2) hyperfine structure of gold is

$$\mathcal{H} = ha\ \underset{\sim}{I}\cdot\underset{\sim}{J} - g_I\ \mu_0\ \underset{\sim}{I}\cdot\underset{\sim}{H} - g_J\ \mu_0\ \underset{\sim}{J}\cdot\underset{\sim}{H} \qquad (2)$$

where $\underset{\sim}{I}$ is the nuclear angular momentum, $\underset{\sim}{J}$ is the electronic angular momentum, g_I and g_J are the corresponding g factors, a is the hfs interaction constant, $\underset{\sim}{H}$ is an applied magnetic field, h is Planck's constant, and μ_0 is the Bohr magneton. The eigenvalues of Eq. (2) for J = 1/2 are given by the Breit-Rabi formula

$$W(F,M_F) = \frac{h\Delta\nu}{2(2I+1)} - g_I\mu_0 HM_F + (F-I)h\Delta\nu\left\{1 + \frac{4M_F x}{(2I+1)} + x^2\right\}^{1/2} \qquad (3)$$

where $\Delta\nu = a(I + 1/2)$, $x = (g_I - g_J)H(\mu_0/h\Delta\nu)$, and $\underset{\sim}{F} = \underset{\sim}{I} + \underset{\sim}{J}$. The energy levels of ^{196}Au as a function of magnetic field are shown in Fig. 1. By measuring the transition frequencies between pairs of (F,M_F) levels and fitting the data to Eq. (2), one can determine a and g_I.

Gold-196 was produced by the reactions ^{196}Pt(d,2n)^{196}Au and ^{195}Pt(d, n)^{196}Au. A .020-inch platinum foil was bombarded with 25 MeV deuterons for 10 to 16 hours. These bombardments were made at either the University of Washington 60-inch cyclotron, the Crocker 76-inch cyclotron at Davis, or the 88-inch cyclotron at Berkeley, depending mainly upon which cyclotron had time available to make the bombardment. After a delay of several days to allow the 39-hour ^{194}Au to decay, the gold was separated from the platinum by a standard chemical procedure using ethyl acetate.[7]

The atomic beam was produced by electron-bombardment heating of a carbon-lined tantalum oven. The oven slit-jaws were channeled carbon blocks. This channeling, which reduces the amount of material used, was necessary because of the limited quantity of ^{196}Au which was available for any one run. The beam was detected by collecting it on sulfur-coated brass buttons which were then placed in thin NaI(Tl) crystal counters set to detect the platinum K x-ray.

The experimental procedure was similar to that used by Vanden Bout et al. in their measurements on ^{198}Au and ^{199}Au, and is described in detail in Ref. 4. Briefly, we observed the $\Delta F = 0$ transition $(5/2, -3/2) \leftrightarrow (5/2, -5/2)$ at several values of magnetic field up to 4775 G. This gave rough values of a and g_I. We next observed the degenerate $\Delta F = \pm 1$ transitions $(5/2, \pm 1/2) \leftrightarrow (3/2, \mp 1/2)$ at low magnetic field ($\sim$1 G) to determine a very accurately. We then observed the doublet $(5/2, -3/2) \leftrightarrow (3/2, -1/2)$, $(5/2, -1/2) \leftrightarrow (3/2, -3/2)$, at its field-independent point, 3199 G. The difference between the frequencies of these two transitions is equal to $2(\mu_0/h)Hg_I$, and determines g_I independently of a. In addition, the absolute values of the frequencies of these latter transitions depend strongly on a and provide a good check on the low field determination of this parameter.

III. RESULTS

The data from the observed resonances for ^{196}Au are shown in Table I. Figures 2 and 3 are examples of resonance curves for the two types of $\Delta F = \pm 1$ transitions observed in this experiment. The normalized counting rate is 100 times the ratio of the flopped-in signal to the flopped-out signal. The actual counting rates in this experiment were usually very low. A button, exposed to the beam for five minutes at the peak frequency of the resonance, typically had a counting rate of 5 to 6 counts per minute. This is to be compared with a button taken off resonance which typically had a counting rate of less than one count per minute. These low counting rates were one of the chief limitations on the precision of this experiment. Despite the low counting rates, the beam intensity was very steady and we believe that the experimental uncertainties listed in Table I are reliable.

A least-squares fit of the data in Table I to Eq. (2), treating a and g_I as variable parameters, gave the following results:

$$\Delta\nu(^{196}\text{Au}) = +21347.2522(15)\ \text{MHz},$$

$$\mu_I(^{196}\text{Au; uncorr}) = +0.5823(14)\ \mu_N,$$

$$\mu_I(^{196}\text{Au; corr}) = +0.5879(14)\ \mu_N,$$

$$^{196}\Delta^{197} = -8.02(24)\ \%.$$

The uncertainties in parentheses are two standard deviations as given by the least-squares fit. With 15 data points and two independent variables, $\chi^2 = 2.8$. When the test of external consistency is used, the quoted errors give a confidence level greater than 99%. The hfs anomaly was computed using[3]

$$\Delta\nu(^{197}\text{Au}) = 6099.321084(13)\ \text{MHz}$$

and

$$\mu_I(^{197}\text{Au; uncorr}) = 0.143491(9)\ \mu_N.$$

The authors of Ref. 4 have shown that second-order corrections to $\Delta\nu$ from excited electronic states, particularly the $^2D_{5/2}$ and $^2D_{3/2}$ states, are much less than the experimental uncertainties and can therefore be neglected.

IV. DISCUSSION

The importance of the hfs anomaly as an aid to understanding nuclear structure is severely limited by the complexity of its interpretation. Neither the electronic nor the nuclear wave functions are known well enough to permit one to make a reliable quantitative comparison between experimental results and theoretical predictions and to extract information about the nuclear magnetism for a particular nucleus.

Present interest in hfs anomalies would seem to derive primarily from their usefulness in gaining an understanding of some details of electronic structure. The hfs anomaly is a very sensitive measure of the relative amount of the electronic wave function which can give rise to a contact hyperfine interaction. This fact was pointed out some time ago by Sandars and Beck[9] for the case of free atoms and more recently by Fox and Stone[1] and by Perlow et al.[2] for hyperfine fields in ferromagnetic solids. The large size of the gold hfs anomaly $^{196}\Delta^{197}$ makes it useful for such an analysis of hyperfine fields and served as the primary motivation for this experiment.

In addition to having the same nuclear spin (I = 2), ^{196}Au and ^{198}Au have nearly equal magnetic moments [$\mu(^{198}Au) = +0.5898\ \mu_N$], and the hfs anomaly $^{196}\Delta^{198} = -0.2(3)\%$ is very small. These quantities each measure somewhat different nuclear properties. The equal spins, nearly equal magnetic moments and the small hfs anomaly indicate that the nuclear ground states of these two isotopes are undoubtedly very similar.

Comparison of the measured nuclear moments with theoretical values is not very profitable because of the great difficulty in making reliable moment calculations for nuclei in this mass region. They are neither sufficiently deformed nor sufficiently near a closed shell to be amenable to nuclear structure calculations. The magnetic moments for the odd-mass I = 3/2 gold isotopes are all quite close to the Schmidt values, and the measured moments of the odd-odd nuclei ^{196}Au and ^{198}Au differ by less than 0.2 μ_N from the simplest single-particle shell model predictions. This agreement is probably fortuitous since the Schmidt values are generally unreliable for nuclei this far removed from closed shells. Straightforward attempts to improve the simplest predictions by such means as configuration mixing seem to give poorer agreement with experiment.[10] These same problems also make it difficult to interpret the hfs anomalies in terms of specific changes in nuclear structure between one isotope and the next.

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FOOTNOTES

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Table I. Resonance Data.

Calibrating Isotope Data				^{196}Au Data		
Run #	Isotope	Frequency (MHz)	H (Gauss)	Transition $(F,M_F)\leftrightarrow(F',M_F')$	Frequency (MHz)	Residual (MHz)
152A	^{85}Rb	50.488(20)	99.980(37)	(5/2,-3/2)↔(5/2,-5/2)	56.6400(250)	-.0019
152B	^{85}Rb	179.115(20)	300.046(27)	(5/2,-3/2)↔(5/2,-5/2)	173.6300(250)	-.0059
152C	^{85}Rb	739.430(25)	799.904(16)	(5/2,-3/2)↔(5/2,-5/2)	488.6350(500)	.0506
153C	^{133}Cs	1313.839(12)	2000.285(11)	(5/2,-3/2)↔(5/2,-5/2)	1397.0380(120)	-.0069
153D	^{133}Cs	6541.276(40)	4775.043(16)	(5/2,-3/2)↔(5/2,-5/2)	4563.9120(360)	-.0239
153E	^{133}Cs	6541.308(30)	4775.056(12)	(5/2,-3/2)↔(5/2,-5/2)	4563.9260(240)	-.0290
154B	^{85}Rb	0.467(12)	1.000(26)	(5/2, 1/2)↔(3/2,-1/2)	21347.2600(450)	.0078
155A	^{133}Cs	3097.926(12)	3199.007(6)	(5/2,-1/2)↔(3/2,-3/2)	19470.0236(25)	-.0010
156B	^{133}Cs	3097.840(15)	3198.961(8)	(5/2,-3/2)↔(3/2,-1/2)	19471.4456(70)	.0010
157A	^{133}Cs	3097.776(50)	3198.927(27)	(5/2,-3/2)↔(3/2,-1/2)	19471.4442(35)	-.0003
157B	^{133}Cs	3097.813(12)	3198.946(6)	(5/2,-3/2)↔(3/2,-1/2)	19471.4442(20)	-.0004
158A	^{133}Cs	3097.7090(25)	3198.8905(14)	(5/2,-1/2)↔(3/2,-3/2)	19470.0248(20)	.0002
158B1	^{133}Cs	0.521(10)	1.489(29)	(5/2, 1/2)↔(3/2,-1/2)	21347.2528(35)	.0005
158B2	^{133}Cs	0.521(10)	1.489(29)	(5/2, 1/2)↔(3/2,-1/2)	21347.2525(14)	.0002
158C	^{133}Cs	3097.815(15)	3198.948(8)	(5/2,-1/2)↔(3/2,-3/2)	19470.0249(20)	.0003

Calibration Constants: ^{85}Rb: $\Delta\nu$ = 3035.732439 MHz; $g_I = 2.9364\times10^{-4}$; $g_J = -2.002332$.

^{133}Cs: $\Delta\nu$ = 9192.631770 MHz; $g_I = 3.9900\times10^{-4}$; $g_J = -2.002542$.

$(\mu_o/h) = 1.399611$; $(m_p/m_e) = 1836.10$.

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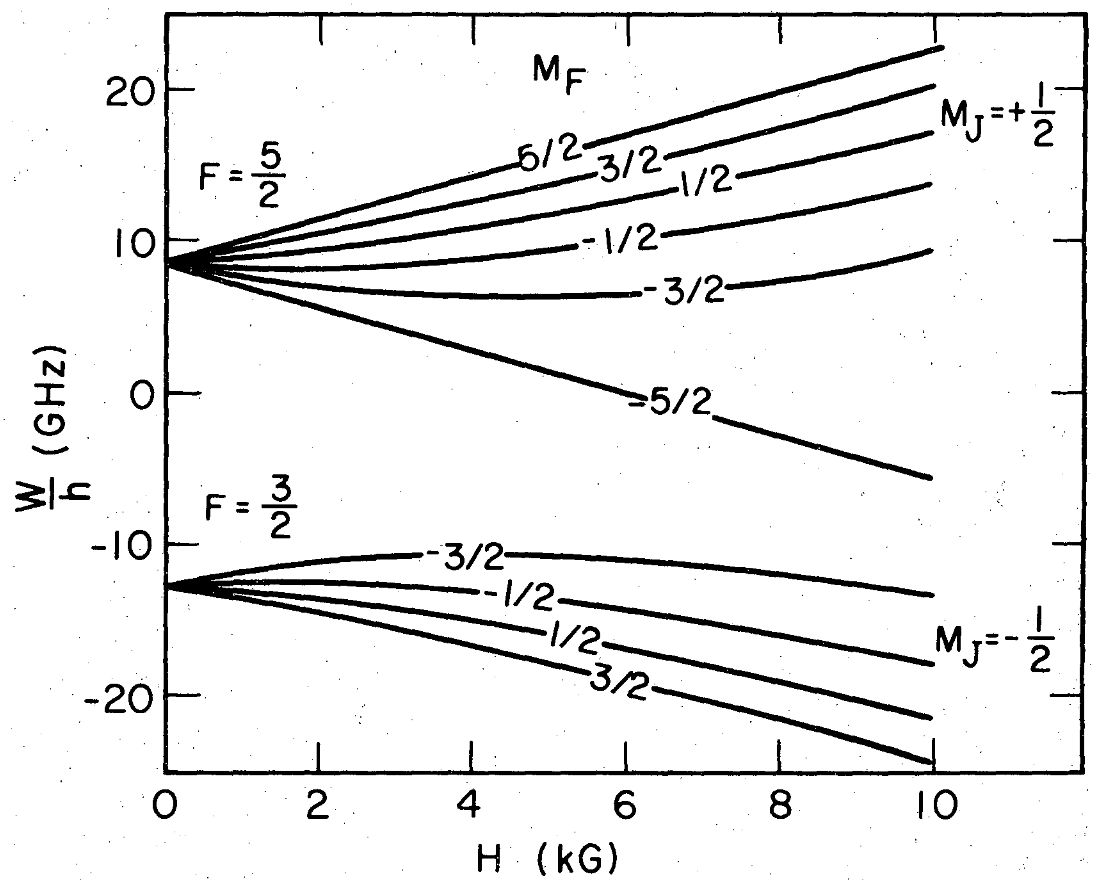

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Fig. 1. Hyperfine energy levels of ^{196}Au as a function of magnetic field.

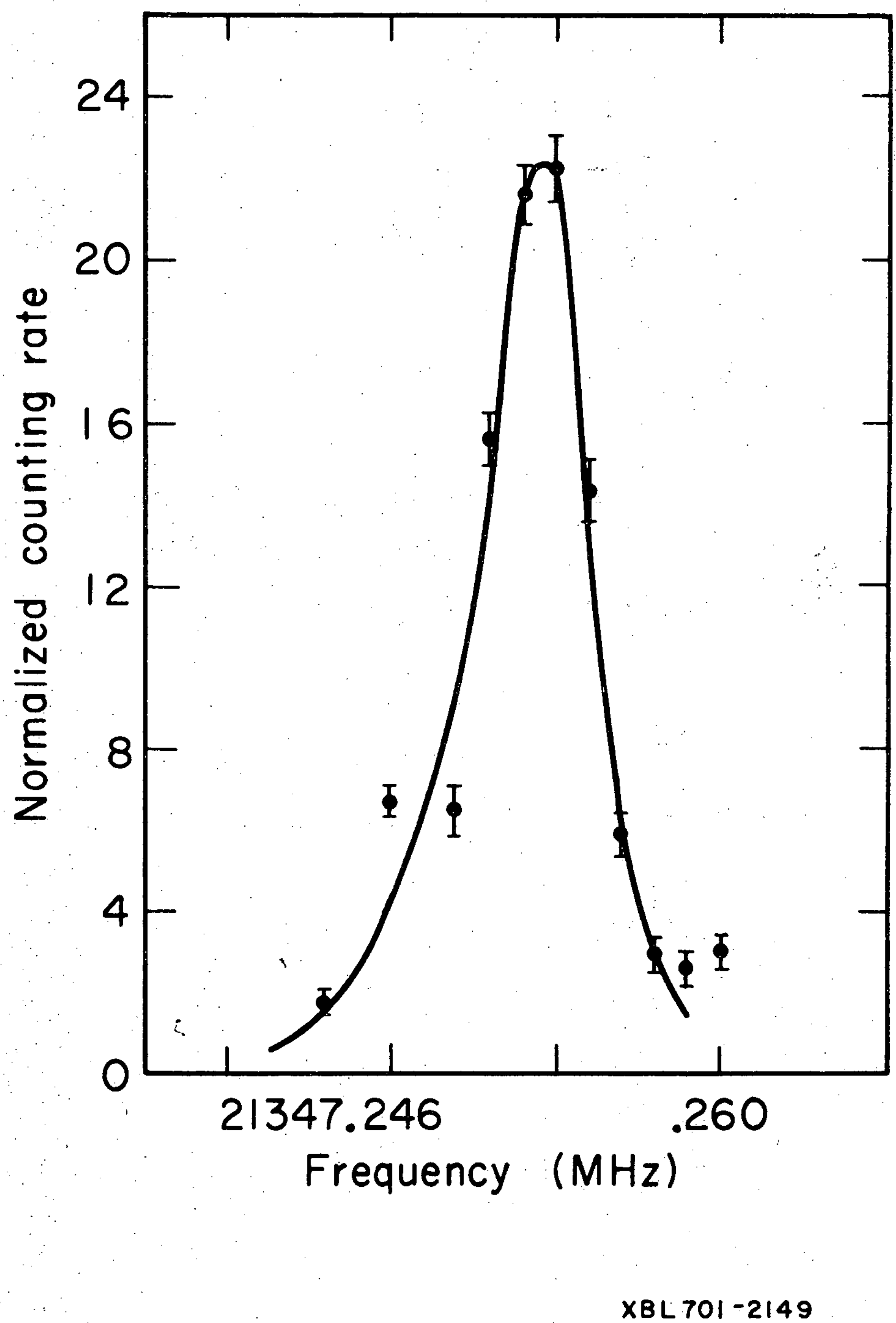

Fig. 2. The degenerate $(5/2, \pm1/2)\leftrightarrow(3/2, \mp1/2)$ transitions in ^{196}Au at 1.5 gauss.

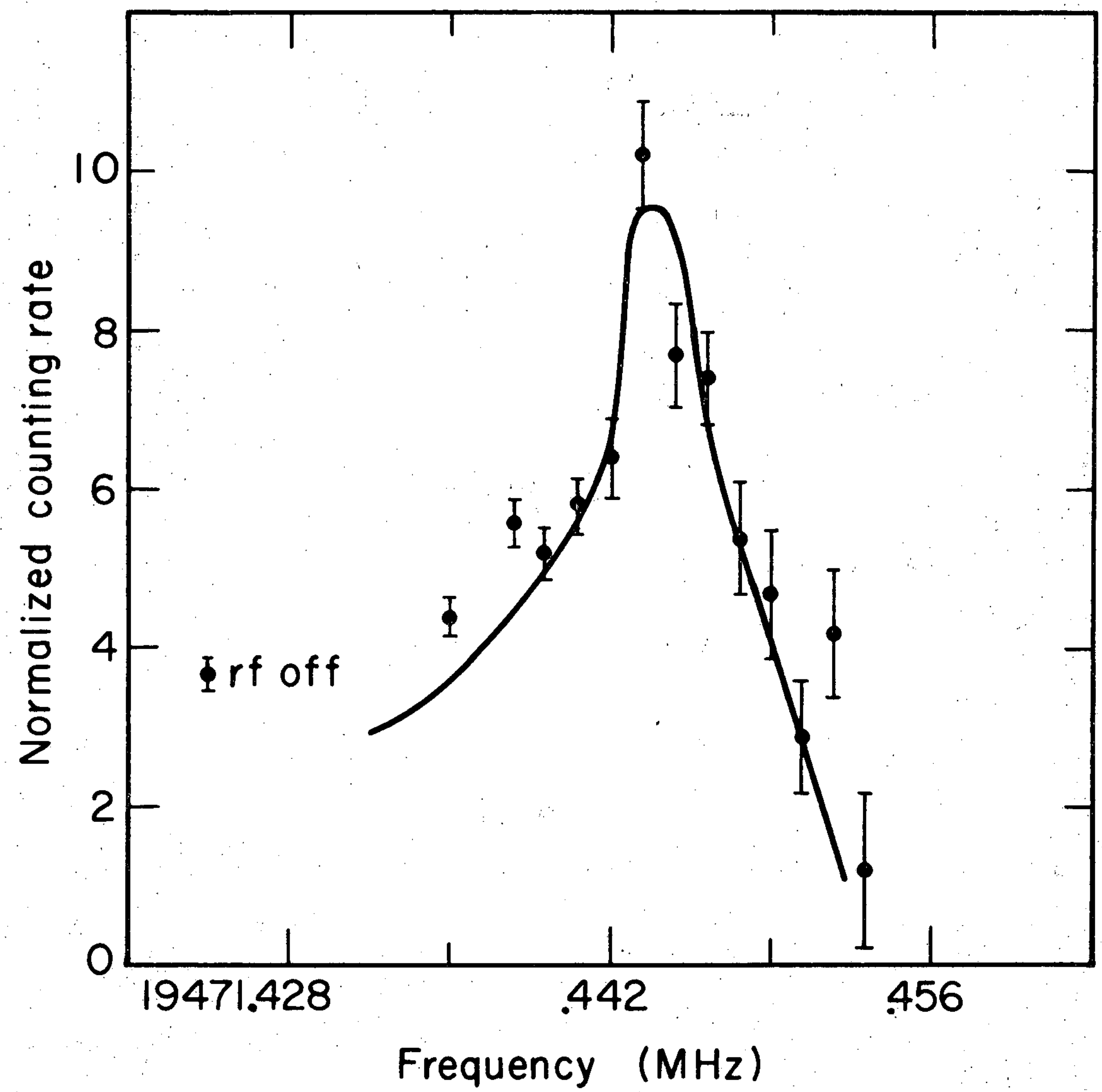

Fig. 3. The (5/2, -3/2)↔(3/2, -1/2) transition at its field-independent point, 3199 gauss.

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