Hyperfine Structure Separation and Magnetic Moment of K^{42}†

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The atomic beam flop-in magnetic-resonance method has been employed to measure the hyperfine structure separation $\Delta\nu$ and the nuclear magnetic moment μ_I in the $^2S_{1/2}$ electronic ground state of the 12.4-h potassium-42. The results are: $\Delta\nu(K^{42})=1258.877(4)$ Mc/sec; $\mu_I(K^{42})=-1.1395(30)$ nuclear magnetons (diamagnetic correction not included). With these values, estimates of the hyperfine structure anomaly with respect to other potassium isotopes can be made: $^{39}\Delta^{42}=+0.20(25)\%$, $^{40}\Delta^{42}=-0.25(25)\%$, $^{41}\Delta^{42}=+0.42(25)\%$.

I. INTRODUCTION

The atomic beam flop-in magnetic-resonance method has been applied to the measurement of the hyperfine structure separation $\Delta\nu$ and the nuclear magnetic dipole moment μ_I of K^{42}. The study of static nuclear properties by the atomic-beam method has been treated by many authors.[1–3] These authors review the over-all atomic-beam technique and the theory of hyperfine-structure interactions in free atoms. In the present work the observable interactions are limited to the simple magnetic-dipole type by the $J=\frac{1}{2}$ electronic ground state of the potassium atom. In view of the previous work it is only necessary here to present the principle points of the calculations and to indicate their relation to this experiment.

II. THEORY OF THE EXPERIMENT

The Hamiltonian which describes the interaction of the K^{42} nucleus with its environment is given by

$$\mathcal{H}=ha\mathbf{I}\cdot\mathbf{J}-\boldsymbol{\mu}_I\cdot\mathbf{H}-\boldsymbol{\mu}_J\cdot\mathbf{H}, \quad (1)$$

where a is the hyperfine structure constant and $\boldsymbol{\mu}_J$ is the electronic magnetic moment. $\mathbf{H}$ is the constant uniform field in the region of space where the transitions of interest take place. The secular equations for $J=\frac{1}{2}$ may be solved exactly, and is known as the Breit-Rabi equation. By choosing appropriate values for the magnetic field for certain transitions, it is possible to evaluate the hyperfine structure separation $\Delta\nu$ and the nuclear magnetic dipole moment μ_I.

In the low-field region ($H\approx 2$ G), the frequency of the unresolved doublet transitions $(F=\frac{3}{2},\ M=\pm\frac{1}{2})\leftrightarrow(F=\frac{5}{2},\ M=\mp\frac{1}{2})$ is related to the hyperfine structure separation by

$$\nu=\Delta\nu[1+12/25x^2] \quad (2)$$

where

$$x=\frac{(-\mu_J/J+\mu_I/I)H}{h\Delta\nu}.$$

The second term on the right side of Eq. (2) is of the order of 10^{-6}.

At a higher field ($H\approx 188$ G) where x takes the value 0.420204103, the two transitions $\nu_+=(\frac{3}{2},\frac{3}{2})\leftrightarrow(\frac{5}{2},\frac{1}{2})$ and $\nu_-=(\frac{3}{2},\frac{1}{2})\leftrightarrow(\frac{5}{2},\frac{3}{2})$ are related to $\Delta\nu$ and μ_I by

$$\nu_I=\bar{\nu}\pm(\mu_I/I)(\mu_0H/h). \quad (3)$$

Their difference is related to μ_I by

$$\mu_I=(\nu_+-\nu_-)hI/(2\mu_0H).$$

Details of the calculation of the field values and transition selection for the μ_I determination are given in the appendix of a paper by Braslau *et al.*,[4] and will not be repeated here. The Breit-Rabi diagram for $I=2$, $J=\frac{1}{2}$, and $g_I<0$ is shown in Fig. 1.

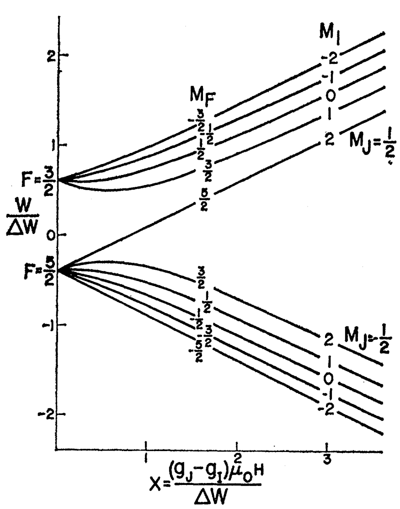

Fig. 1. Breit-Rabi diagram, $I=2$, $J=\frac{1}{2}$, g_I is negative.

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[1] N. F. Ramsey, *Molecular Beams* (Oxford University Press, New York, 1956).
[2] H. Kopferman, *Nuclear Moments* (Academic Press Inc., New York, 1958).
[3] K. F. Smith, *Molecular Beams* (Methuen & Company Ltd., London, 1955).
[4] N. Braslau, G. O. Brink, and J. M. Khan, Phys. Rev. 123, 1801 (1961).

Table I. Experimental run data.

Run No.	Hairpin orientation	Transition observed	Calibration frequency (Mc/sec) (K^{39})[a]	Magnetic field (G)	Resonances (visual fit)[b] (Mc/sec)	Least-squares fit[c] (Mc/sec)
1	+	ν_+	780.508(100)	188.806(40)	1148.1340(25)	1148.13395(7)
2	+	ν_-	780.508(100)	188.806(40)	1148.2980(25)	1148.29805(7)
3	+	ν_+	780.500(300)	188.801(86)	1148.1341(25)	1148.13425(7)
4	+	ν_-	780.500(300)	188.801(86)	1148.2980(25)	1148.29795(7)
5	−	ν_+	780.250(100)	188.665(50)	1148.1340(25)	1148.13405(7)
6	−	ν_-	780.250(100)	188.665(50)	1148.2980(25)	1148.29815(7)
7	−	ν_0	461.988(50)	1.40(5)	1258.883(40)	1258.8834(7)

[a] The K^{39} calibration transition was the unresolved doublet: $(2,1) \leftrightarrow (1,0)$. $(2,0) \leftrightarrow (1,1)$

[b] Typical Ramsey pattern is shown in Fig. 2.

[c] To a bell-shaped curve.

III. DATA AND ANALYSIS

Seven experimental runs were performed as shown in Table I. Six of these were at approximately 188 G, where the transitions $\nu_-=(\frac{3}{2},\frac{1}{2})\leftrightarrow(\frac{5}{2},\frac{3}{2})$, $\nu_+=(\frac{3}{2},\frac{3}{2})\leftrightarrow(\frac{5}{2},\frac{1}{2})$ are field-independent. The seventh experimental run measured directly the $\Delta\nu$ at 1.4 G using the transition $\nu_0=(\frac{3}{2},\pm\frac{1}{2})\leftrightarrow(\frac{5}{2},\mp\frac{1}{2})$. The magnetic field was determined by measurement of the transition frequency of a resonance in K^{39} shown in Table I.

For the evaluation of g_I the experiments were performed with two orientations of the separated field hairpin. The purpose of this was to test for the existence of a phase shift of the radio-frequency signal at one leg with respect to that of the other. Any shift existing was found to be less than the experimental error of the measurements.

The hyperfine structure separation is obtained in the following manner. The frequency of the low-field transition is directly related to $\Delta\nu$ by Eq. (2). The value of $\Delta\nu$ is also related to the frequencies of the high-field transitions by Eq. (3). When evaluated numerically the result is

$$\nu_\pm=0.912\,095\,585\Delta\nu\pm(g_I\mu_0H/h).$$

The seven independent measurements yield

$$\Delta\nu=1258.877(4)\ \text{Mc/sec}.$$

The magnetic moment is obtained by taking values of

$$\mu_I=(\nu_+-\nu_-)hI/(2\mu_0H).$$

These are tabulated in Table II.

IV. ERROR ANALYSIS

In order to evaluate either the $\Delta\nu$ or μ_I it is necessary to know the magnetic field, the frequency of the transitions, and the reliability of the resonance line shape in yielding the resonance frequency. The frequency was established by comparison with a secondary standard, good to 1 part in 10^9, which was in turn compared with a National Company Atomichron (atomic-beam-frequency standard). The measurement of the magnetic field was effected through the continuous observation of the field-dependent resonance in stable K^{39}. The properties of the Ramsey separated field hairpin used here have been analyzed and presented in an earlier paper.[4]

The criterion employed in establishing the probable error in the resonance frequency from the central Ramsey peak shape was $\pm\frac{1}{5}$ of the half-width at half-maximum. (See Fig. 2.)

V. HYPERFINE STRUCTURE ANOMALY

With values for $\Delta\nu$ and μ_I it is possible to calculate values for the hyperfine structure anomaly with respect to other potassium isotopes by the following formula[5–8]:

$$^1\Delta^2=\left[\left(\frac{\Delta\nu_1}{\Delta\nu_2}\frac{\mu I_2}{\mu I_1}\frac{I_1}{I_2}\frac{2I_2+1}{2I_1+1}\right)-1\right]\times100\%.$$

By convention the subscript (1) refers to the lighter

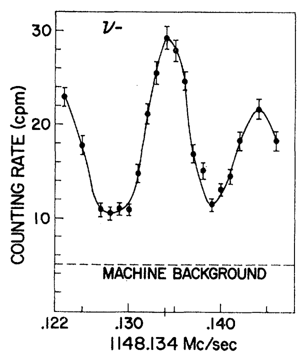

Fig. 2. Typical Ramsey pattern.

[5] F. Bitter, Phys. Rev. **76**, 150 (1949).

[6] A. Bohr, Phys. Rev. **81**, 331 (1951).

[7] J. Eisinger and V. Jaccarino [Rev. Mod. Phys. **30**, 528 (1958)] give a review of theories of distribution of nuclear magnetism.

[8] H. H. Stroke, Quarterly Progress Report No. 54, Research Laboratory of Electronics, MIT, July 15, 1959 (unpublished).

TABLE II. Data analysis.

Run	ν_+ (Mc/sec)	ν_- (Mc/sec)	$\nu_+ - \nu_-$ (Mc/sec)	H (G)	μ_I (nm)
1, 2	1148.29805(25)	1148.13395(25)	0.16410(35)	188.806(40)	−1.1402(25)
3, 4	1148.29795(25)	1148.13425(25)	0.16370(35)	188.801(40)	−1.1374(25)
5, 6	1148.29815(25)	1148.13405(25)	0.16410(35)	188.665(50)	−1.1395(25)
					Average value: $\mu_I = -1.1395(30)$[a]

[a] Value does not include diamagnetic correction.

isotope. The results are

$$^{39}\Delta^{42} = +0.20(25)\%,$$

$$^{40}\Delta^{42} = -0.25(25)\%,$$

$$^{41}\Delta^{42} = +0.42(25)\%.$$

These results do not serve as a critical test of the current theories of the distribution of nuclear magnetism.

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Spin and Nuclear Moments of 245-Day Zn^{65}; Redetermination of the hfs of Zn^{67} and $\tau(^3P_1)$ of Zinc*

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The hfs of the $(4s4p)^3P_1$ state of 245-day Zn^{65} and of Zn^{67} has been determined by the optical double-resonance technique. The nuclear spin I, and the hfs splittings are: Zn^{65}: $I=5/2$, $\nu(7/2-5/2)=1875.475(6)$ Mc/sec, $\nu(5/2-3/2)=1334.123(6)$ Mc/sec; Zn^{67}: $\nu(7/2-5/2)=2111.300(3)$ Mc/sec, $\nu(5/2-3/2)=1551.565(4)$ Mc/sec. The hfs coupling constants, corrected to second order for interaction with the $^3P_2$ and $^3P_0$ states, are: Zn^{65}: $A(65)=+535.163(2)$ Mc/sec, $B(65)=+2.870(5)$ Mc/sec; Zn^{67}: $A(67)=+609.086(2)$ Mc/sec, $B(67)=-18.782(8)$ Mc/sec. If quadrupole shielding effects are neglected, the corresponding moments of Zn^{65} are: $\mu(65)=+0.7692(2)\,\mu_N$ and $Q(65)=-0.024(2)$b. The value given for $\mu(65)$ includes an estimated correction of 0.09(8)% for the hfs anomaly. The ratio of the Zn^{65} and Zn^{67} quadrupole moments is $Q(65)/Q(67)=-0.1528(3)$; this result is independent of the shielding corrections. The Zn^{65} spin and magnetic moment are consistent with a $(2p_{3/2})^4(1f_{5/2})^3$ neutron assignment with some configuration mixing. The small quadrupole moment is compatible with the zero moment expected for a half-filled f shell. In the course of this work, the lifetime of the $(4s4p)\,^3P_1$ state of zinc was redetermined and found to be $\tau(^3P_1)=20(2)\,\mu$sec. This result includes a large correction for the effects of wall collisions. The theory of wall broadening of optical double-resonance lines is developed.

I. INTRODUCTION

THIS is the third paper in a series devoted to the nuclear spins and moments of the radioactive isotopes of the group II elements.[1,2] The $(ns^2)\,^1S_0$ atomic ground state of these elements is diamagnetic and exhibits no hfs. The paramagnetic, metastable $(nsnp)\,^3P_1$ state can be readily studied by optical double resonance and exhibits both magnetic dipole and electric quadrupole hfs. Previously we have reported on Cd^{109} (Ref. 1) and Cd^{107} (Ref. 2). Here we report on 245-day Zn^{65}.

The determination of the nuclear moments in a series of odd neutron Group II isotopes will complement the large body of information that already exists on odd proton nuclei.

The neutron assignments in Zn^{65} and Zn^{67} are $(2p_{3/2})^4(1f_{5/2})^3$ and $(2p_{3/2})^4(1f_{5/2})^5$, respectively. The proton as-

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[1] M. N. McDermott and R. Novick, Phys. Rev. **131**, 707 (1963).
[2] F. W. Byron, Jr., M. N. McDermott, and R. Novick, Phys. Rev. **132**, 1181 (1963).