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

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The hyperfine structure in the $^2S_{1/2}$ electronic ground state of K^{42} (12.4-h) has been studied using a high-precision atomic-beam apparatus. The hyperfine separation is shown to be $\Delta\nu = 1\,258\,876\,947(15)$ Hz. The nuclear magnetic dipole moment, measured independently of $\Delta\nu$, is $\mu_I = 1.142\,4(2)\ \mu_N$. The hyperfine magnetic anomaly is evaluated as ${}_{39}\Delta_{42} = +0.000\,3 + 0.003\,36(38)$.

I. INTRODUCTION

THE hyperfine structure of K^{42} (12.4-h) has been studied previously[1,2] with the determinations of the spin ($I=2$) and a value of the magnetic moment ($-1.141 \pm 0.033\ \mu_N$) which permitted only a crude value of the hyperfine anomaly. The purpose of this investigation was to determine the anomaly with greater precision. The basic technique used is that of atomic-beam magnetic resonance with the equipment previously used at this laboratory.[3,4]

The K^{42} was prepared by irradiation of natural potassium metal in the Brookhaven Graphite Research Reactor for 48 h in a neutron flux of about $10^{13}\ n/\text{cm}^2$ sec. During the experiment the resonance line of the field-dependent transition ($\Delta F=0$) for K^{39} was used to monitor the beam intensity and the C magnetic field strength.

The principal feature of the magnetic-moment determination lies in the fact that the measured difference in frequency between the transitions α, $(\frac{3}{2},\frac{3}{2}) \leftrightarrow (\frac{5}{2},\frac{1}{2})$, and β, $(\frac{3}{2},\frac{1}{2}) \leftrightarrow (\frac{5}{2},\frac{3}{2})$, is exactly equal to $2g_I\mu_B H/h$. Furthermore, these two transitions have frequency minima at nearly the same magnetic field (about 189 G), so that the resonance line is not appreciably broadened by field inhomogeneities. Also, a Ramsey-type separated oscillating field resonance can be observed. Furthermore, the g_J dependence of these transition frequencies is small enough to secure the precise measurement of g_I. This same pair of transitions can be used for a determination of $\Delta\nu$. The parameter $\Delta\nu$ can also be determined independently from the transitions δ and γ, $(\frac{3}{2}, \pm\frac{1}{2}) \leftrightarrow (\frac{5}{2}, \mp\frac{1}{2})$, in the vicinity of $\frac{1}{2}$ G. The consistency of these two sets of transitions at different values of the magnetic field serves as a check against possible systematic errors due to the apparatus.

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II. RESULTS

In order to evaluate the data for determination of the hyperfine magnetic interaction constant A $[=h\Delta\nu/(I+\frac{1}{2})]$ and g_I, one must note several factors: (1) The magnetic field is not uniform over the entire trajectory, (2) the separated rf loop method can indicate an average resonance frequency over the trajectory between the rf loops, and (3) the frequencies ν_α and ν_β are quadratic in the field increment $H-H_{\text{min}}$, where H_{min} is the value of H at which the frequency minimum occurs.

The field-calibrating frequency in K^{39} is closely approximated by a linear function in the region 188.77–188.80 G. The arithmetic average of ν_{39} can therefore be used to evaluate the average H, which in turn enters into the calculation of g_I. In performing the experiment a value of H is chosen so that the average H is midway between the minima of ν_α and ν_β.

To evaluate the constant A from the observed transitions ν_α and ν_β, one must evaluate $(H-H_{\text{min}})^2$ over the region between the rf loops. Figure 1(a) shows the behavior of ν_{39} along the trajectory. Figure 1(b) shows the behavior of ν_α.

In order to evaluate the constant A we define a parameter H_e as that value of a uniform field which will produce frequencies ν_α and ν_β equal to the average frequencies observed. We use an iterative procedure, starting with the average H and continuing until the increments are less than 1 mG. In this we utilize the computer program F2–6600 developed by the Atomic Beam Group[5] at the University of California to provide all the frequency tables, and Argonne National Laboratory's[6] computer program P126 to evaluate A and g_I by a least-squares fit to the data. In the example shown in Fig. 1, $H_e - H_{\text{Av}}$ is 6 mG.

Table I summarizes the observed data and calculation. Column 1 identifies the run, and column 2 identifies the designation of the transition involved. Column 3 indicates the observed frequency determined visually from a graphical plot of the data with linewidths about 1.2 kHz. Frequencies are referred to atomic time

[5] Kindly supplied by Professor H. A. Shugart.

[6] This program was kindly supplied by L. S. Goodman, Argonne National Laboratory.

TABLE I. Summary of results of observations and calculations.

1 Run No.	2 Transition	3 ν_{obs} (Hz)	4 H_{av} (G)	5 H_e (G)	6 $\nu_{obs}-\nu_{cal}$ (Hz)
High field		1 148 000 000 plus	188+	188+	
H1	α	298 195(50)	0.782(7)	0.789(7)	−6
H2	β	134 015(75)	0.781(7)	0.772(7)	−7
H3	α	289 185(50)	0.787(7)	0.793(7)	−18
H4	β	134 025(50)	0.787(7)	0.778(7)	6
H5	α	298 215(75)	0.786(7)	0.793(7)	12
H6	β	134 055(75)	0.787(7)	0.778(7)	36
H7	α	289 235(75)	0.786(7)	0.793(7)	32
H8	β	134 055(50)	0.787(7)	0.778(7)	36
H9	α	298 245(75)	0.786(7)	0.793(7)	42
H10	β	134 025(50)	0.786(7)	0.777(7)	6
H11	α	298 195(50)	0.786(7)	0.793(7)	−8
H12	β	134 025(50)	0.782(7)	0.775(7)	5
H13	α	298 205(50)	0.782(7)	0.789(7)	4
H14	β	134 025(50)	0.782(7)	0.775(7)	5
H15	α	298 195(75)	0.782(7)	0.789(7)	−6
H16	β	134 023(50)	0.782(7)	0.775(7)	3
H17	α	298 253(75)	0.782(7)	0.789(7)	52
H18	β	134 040(75)	0.783(7)	0.776(7)	20
H19	α	298 195(50)	0.782(7)	0.789(7)	−6
H20	β	133 995(50)	0.781(7)	0.774(7)	−26
H21	α	289 205(50)	0.782(7)	0.789(7)	4
H22	β	133 995(50)	0.781(7)	0.774(7)	−26
Low field		1 258 000 000 plus			
L1a	γ	877 665(75)	0.575(7)	0.576(7)	−25
L1b	δ	878 165 (75)	0.575(7)	0.576(7)	−26
L2a	γ	877 681(75)	0.585(7)	0.586(7)	−39
L2b	δ	878 189(75)	0.585(7)	0.586(7)	−41
L3a	γ	877 737(75)	0.592(7)	0.593(7)	−5
L3b	δ	878 253(75)	0.592(7)	0.593(7)	−5

Results: $A=-503\ 550\ 779(5)$ Hz, $g_I=3.106\ 72(45)\times10^{-4}$, with $\chi^2=3.4$ for 28 observations.
Assuming: $\mu_B/h=1.399\ 677$, $g_J(K)=2.002\ 295$, $m_p/m_e=1836.125$.

through the National Bureau of Standards transmission from station WWVL. The figures in parentheses indicate the estimated uncertainties. Columns 4 and 5 list the values of H_{Av} and H_e, respectively. Column 6 lists the difference between the observed frequency and that computed using the final values of A and g_I and the constants listed at the foot of the table.

From Table I, the final results are

$$A=-503\,550\,779(5)\text{ Hz}$$

and

$$g_I=3.106\,72(45)\times10^{-4}\qquad(\text{in }\mu_B),$$

with $\chi^2=3.4$ for 28 observations. However, if only the high-field measurements are used, we have

$$A=-503\,550\,780(5)\text{ Hz}$$

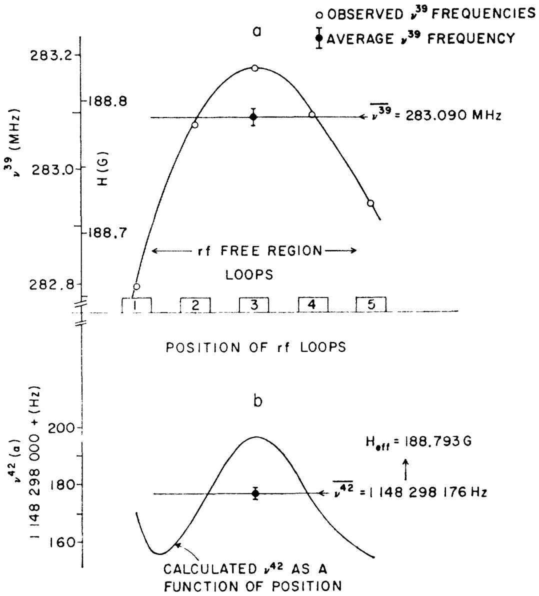

FIG. 1. Effects due to variation of magnetic field intensity along the beam trajectory in the c-field region. Sections 1–5 represent the locations of the various transition loops. The "Ramsey" interference pattern was produced by loops 1 and 5. (a) Solid curve shows the frequency of the calibrating transition in K^{39} ($\Delta F=0$) with the solid point as the average frequency. (b) Curve shows the calculated frequency for the field distribution as shown in (a).

and

$$g_I = 3.106\ 73(45)$$

with $\chi^2 = 2.5$ for 22 observations; and if only the low-field measurements are used, with a fixed value of $g_I = -3.106\ 72 \times 10^{-4}$, we have

$$A = -503\ 550\ 769(13)\ \text{Hz},$$

with $\chi^2 = 0.3$ for 6 observations.

By evaluating A from two different groups of data obtained at widely differing values of the magnetic field, we find agreement within the stated uncertainties. We may, therefore, have confidence that systematic errors due to rf phase shifts, irregularities in magnetic field, and similar effects are negligible.

Using the frequency difference of each α and β pair and the average value of H_{Av} from the same pair for all high-field measurements in Table I, we obtain

$$g_I = 3.106\ 74(43) \times 10^{-4}.$$

Within the uncertainty, this result agrees with that given previously.

In conclusion, we may state that the over-all results of these measurements yield values for K^{42} of

$$\Delta\nu = 1\ 258\ 876\ 947(15)\ \text{Hz}$$

and

$$\mu_I = -1.140\ 87(20)\ \mu_N$$

$$= -1.142\ 39(20)\ \mu_N \text{ (with diamagnetic correction[7])},$$

where the stated uncertainties are standard deviations.

Using $A(K^{39}) = 230\ 859\ 860(6)$ Hz [8] and $g_I(K^{39}) = -1.419-44(22) \times 10^{-4}$,[9] the hfs anomaly of K^{42} relative to K^{39} is given by

$$_{39}\Delta_{42} = 0.003\ 44(38).$$

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[8] The A value is a preliminary, unpublished measurement.

[9] Atomic-beam measurement by J. T. Eisinger, B. Bederson, and B. T. Feld, Phys. Rev. **86**, 73 (1962).