to be in coincidence with the gamma rays of these energies. The levels at 970 and 1140 keV are indicated by the coincidence data. A 970-keV and/or an 1140-keV transition from the 2110-keV level to the 1140-keV level or the 970-keV level, respectively, is indicated by the coincidence measurements. In Fig. 8 only, the first of these two possible modes of depopulating the 2110-keV level is shown. The 750-keV transition from the 1890-keV level to the 1140-keV level agrees with the coincidence measurements. The transition probabilities shown on the decay scheme have been calculated in Table I.

Kundu and McGinnis[9] have proposed a 10-min metastable level at 530 keV with spin and parity $\frac{1}{2}^-$ by analogy with In^{113} and In^{115}. A gamma ray of this energy could not be confirmed because of the high intensity of the nearby 511-keV peak.

ACKNOWLEDGMENTS

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[9] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C., 1960) NRC 60-2-85.

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Spin, Hyperfine Structure, and Nuclear Magnetic Dipole Moment of 7.7-Min K^{38}†

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The spin and hyperfine structure of 7.7-min K^{38} have been determined by the atomic-beam magnetic-resonance method. In this experiment about 100 mg of K^{39} was placed in an oven in the resonance apparatus and was bombarded with an 0.3 μA beam of 18-MeV protons. K^{38} was produced by the reaction K^{39} (p, d or pn)K^{38}, and the resulting specific activity was high enough so that an adequate atomic beam could be maintained for 2 to 3 h before the oven was empty. Both $\Delta F=0$ and $\Delta F=1$ resonances were observed, and final values are $I=3$, $\Delta\nu=1415.292\pm0.009$ Mc/sec. Comparison with other potassium isotopes yields $\mu_I=+1.3735\pm0.0010$ nm (diamagnetically corrected). The value for the magnetic dipole moment is in good agreement with the prediction based on the coupling of a $d_{3/2}$ neutron hole and a $d_{3/2}$ proton hole to the above spin value.

INTRODUCTION

THIS work represents a continuation of two long-standing programs in this laboratory, a study of the properties of odd-odd nuclei, and spin and moment measurements on short-lived radioactive isotopes.

The nucleus K^{38} is self-conjugate, i.e., $N=Z=19$, and should be a particularly attractive case for nuclear-structure studies since it is just one proton and one neutron short of doubly-magic Ca^{40}. One would expect the ground-state configuration to be predominantly $(d_{3/2})^{-1}$ for both proton and neutron, and in agreement with the predictions of Brennan and Bernstein[1] the lowest two states in this nucleus are 3^+ and 0^+, the sum and the difference of the nucleon spins. The ground state has a 7.7-min half-life, and our measurements show it to have $I=3$ as expected from earlier experiments.[2]

The experiment was carried out with the resonance apparatus used to measure the spin and hyperfine structure in 23-sec Na^{21}, and described in an earlier paper.[3]

The theory of hyperfine structure relevant to this experiment has been frequently described in the recent literature, so we shall not repeat it here. The reader is referred to books by Ramsey[4] or Kopfermann[5] for a detailed discussion.

EXPERIMENTAL DETAILS

The K^{38} was produced by the reaction $K^{39}(p, d$ or $pn)K^{38}$ using the 18-MeV proton beam from the Princeton cyclotron. The oven containing the K^{39} was placed in the resonance apparatus, and the proton beam was brought into the oven chamber and passed through

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[1] M. H. Brennan and A. M. Bernstein, Phys. Rev. 120, 927 (1960).
[2] See the Landolt-Börnstein Tables, *Energy Levels of Nuclei: A=5 to A=257*, edited by A. M. Hellwege and K. H. Hellwege (Springer-Verlag, Berlin, 1961).
[3] O. Ames, E. A. Phillips, and S. S. Glickstein, Phys. Rev. 137, B1157 (1965).
[4] N. F. Ramsey, *Molecular Beams* (Oxford University Press, London, 1956).
[5] H. Kopfermann, *Nuclear Moments* (Academic Press Inc., New York, 1958).

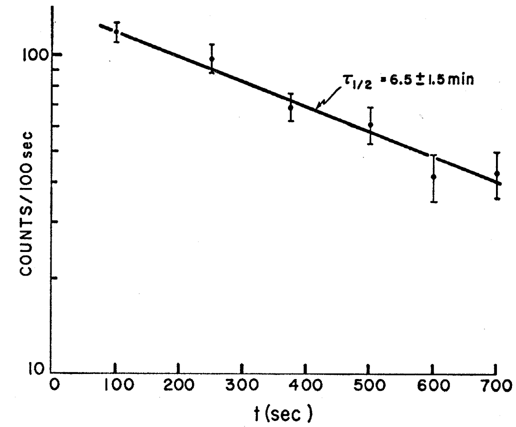

FIG. 1. Decay curve of the activity on the beam collector. Background has been subtracted.

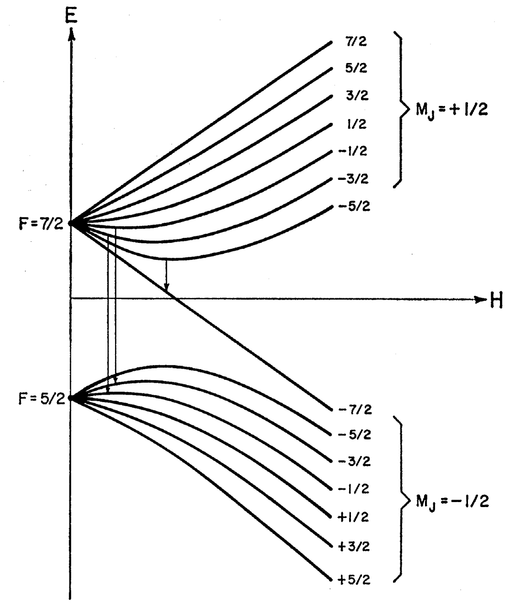

FIG. 2. The hyperfine-structure diagram for $J=\frac{1}{2}$, $I=3$, and $\mu_I>0$. The $\Delta F=0$ and $\Delta F=1$ transitions observed in the experiment are indicated by the arrows.

a foil in the side of the oven. The oven was identical in design to that used in the Na^{21} experiment[3] except that the target depth was reduced so that the protons only lost enough energy in the potassium to bring them down to the Q value for the reaction (11 MeV). In this manner we could maximize the resulting specific activity. About 100 mg of K^{39} was put into the oven, and it was heated so that it emptied in about 3 h. The radioactive beam held up well for the entire time and then dropped very quickly in the last few minutes to an unusable value. A proton beam current of about 0.3 μA, the maximum attainable external beam, was found to produce adequate activity.

The magnet system of the machine has been described in earlier papers.[3,6] We only note here that the apparatus uses a 6-pole A magnet and a 2-pole B magnet. An attempt was made to adjust the magnetic fields to give optimum transmission and optimum state separation at the B magnet exit.

Two collector surfaces were placed at the exit to the B magnet; the "beam" collector picked up most of the transmitted beam while the "flop" collector, located on the other side of the magnet gap, picked up those atoms that had undergone the appropriate transition in the radio-frequency field. We employed a method of holding the collectors different from that used in the Na^{21} work.[3] They were mounted on the end of a plunger which could be inserted into the apparatus via an air-lock. The surfaces were clean iron, and after an exposure they were removed from the machine and the activity was counted in a low-background area using thin plastic scintillators. The ratio of the number of atoms on the two surfaces, flop/beam, varied from 0.07 with the rf turned off to about 0.2 on the peak of a resonance. Typical exposure times varied from 5 to 10 min during which time the cyclotron beam was on. Between exposures the cyclotron was turned off, and during this time the stable K^{39} beam intensity could be checked with a hot-wire detector. This beam was also used to calibrate the field strength in the C magnet. The total time between exposures was typically 2 to 3 min. A 10-min count of the beam collector might show anywhere from 200 to 500 counts depending on the beam intensity.

[6] R. A. Haberstroh, W. J. Kossler, O. Ames, and D. R. Hamilton, Phys. Rev. **136**, B932 (1964).

RESULTS

In Fig. 1 we show a decay curve of the beam activity; the counter background has been subtracted from these points. The curve indicates a $\tau_{1/2}=6.5\pm1.5$ min. A more precise value was obtained by collecting the beam in the oven chamber a short distance in front of the oven hole. This yielded a $\tau_{1/2}=7.2\pm0.4$ min in closer agreement with the recent value of 7.7 ± 0.3 min.[7]

The first runs to determine the nuclear spin and to obtain $\Delta\nu$ involved observing the transition $(F,M_F)=(7/2,-5/2)\rightarrow(7/2,-7/2)$. This is indicated by the short arrow in Fig. 2. Runs with the C field set below 7 G showed that $I=3$ for the K^{38} nucleus. A series of runs between 7 and 59.5 G was then carried out to obtain the hyperfine-structure separation $\Delta\nu$. In all of these runs the amplitude of the transition-inducing rf field was set to the expected optimum value for the above single-quantum transition. Amplitude calibration was made with reference to the optimum amplitude for inducing single-quantum transitions in K^{39}. The results of these runs are summarized in Table I and also in Fig. 3. In Fig. 3 we have plotted the values of the magnetic-dipole interaction constant a $(=\Delta\nu/(I+1/2))$ determined by each resonance as a function of the frequency at which the resonance

[7] D. Green and J. R. Richardson, Phys. Rev. **101**, 776 (1956).

TABLE I. Summary of K^{38} $^2S_{1/2}$ data.

K^{39} Calibration frequency (Mc/sec)	Magnetic field (gauss)	K^{38} frequency (Mc/sec)	F_1	M_1	F_2	M_2	Residual (kc/sec)
5.098(4)	7.047	2.857(8)					+4
9.774(2)	13.136	5.365(10)					−10
10.746(5)	14.360	5.888(5)					0
18.030(3)	23.130	9.631(3)					+1
35.032(4)	41.274	17.740(15)	7/2	−5/2	7/2	−7/2	−1
54.820(4)	59.352	26.358(10)					+4
54.967(4)	59.477	26.414(6)					−1
54.886(4)	59.408	26.385(7)					+4
0.975(5)	1.383	1414.200(40)					+11
0.877(5)	1.245	1414.275(65)	7/2	−1/2	5/2	−3/2	−23
1.075(5)	1.524	1414.085(15)			or		+8
0.703(4)	0.999	1414.490(10)	7/2	−3/2	5/2	−1/2	−4

Comparing and calibrating isotope
K^{39}, $^2S_{1/2}$, $I=3/2$
$g_J=-2.002310$
$g_I=1.42111\times10^{-4}$
$\Delta\nu=461.7197$ Mc/sec
$a=230.8598$ Mc/sec

occurred, and have done this for both signs of the dipole moment. The data strongly suggest that $\mu_I>0$. The point on the far right of the figure is the value of a determined from the direct $\Delta F=1$ transitions, and completely confirms this choice of sign. The best fit to all the $\Delta F=0$ data yields

$$\Delta\nu=1414.63\pm2.14\text{ Mc/sec}.$$

Following these runs a search was started to observe a $\Delta F=1$ resonance. One was found made up of the transitions $(F,M_F)=(7/2,-1/2)\to(5/2,-3/2)$ and $(7/2,-3/2)\to(5/2,-1/2)$. These are split by only 1 kc/sec at a field of 1.4 G. The resonance was observed at 4 different values of the static C field, thus confirming its identity. A typical resonance is shown in Fig. 4. The results are summarized in Table I and in Fig. 5. In this figure we have plotted the observed positions of the $\Delta F=1$ resonance versus the frequencies of the stable K^{39} calibrating resonance. The position of the line is a best fit to the data. The slope is that calculated for the above-mentioned transitions; no other combination of transitions is consistent with the points. This best fit to all the $\Delta F=1$ data yields

$$\Delta\nu=1415.292\pm0.009\text{ Mc/sec}.$$

Since we have data for other isotopes of potassium, it is possible to compute the magnetic dipole moment of K^{38} from our value for $\Delta\nu$ using the formula of Fermi and Segrè[4]:

$$\frac{\mu_{I_1}}{\mu_{I_2}}=\frac{\Delta\nu_1 I_1(2I_2+1)}{\Delta\nu_2 I_2(2I_1+1)}. \quad (1)$$

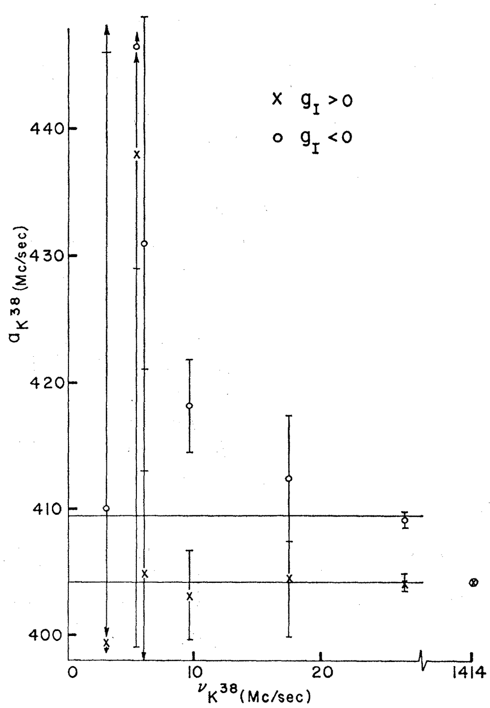

FIG. 3. A summary of the $\Delta F=0$ data. For each frequency the magnetic-dipole interaction constant a was calculated assuming each sign for g_I.

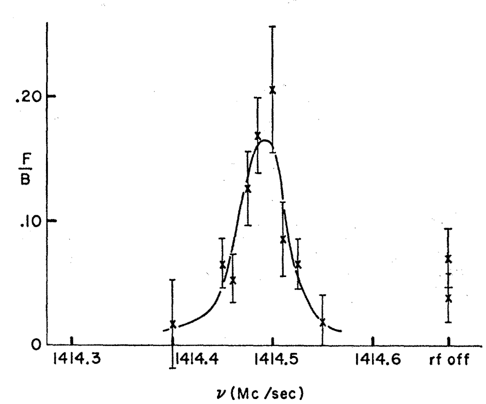

FIG. 4. A typical $\Delta F=1$ resonance.

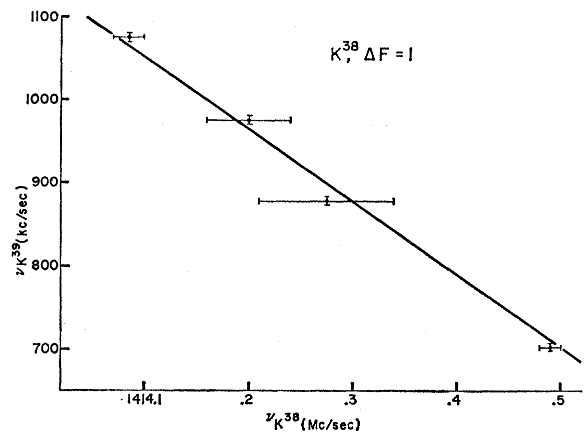

FIG. 5. The four observed $\Delta F=1$ resonances are plotted as a function of the frequency of the K^{39} calibrating resonance. The position of the line is a best fit to the points; its slope is theoretical.

The formula is valid for a point nucleus, and deviations from it arising from the fact that the nuclear magnetic moment is spatially distributed can be as large as a few tenths of a percent. This particular hyperfine-structure anomaly is known as the Bohr-Weisskopf effect,[8] and is of some importance in the potassium isotopes.[9] We have computed the quantity

$$\Delta=\frac{(a/g_I)_{K^{39}}-(a/g_I)_{K^{38}}}{a/g_I},$$

assuming a $(d_{3/2})^{-1}$ configuration for K^{39}, and assuming a $d_{3/2}$ proton hole and a $d_{3/2}$ neutron hole coupled to $I=3$ for the case of K^{38}. We obtain $\Delta\approx+0.17\%$. The calculation gives the order of magnitude of the effect to be expected but probably should not be trusted to better than 30%. Using $\Delta\nu(K^{39})=461.7197$ Mc/sec[10], $\mu_I(K^{39})=+0.39140$ nm[11] (diamagnetically corrected), Eq. (1) above, and our computed value of Δ for this pair of isotopes, we find

$$\mu_I(K^{38})=+1.3735\pm0.0010\text{ nm}.$$

The quoted error is due primarily to the 30% uncertainty in the hyperfine-structure anomaly correction.

DISCUSSION

In studying the low-lying levels of odd-odd nuclei it is often useful to assume that the wave function is a simple vector-coupled product of the wave functions of the neutron and proton groups. If the spins of the odd groups are assumed to be good quantum numbers, it is easy to show that the magnetic dipole moment is[12]

$$\mu_I=\tfrac{1}{2}I(g_p+g_n)+(g_p-g_n)\frac{j_p(j_p+1)-j_n(j_n+1)}{2(I+1)}, \quad (2)$$

where g_p and g_n are the g factors of the proton and neutron groups, and j_p and j_n are the corresponding spins. When neutron and proton groups have the same j, as in K^{38}, we have the simple result

$$\mu_I=\tfrac{1}{2}I(g_p+g_n). \quad (3)$$

Since for $I=3$ the odd group moments add, we may use the reasoning of the Sachs mirror theorem[13] to conclude that meson-exchange effects will not contribute to μ_I. Likewise the quenching of the isotopic-vector part of the anomalous nucleon moments will not change μ_I.[14] We can insert the Schmidt g factors in Eq. (3), and if we do so for the $d_{3/2}$ nucleons, we obtain $\mu=+1.272$ nm in satisfactory agreement with the experimental value.

One way of taking configuration mixing into account is to use the experimental g factors of neighboring odd-A nuclei instead of the Schmidt values.[1] In this case we can use ${}_{19}K^{39}$ for g_p but must go to ${}_{16}S^{35}$ to get g_n, as the moment measurement on Ar^{37} is not sufficiently accurate. The sum of the moments of these isotopes is $+1.39$ nm, in excellent agreement with our value for K^{38}. This close agreement may be fortuitous as S^{35} is rather far down in the *sd* shell to be used for an empirical value of g_n. In any case it would be interesting to have a better value for the moment of Ar^{37} or to have the moment of 1-sec Ca^{39}.

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