Nuclear Spins and Magnetic Moments of Rb^{85} and Rb^{87}

S. MILLMAN* AND M. FOX, *Columbia University*

(Received May 27, 1936)

The atomic beam method of "zero moments" has been applied to measure the nuclear spins and h.f.s. separations, $\Delta\nu$, of the $^2S_{\frac{1}{2}}$ states of Rb^{85} and Rb^{87}. We find the spin of Rb^{85} to be 5/2 and that of Rb^{87} 3/2, in agreement with the most probable values given by Kopfermann. With the value of $\Delta\nu$ for sodium as a standard we were able to measure the $\Delta\nu$'s of the Rb isotopes with a precision of 1 percent. We find these values to be 0.1018 cm^{-1} for Rb^{85} and 0.229 cm^{-1} for Rb^{87}, as compared with Kopfermann's values of 0.105 cm^{-1} and 0.240 cm^{-1} respectively. The magnetic moments calculated from the modified Goudsmit formula, are 1.44 nuclear magnetons for Rb^{85} and 2.92 for Rb^{87}. The ratio of magnetic moments, μ_{87}/μ_{85}, is found to be 2.026, with a precision of 0.2 percent. The $\Delta\nu$ for Cs was also measured with a precision of 1 percent. The result, 0.307 cm^{-1}, is in excellent agreement with the value 0.3067 cm^{-1} of Granath and Stranathan.

INTRODUCTION

THE nuclear spins and h.f.s. separations of the $^2S_{\frac{1}{2}}$ states of Li^7, Na, K^{39}, K^{41} and Cs have been measured in this laboratory by the method of atomic beams.[1, 2, 3, 4, 5] The h.f.s. separations of Li, Na and K were determined with a precision of 1 percent while that of Cs was good to only about 4 percent. These nuclear properties of Rb^{85} and Rb^{87} have never been measured by this method. Results obtained for the nuclear spins of the Rb isotopes by spectral methods have not been altogether decisive. From intensity measurements of the hyperfine structure patterns of the resonance lines Jackson[6] concluded that the most probable values for these spins are 3/2 for Rb^{85} and 5/2 for Rb^{87}, although other possibilities were not excluded. Kopfermann,[7] working on the spark spectrum of Rb, applied the interval rule and obtained results which indicated that the most probable values were 5/2 for Rb^{85} and 3/2 for Rb^{87}, but the values 6/2 and 7/2 for Rb^{85} could not be excluded. It seemed desirable to determine decisively the nuclear spins of the Rb isotopes by the method of atomic beams, and also to obtain the h.f.s. separations of the normal states of Rb^{85}, Rb^{87} and Cs with the same precision as that obtained for Li^7, Na, K^{39} and K^{41}.

METHOD

The method of determining the nuclear spins of the Rb isotopes and for measuring the h.f.s. separations for Rb and Cs was that of the "zero moments" as used for other alkali atoms and described in detail by Cohen[2] and Millman.[3] In the present investigation however, the magnetic field was not calculated from the geometry of the apparatus but was calibrated by means of the zero moment peak of sodium.[4]

APPARATUS

The apparatus used in the work on Li, Na, and K^{39} [3, 4] had to be modified to permit the use of very high currents in the field wires. The length of the field wires was increased to 115 cm and was divided into two sections. The section nearest the oven was made 33 cm long and the one nearest the detector 75 cm long. In the space of 7 cm between the sections the collimating slit was placed. In order to carry through the investigation on Rb it was necessary to send currents as high as 1500 amp. through the field wires, and our batteries were such that this could not be done with both sections of the wires in series. External connections to the field wires, which were easily interchangeable, permitted the use of either the short section of the field alone in the case of high currents, or of both sections to form one long field, in the case of lower currents. The maximum current that could be sent through the long field of 115 cm was about 900 amp. This was sufficient to provide the magnetic fields required for the two zero moment peaks of Rb^{85}. The peak of Rb^{87} required the high currents and it was in

* John Tyndall Fellow.

[1] Rabi and Cohen, Phys. Rev. **46**, 707 (1934).
[2] Cohen, Phys. Rev. **46**, 713 (1934).
[3] Millman, Phys. Rev. **47**, 739 (1935).
[4] Fox and Rabi, Phys. Rev. **48**, 746 (1935).
[5] Manley, Phys. Rev. **49**, 921 (1936).
[6] Jackson, Proc. Roy. Soc. **A139**, 673 (1933).
[7] Kopfermann, Zeits. f. Physik **83**, 417 (1933).

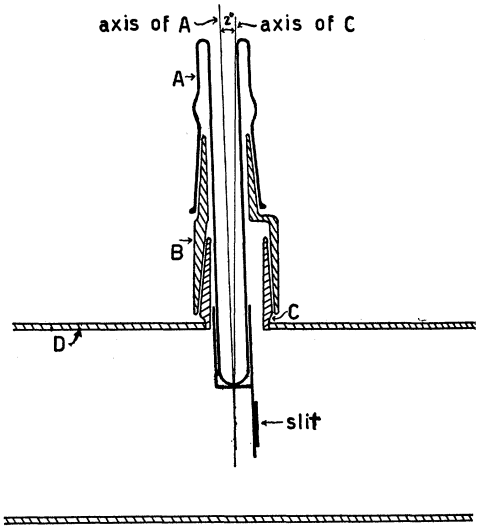

FIG. 1. Slit mount. *A*, standard No. 30 Pyrex female gd. joint; *B*, brass collar; *C*, standard No. 40 brass male gd. joint; *D*, portion of apparatus cylinder.

the location of this peak that the short section of the field was used. The decrease in resolution as a result of shortening the field length did not matter because of the high gradients which accompany the high fields.

The height of the beam was limited by stops to 2 mm, over which height the field was constant to about 0.5 percent. Four slits were placed along the path of the beam. The first was a wide fore slit of 0.1 mm separating the oven chamber from the receiving chamber. The second was 0.035 mm wide and was placed at the oven end of the short section of the field. The third, 0.030 mm wide, was the collimating slit. It was situated in the place between the two sections of the field. The fourth, 0.035 mm wide, was placed at the end of the longer section of the field. The second and fourth slit were included in the arrangement to eliminate scattered atoms from the detector. The collimating slit was mounted eccentrically on a ground joint which was in turn mounted on a second ground joint with axis inclined at an angle of 2 degrees to that of the first. A schematic diagram of this arrangement is shown in Fig. 1. If the brass collar *B* is kept fixed and the ground joint *A* turned, the distance of the slit from the plane of the wire axes is changed. If the collar is rotated and *A* held in place, the orientation of the slit with respect to the beam plane is varied. By the term beam plane is meant the plane defined by the oven slit and the center of the collimating slit. With the aid of the atomic beam the collimating slit can be brought into the beam plane more accurately than by optical means alone. The second and fourth slits, as well as the one mil tungsten detector were mounted in the same manner as the collimating slit. The fore slit was made movable in a direction normal to the beam plane by means of a screw coupled to the slit holder through the oven chamber. The pegs which supported the oven were fixed to a dovetail slide that could be moved in the same manner as the fore slit. These motions enabled us to set the beam plane parallel to the plane of the field wire axes and at any desired distance from it.

PROCEDURE

The Rb and Cs used in this work were distilled under vacuum from a mixture of freshly cut calcium shavings and the chlorides of these alkali metals. The metals were collected in small glass bulbs which were sealed off under vacuum and dropped directly into the oven. To prevent oxidation of the metal the bulb was broken in an atmosphere of nitrogen in the process of forcing the lid into the oven.

The beam was first detected with only the fore slit to define it. The collimating slit was brought in and its orientation with respect to the beam plane varied in small steps by means of the brass collar. For each collar position the maximum beam intensity obtained with various detector collar positions were recorded. The greatest maximum intensity thus obtained corresponded to the collar positions for which the collimating slit and detector were in the plane of the beam. With the collimating slit and detector fixed in the optimum positions the second slit and later the fourth slit were brought into the beam plane in a manner similar to that outlined for the collimating slit. The magnetic field was then turned on and a zero moment peak located, first using the whole field and then only the short section. If the two current readings for the same peak were not the same the beam plane was not parallel to the plane of the field wire axes. The slits and detector were then moved as required until the desired parallelism was achieved.

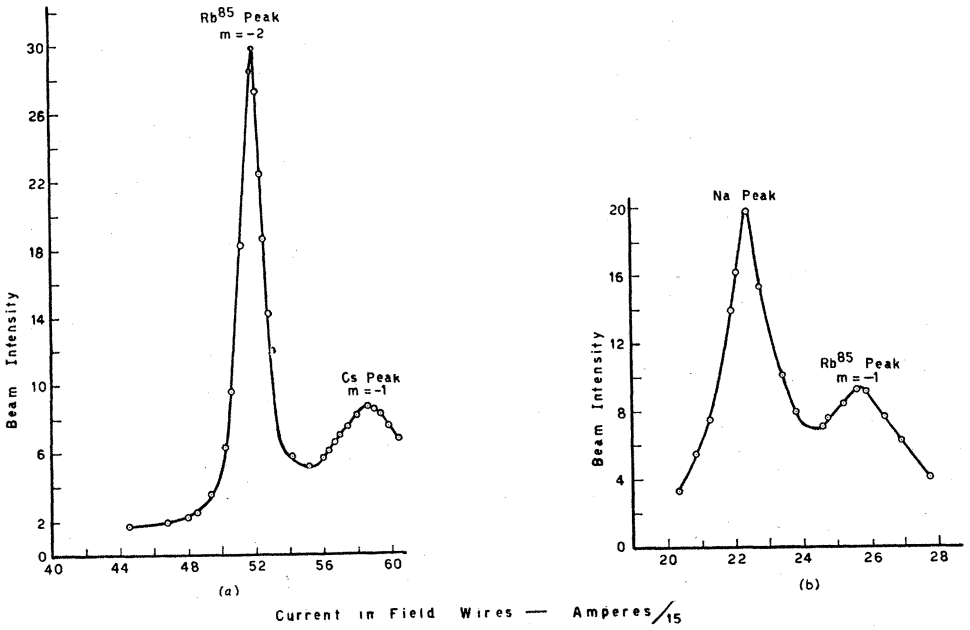

FIG. 2. (a) Variation of beam intensity with field in the region of $m=-2$ peak of Rb^{85} and $m=-1$ peak of Cs. (b) Variation of beam intensity with field in the region of $m=-1$ peak of Rb^{85} and the Na peak.

A Leeds & Northrup type K potentiometer was used to read the potential drop across a 50 mv, 1500 ampere shunt in the field wire circuit. It was not necessary to know the resistance of this shunt accurately since our measured values of the $\Delta\nu$'s depend only on ratios of currents. To obtain the ratio of currents for any two zero moment peaks, the current was first set for maximum intensity of one of the peaks and then for that of the other alternately for a series of readings taken over a period of about 30 minutes. It was found necessary to take into account the warping of the field block due to the rise in temperature of the field wires, which amounted in the most extreme case to about 16°C. Thermometers were placed in the water line so as to read the temperature of the water which came out of each wire. Since each wire had its own water inlet and outlet the flow in each could be regulated to adjust the temperature of each wire. In comparing the currents corresponding to two zero moment peaks the water flow through the wires was regulated so that the temperature of the exit water was the same for both current values. This eliminated errors due to temperature changes in the shape of the field wires.

Runs were taken with mixtures of Na and Rb in the oven in order to find the ratio of the $\Delta\nu$'s of Na and Rb^{85}. The zero moment peak of Na and the lower field peak of Rb^{85} occur at only slightly different values of the field, but separated sufficiently so that they are clearly resolved. When the oven temperature was about 200°C the beam was almost entirely Rb, and during each run the zero moment peaks of Rb^{85} were located many times over a period of a few hours. As the oven temperature was slowly raised the Rb beam increased in intensity at first and then decreased when very little of the metal was left in the oven. At about 350°C the sodium began to appear in the beam. Fig. 2b is a plot of the intensity pattern in the neighborhood of the Na and Rb peaks. At the time these data were taken the Rb was rapidly disappearing from the beam. After the Rb was completely boiled off the Na peak was located many times. It was found that the current readings did not vary over a period of several hours by more than 0.3 percent. Mixtures of Cs and Rb were also put into the oven to get the ratio of their $\Delta\nu$'s. The higher field peak of Rb^{85} and the lowest field peak of Cs occur at only slightly different values of the

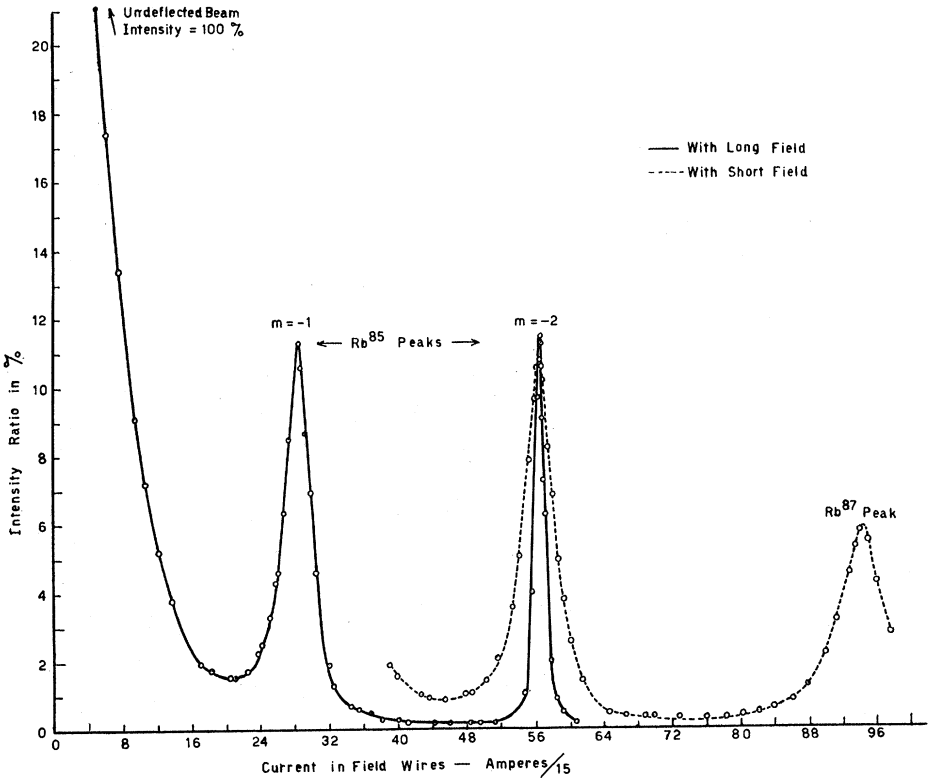

FIG. 3. Variation of beam intensity with field at the position of zero deflection. 1 amp. =0.85 gauss.

field and the same procedure was followed in locating these peaks as described above. Fig. 2a is a plot of the intensity pattern in the region of these peaks.

RESULTS AND DISCUSSION

Fig. 3 is a plot of the beam intensity at the position of zero deflection as a function of the current in the field wires. The solid line portion of the curve was obtained with the whole field. As previously stated sufficient current could be obtained with this arrangement to get the two peaks of Rb^{85}. For regions beyond 900 amperes the short section of the field was used. The broken line portion of the curve, obtained with this section of the field, shows the peak due to Rb^{87}. The region of the second peak of Rb^{85} was investigated with this arrangement for the purpose of comparing the $\Delta\nu$'s of the two isotopes and also to aid us in determining the spin of Rb^{87}. The first two peaks are of approximately equal intensity and are due to Rb^{85}. The current ratio for these peaks was accurately determined to be 2 : 1 to 0.2 percent. The fact that there are two peaks having the field ratio 2 : 1 immediately shows that the nuclear spin is 5/2 for Rb^{85}. The intensities of these peaks is in good agreement with theory. Since Rb^{85} is prevalent to about 72 percent the intensity of each peak should be 1/6 of 72 percent or 12 percent. The experimental intensities obtained from a great number of settings gave a value of 11.6 percent.

The value of $\Delta\nu$ for the ^2S state of Rb^{85} can be obtained at once from the knowledge of the current ratio of the first Rb peak and the Na peak. This ratio was found to be 1.139 ± 0.002. Since

$$x=2\mu_0 H/hc\Delta\nu \qquad (1)$$

for any alkali atom in the ground state, and the value of x at a zero moment peak is known when the spin is known, we have

$$\Delta\nu/\Delta\nu_0=(H/H_0)\times(x_0/x), \qquad (2)$$

where $\Delta\nu_0$, H_0 and x_0 refer to the atom used as a

standard and H/H_0 is the observed current ratio. Taking the value 0.0596 cm^{-1} for the $\Delta\nu$ of Na as given by Fox and Rabi,[4] and since x_0 is 1/2 for the Na peak and x is 1/3 for the first Rb peak, we obtain for the h.f.s. separation of $^2S_{\frac{1}{2}}$ state of Rb^{85} the value

$$\Delta\nu_{Rb^{85}} = 0.1018 \text{ cm}^{-1}.$$

The precision of this measurement is limited by the precision of the Na measurement, which is 1 percent.

The third peak in Fig. 3 is the only one due to Rb^{87}. Although it was not possible to investigate this curve at very much greater fields on this apparatus, it is known from some unpublished work of Paul Rosenberg in this laboratory that there are no other peaks in the region of higher fields. Rosenberg, working on the apparatus used by Cohen[2] in his Cs investigations, was able to investigate the region of fields higher than the Rb^{87} peak and found no trace of any additional peaks although it was possible to resolve them in case any were present. From this consideration it follows at once that the spin of the Rb^{87} nucleus is either 2/2 or 3/2. The following evidence shows that the value 3/2 is the correct one. Since Rb^{87} is prevalent to about 28 percent the intensity of the peak should be 7 percent if the spin is 3/2, while for 2/2 it should be 9.3 percent. The experimental value of this intensity is 6.4 percent in agreement with theory for a spin of 3/2.

Another method for determining the spin of one of two isotopes, when the spin of the other is known, and when each of the isotopes have at least one clearly resolved zero moment peak, was suggested by Rabi and first used by Manley[5] in determining the nuclear spin of K^{41}. For our case the method consists of replotting the curve in the region of the Rb^{87} peak of Fig. 3 by multiplying the abscissa of each experimental point in the curve by the value of the magnetic moment of the atom corresponding to this current, and comparing this with a similarly replotted curve of the second peak of Rb^{85}. Since the magnetic moment of the atom is a function of the nuclear spin we will get different curves for the Rb^{87} peak for different values of the spin. Now the force on an atom in an inhomogeneous magnetic field is proportional to the product of the magnetic moment of the atom and the field gradient (or current in the field wires). Hence if the intensity at the zero deflection position is due solely to atoms of one magnetic state the fraction of remaining intensity will depend on the product of magnetic moment

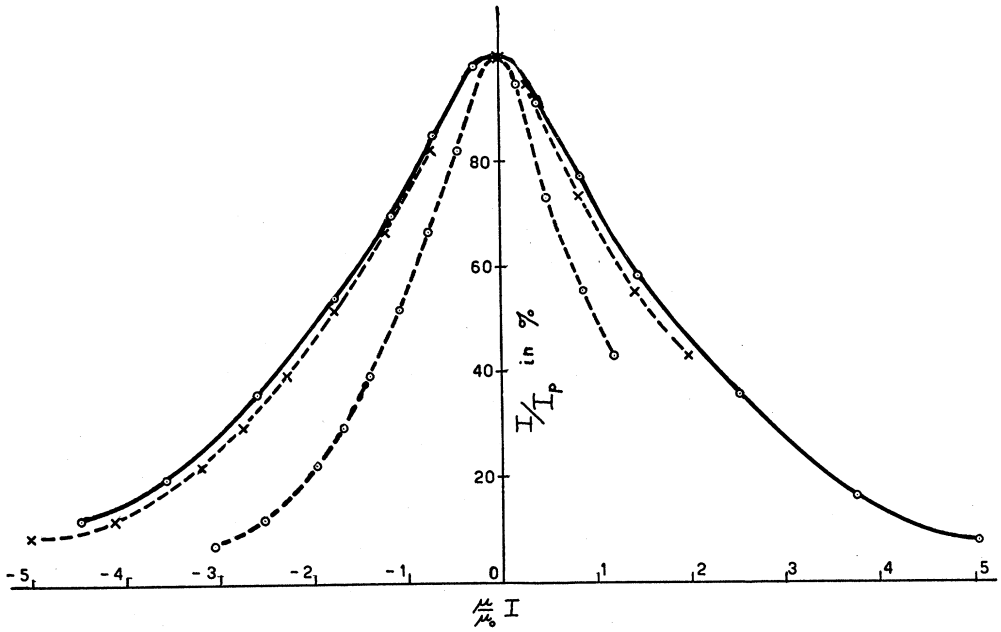

FIG. 4. Shape of zero moment peaks when plotted as a function of force on the atom. ——o——Rb^{85}, $m=-2$; ——×——Rb^{87}, $i=3/2$; - - -o- - -Rb^{87}, $i=2/2$.

and current, and on other quantities such as oven temperature, beam shape, etc. that are common to both isotopes. Thus, calling the peak intensity I_p and the intensity at points close to the peak I, if the ratio I/I_p is plotted as a function of the product of current and magnetic moment, the experimental curves in the region of the Rb^{87} peak and of the second peak of Rb^{85} should coincide for a correctly chosen value for the spin of Rb^{87}. This was done in Fig. 4. The curves fit well for an assumed spin of 3/2 for Rb^{87} and not for a spin of 2/2.

It may be mentioned that this method of analysis would limit the spin of the Rb^{87} nucleus to 3/2 even if one were not certain of the nonexistence of peaks beyond the Rb^{87} peak under discussion. If the spin of Rb^{87} were 4/2 or greater the peak would have to be the first zero moment peak. It can easily be shown that for an assumed spin of 5/2 the curve plotted as in Fig. 3 would coincide with the one plotted for an assumed spin of 2/2, and that for any other spin greater than 3/2 the curve would lie inside the curve given for 2/2 and would certainly not fit the Rb^{85} curve.

The value of $\Delta\nu$ for the $^2S_{\frac{1}{2}}$ state of Rb^{87} is obtained from equation (2) using Rb^{85} as the standard. The experimental ratio of the current at the Rb^{87} peak to that of the second peak of Rb^{85} is 1.688 ± 0.2 percent. The value of x_0 for the second peak of Rb^{85} is 2/3 and the value of x for the Rb^{87} peak is 1/2 for a spin of 3/2. This gives for Rb^{87}

$$\Delta\nu_{Rb^{87}}=0.229\ \text{cm}^{-1}.$$

Here again the precision is limited by that of our standard to 1 percent.

The results obtained for the nuclear spins of the two isotopes agree with the most probable values cited by Kopfermann,[7] but the values for the $\Delta\nu$'s of Rb^{85} and Rb^{87} are lower than his values of 0.105 and 0.240 cm^{-1}. It may be remarked in reference to the correctness of the value 3/2 for the nuclear spin of Rb^{87} that, if the spin were assumed to be 2/2, the $\Delta\nu$ would turn out to be 0.343 cm^{-1}. Such a disagreement is far beyond Kopfermann's experimental error.

The ratio of the $\Delta\nu$'s for the two isotopes as well as the ratio of the magnetic moments is established very accurately from these experiments. They are

$$\Delta\nu_{Rb^{87}}/\Delta\nu_{Rb^{85}}=2.251\pm0.2\ \text{percent},$$

$$\frac{\mu_{87}}{\mu_{85}}=\left(\frac{\Delta\nu_{87}}{\Delta\nu_{85}}\right)\left(\frac{[2I/(2I+1)]_{87}}{[2I/(2I+1)]_{85}}\right)$$
$$=2.026\pm0.2\ \text{percent}.$$

TABLE I. *Values of nuclear spins and magnetic moments.*

	Nuclear spin	$\Delta\nu$ of $^2S_{\frac{1}{2}}$	μ
Li^7	3/2	0.0267 cm^{-1}	3.20
Na	3/2	0.0596	2.08
K^{39}	3/2	0.0154	0.397
K^{41}	3/2	0.00853	0.220
Rb^{85}	5/2	0.1018	1.44
Rb^{87}	3/2	0.229	2.92
Cs	7/2	0.307	2.82

Cs

The h.f.s. separation of the $^2S_{\frac{1}{2}}$ state of Cs is obtained from Eq. (2) in the same way as for the Rb isotopes. The ratio of the current in the first Cs peak to that of the second Rb^{85} peak is found to be 1.131 ± 0.002. With the values 2/3 for x_0 of Rb^{85} and 1/4 for x of Cs, we obtain

$$\Delta\nu_{Cs}=0.307\ \text{cm}^{-1}$$

in excellent agreement with the value 0.3067 ± 0.0004 obtained by Granath and Stranathan,[8] who have made extremely precise measurements of this quantity by hyperfine structure methods.

Table I contains the nuclear spins and $\Delta\nu$'s of the $^2S_{\frac{1}{2}}$ states of Li^7, Na, K^{39}, K^{41}, Rb^{85}, Rb^{87} and Cs as measured by atomic beam methods as well as the magnetic moments calculated from the modified Goudsmit[9] formula.

The moments are not to be considered as having the same precision as that of the $\Delta\nu$'s, since it is not yet known how reliable the modified Goudsmit formula is. However the ratio of moments for two isotopes can be considered reliable to 0.2 percent under the present view of the cosine law of interaction between nuclear and electronic spins.

We are indebted to Professor I. I. Rabi for his continued interest in this work and for helpful discussions.

[8] Granath and Stranathan, Phys. Rev. **48**, 725 (1935).
[9] Goudsmit, Phys. Rev. **43**, 636 (1933): Fermi and Segrè, Zeits. f. Physik **82**, 729 (1933).