The Nuclear Spin and Magnetic Moment of Potassium (41)

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The spin of the K^{41} nucleus and the h.f.s. separation of the ${}^2S_{\frac{1}{2}}$ normal state have been measured by the method of zero moments. The high resolution necessary to separate the two isotopes was obtained by passing a beam of neutral potassium atoms through a weak inhomogeneous magnetic field 153 cm long. The total beam length was 201 cm. A new method of analysis of the zero moment peak of K^{41} in relation to that of K^{39} was used in the determination of the spin. The spin was found to be 3/2 and the h.f.s. separation to be 0.554±0.2 percent of that of K^{39}. The same ratio applies to the magnetic moments, hence this ratio and the values for K^{39} given by Fox and Rabi yield

$$\Delta\nu(K^{41})=0.00853\pm 0.0001\ \text{cm}^{-1}$$

$$\mu(K^{41})=0.22\ \text{nuclear Bohr magneton.}$$

From the peak intensities it is possible to give the abundance ratio K^{39}/K^{41} as 13.4±0.5.

INTRODUCTION

In view of the encouraging results of Millman,[1] and of Fox and Rabi[2] in detecting the presence of K^{41} atoms in a potassium beam and their ability to set limits for the spin and magnetic moment of that nucleus, it has seemed advisable to complete the determination of these values with a molecular beam apparatus of sufficiently high resolving power.

APPARATUS

A diagram of the apparatus used to secure this resolution is shown in Fig. 1. The vacuum chamber is a brass cylinder $7\frac{1}{2}$ feet long, 5 inches in diameter, on which the oil diffusion pumps are mounted. The pumping system maintains a pressure of less than 10^{-6} mm throughout the apparatus.

The inhomogeneous magnetic field is obtained with the parallel two-tube system described by Rabi, Kellogg and Zacharias,[3] with the exception that the field is divided into two equal lengths to facilitate cooling. The collimating slit is inserted in the one-centimeter space between these two divisions. The duralumin block in which the tubes are mounted is supported at each end. Two stops which limit the height of the beam to 1.6 mm are attached to the support at the detector end. The support at the oven end is a disk which divides the apparatus into two chambers. A fore channel, 0.4 mm wide, 1.6 mm high, and 2 mm long is mounted over a hole in this disk. The oven support is also attached to the disk which makes it possible to adjust the oven and fore channel relative to the field block before the three are inserted into the vacuum chamber as a unit. The beam emerges from a 0.013-mm slit in the oven and passes through the fore channel into the receiving chamber. There it is further defined by a collimating slit located at the center of the magnetic field. This position of the collimating slit yields practically maximum resolution in an apparatus of this type.

The beam is detected by a surface ionization gauge with a one-mil tungsten filament. The current to the collector plate is measured by an FP-54 vacuum tube electrometer and sensitive galvanometer. The overall sensitivity is about 5×10^{-15} ampere per millimeter at the five-meter scale distance used. Both the detector filament and collimating slit are mounted on double ground joints which permit their adjustment parallel to and at any distance from the field. Since the oven is also movable under vacuum, most of the lineup is accomplished with the beam itself. The only careful optical adjustments necessary are those of setting the oven and collimating slits parallel to the field.

The distance from the oven to the detector is 201 cm; from oven to collimating slit, 89 cm; from end of field to detector, 35 cm. The deflection at the detector of a potassium atom of the most probable velocity at 580°K is of the order of one millimeter per Bohr magneton for a 25-ampere current in the field.

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[1] S. Millman, Phys. Rev. **47**, 739 (1935).

[2] M. Fox and I. I. Rabi, Phys. Rev. **48**, 746 (1935).

[3] Rabi, Kellogg and Zacharias, Phys. Rev. **46**, 157 (1934).

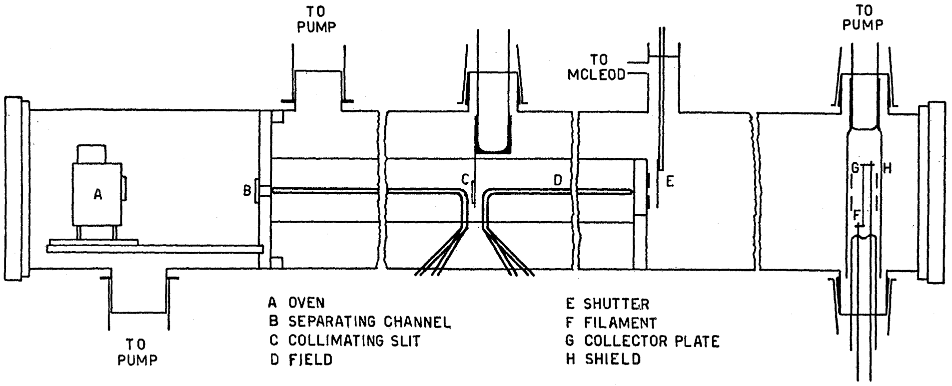

FIG. 1. Diagram of the apparatus.

PROCEDURE

Fresh potassium metal is placed in the oven, the apparatus closed and immediately evacuated. As soon as the pressure is sufficiently low, the oven is heated slowly until a beam of the desired intensity is obtained. The oven is maintained at this temperature thereafter. The collimating slit is then adjusted to the desired working position with the aid of the K^{39} zero moment peak. Since the spin and hyperfine structure separation, $\Delta\nu$, for this isotope are known, the average distance of the beam from the field can be calculated with these data, the geometry of the field, and the current value at the peak. The working distance is chosen so that the field and gradient of the field are approximately constant over the height of the beam. This adjustment does not guarantee that the beam is parallel to the field block, but if it is not, it must pass through regions of field which will not produce zero moment states. In such case the zero moment peak does not attain its maximum value. The oven and detector are therefore moved until this maximum is obtained.

With these preliminary adjustments complete, an entire curve of the collector current or beam intensity as a function of field current is obtained. Regions in which there is a theoretical possibility of other peaks are carefully explored, and peak intensities relative to total intensity and background are repeatedly checked.

The current value for each peak is taken as the value from which a small variation in either direction produces the same decrease in intensity. The currents were measured with a Leeds and Northrup type K potentiometer across a 150-ampere, 100-millivolt shunt.

RESULTS

Curve *A* of Fig. 2 illustrates the results obtained. The smaller peak at approximately 50 amperes has the correct intensity relative to the large peak at 90 amperes to be definitely K^{41}. Its location is also correct in regard to the previous work.[1, 2] The curves *B* and *C*, Fig. 2, cover more minutely the regions in which peaks associated with a nuclear spin greater than 3/2 would occur.[4] The absence of any peaks limits the spin of K^{41} to 2/2 or 3/2. The intensity of the 50-ampere peak also precludes a spin greater than 3/2. The distinction between the possible values, 2/2 and 3/2, can be made on two grounds, the peak intensity and the shape of the curve.

Since a spin of 2/2 signifies six components, two of which become zero to form the peak, the intensity ratio of the K^{41} peak to the full beam should be 1/3 of 6.7 percent or 2.2 percent (the abundance of K^{41} is given by Brewer and Kueck[5] as 6.7 percent). A spin of 3/2 would yield 1/4 of 6.7 or 1.67 percent. The average of several determinations of this ratio is 1.7 ± 0.05 percent.

Lack of complete homogeneity of the field and gradient over the cross section of the beam will

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[4] One exception must be made: A spin of 4/2 could produce a peak at 150 amperes, but this region has been explored by Millman with a resolution sufficient to have indicated any increase of intensity of the required order.

[5] Brewer and Kueck, Phys. Rev. **46**, 894 (1934).

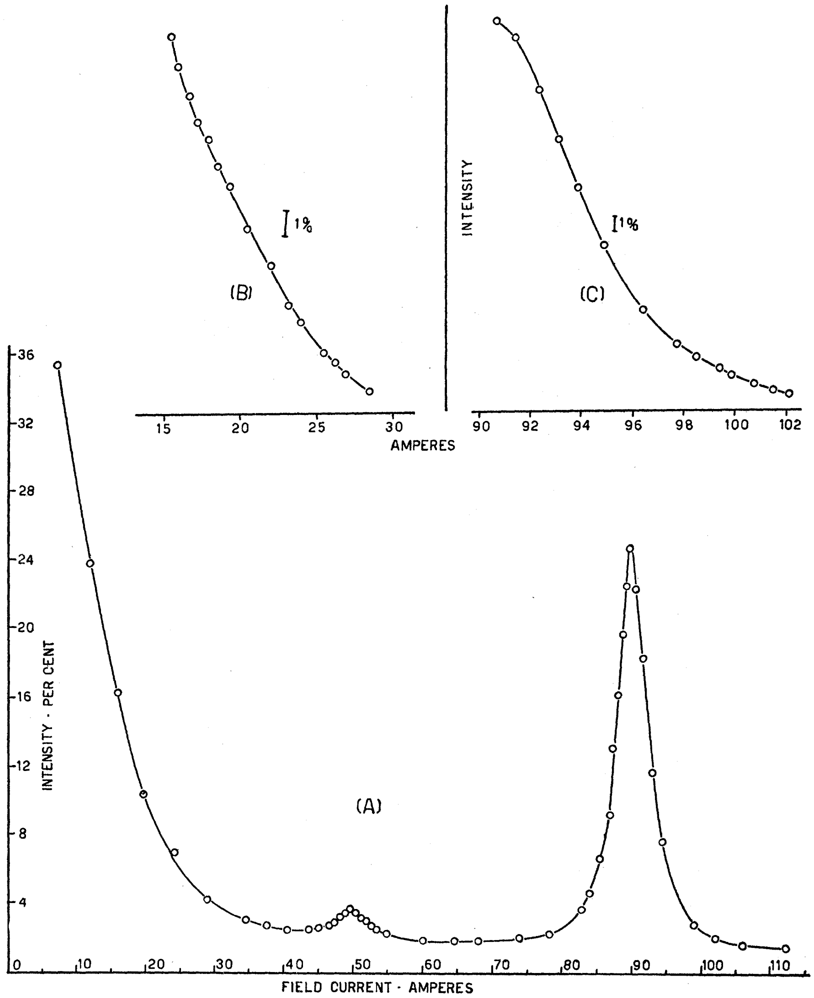

FIG. 2. *A*, variation of beam intensity with field current at the position of the undeflected beam. *B* and *C*, portions of *A* enlarged to show the absence of any peaks due to a spin greater than 3/2.

always cause the observed intensity to be less than the theoretical. It is therefore more accurate to compare the intensity of K^{41} to that of K^{39}. For a spin of 2/2 this ratio should be 0.0958; for 3/2, 0.0718. The observed value is 0.073 ±0.002. The chief error in these intensity considerations is due to a background of the same order of intensity as that of K^{41}.

Since the experimental results include the K^{39} zero moment peak, a comparison of the shapes of the two peaks may be made in a manner suggested by Professor Rabi: The energy distribution of the isotopes is the same, for they have the same source, and the collision cross section and mass differences can produce only a negligible effect. The geometry of the apparatus is also the same for each. Moreover, the resolution is sufficient in each case so that only the states which produce the zero moment peaks contribute to the intensity near the peak. It therefore follows that, for a given geometry and energy distribution, the intensity in the neighborhood of any peak is a function only of the deflecting force on the atom, that is, the product of the effective moment, μ/μ_0, and the field current, I, since the gradient is directly proportional to the current. The effective moment, μ/μ_0, depends on the nuclear spin. A plot

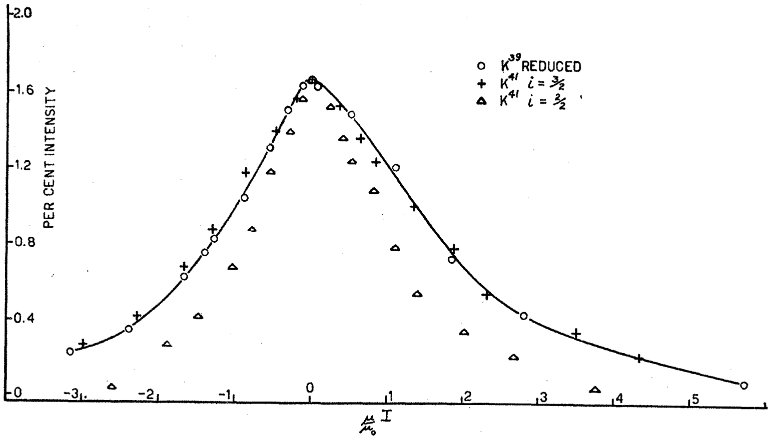

FIG. 3. The measured intensities of the K^{39} and K^{41} zero moment peaks as a function of the force on an atom in units of $(\mu/\mu_0)I$ about the peak values. μ/μ_0 is the effective moment and I the current in the field. The intensity scale for K^{39} has been reduced so that the maxima coincide.

of the intensity of the K^{39} peak against the force in units of $(\mu/\mu_0)I$ therefore yields a curve characteristic of the known spin 3/2. Fig. 3 shows this curve with ordinates reduced by 6.7/93.3. The K^{41} intensities plotted for spins of 2/2 and 3/2 are also indicated in Fig. 3. The K^{41} intensities are in good agreement for a spin 3/2 of this nucleus, but not for 2/2.

In view of the excellent agreement of intensity ratios it should be mentioned that with a few refinements toward elimination of background, increase of intensity, and higher resolution, the molecular beam method is capable of giving abundance ratios with considerable accuracy. The observed ratio of the peak intensities, K^{39}/K^{41}, corrected for background is 13.7±0.5. Correction for the rate of effusion from the oven reduces this ratio to 13.4±0.5. The agreement with the measurements of Brewer and Kueck[5] and of Nier[6] is within the limit of error.

The measurements of the current ratio of the K^{41} and K^{39} peaks give directly the ratio of the hyperfine structure separations for the normal $^2S_{\frac{1}{2}}$ states:

$$\Delta\nu(K^{41})/\Delta\nu(K^{39}) = 0.554 \pm 0.2 \text{ percent.}$$

From the value of Fox and Rabi[1] for $\Delta\nu(K^{39})$ of 0.0154 ± 0.0002 cm^{-1} is obtained:

$$\Delta\nu(K^{41}) = 0.00853 \pm 0.00012 \text{ cm}^{-1}.$$

Similarly, the magnetic moment becomes

$$\mu(K^{41}) = 0.397(0.554)$$
$$= 0.22 \text{ nuclear Bohr magneton.}$$

The writer wishes to thank Professor I. I. Rabi who suggested this problem and others of the molecular beam laboratory who so generously gave their assistance.

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[6] A. O. Nier, Phys. Rev. **48**, 283 (1935).