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The Nuclear Spin of Caesium

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The spin of the caesium nucleus has been measured by the deflection of a beam of atoms in a weak inhomogeneous magnetic field. The method utilizes the fact that the magnetic moment of the atoms in some of the magnetic levels vanishes at certain values of the magnetic field. An examination of the variation of the intensity at the center of the pattern yields distinct maxima at these fields. From the number and position of these maxima, the spin can be uniquely deduced. If the magnetic field is known, the hyperfine structure separation can be deduced with accuracy. The nuclear spin of Cs was found to be 7/2 in units of $h/2\pi$ and the hyperfine structure separation for the normal state was found to be 0.295 ± 0.01 cm^{-1}.

INTRODUCTION

ALTHOUGH the nuclear spin of caesium has been investigated by the hyperfine structure of spectral lines the results have not been decisive. Kopfermann[1] from an investigation of the intervals of the hyperfine structure of some spectral lines of Cs II concluded that the most probable value was 7/2, but was not able to exclude the values 8/2 or 9/2. Jackson[2] found the intensity ratio of the two components of the resonance lines to be 1.27 ± 0.02, consistent with a spin of either 7/2 or 8/2 for which the ratios would be 1.286 and 1.25, respectively. In view of the known difficulties in measurement and interpretation of intensity ratios the possibility of 9/2 is not entirely excluded by this experiment. In view of the importance of having an accurate knowledge of this fundamental nuclear property it was considered worth while to investigate this element with the method of molecular beams.

The method used for sodium[3] was difficult to apply caesium without a considerable change in the constants of the apparatus. For cases where the spin is large, the deflection pattern must be spread over a wide region in order that the $2i+1$ components be resolved. This was difficult with the apparatus at hand. However, the alternative method* to be described is particularly suitable for spins where $i>3/2$ and is almost as direct.

In the present experiment the nuclear spin of caesium is measured by its effect on the Stern-Gerlach pattern of the neutral Cs atom. The theory of this experiment is similar to that of the anomalous Zeeman effect for doublets as developed by Heisenberg and Jordan.[4, 5, 6] The force acting on an atom in a $^2S_{\frac{1}{2}}$ state, situated in an inhomogeneous magnetic field, of such strength that there is strong interaction both between the nuclear and electronic spins and between each spin and the field, is given by

$$F=\pm\frac{2m/(2i+1)+x}{2(1+[4m/(2i+1)]x+x^2)^{\frac{1}{2}}}g\mu_0\frac{\partial H}{\partial y}, \qquad (1)$$

where $$x=\frac{g}{\Delta W}\frac{eh}{4\pi m_0 c}H=\frac{g\mu_0}{\Delta W}H.$$

ΔW is the separation of the hyperfine structure levels in the absence of field, g is the Landé g factor for the electronic configuration, m is the total magnetic quantum number, and i is the nuclear spin quantum number. Eq. (1) shows that the magnetic moment of the entire atom depends upon the nuclear spin and is a multiple-valued function of the field H. The behavior of the function F for a value of 7/2 and 6/2 for i is shown in Fig. 1. Obviously F vanishes for states with negative m when

$$x=-2m/(2i+1), \qquad (2)$$

where $-m=i-1/2,\ i-3/2,\ \cdots\ 0$ for odd spins, and $i-1/2,\ i-3/2,\ \cdots\ 1/2$ for even spins. For these states the magnetic moment may become positive if the field be increased, and negative if the field be decreased or *vice versa*. The atoms in this state will suffer no deflection in the magnetic

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[1] Kopfermann, Zeits. f. Physik **73**, 437 (1932).

[2] Jackson, Proc. Roy. Soc. **A143**, 455 (1933).

[3] The preceding paper in this issue of the Physical Review.

* The writer is greatly indebted to Professor I. I. Rabi for the suggestion of this method.

[4] Breit and Rabi, Phys. Rev. **38**, 2082 (1931).

[5] Pauling and Goudsmit, *Structure of Line Spectra*, p. 219, McGraw-Hill, 1930.

[6] Heisenberg and Jordan, Zeits. f. Physik **37**, 263 (1926).

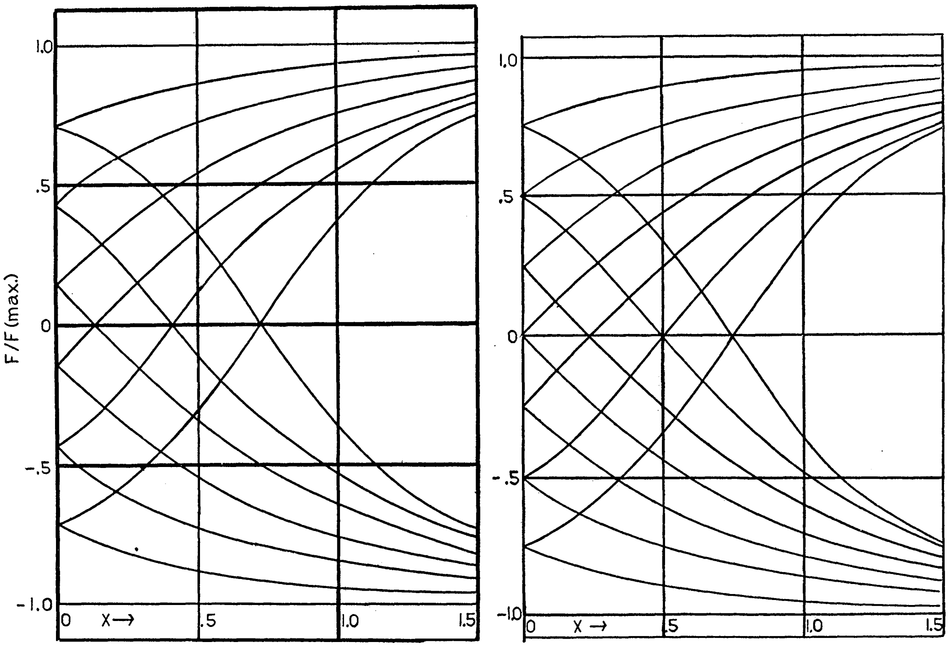

FIG. 1a. FIG. 1b.

FIG. 1. Theoretical curve showing magnetic moment of the atom in Bohr magnetons plotted against x for the different nuclear magnetic levels (a) for $i=6/2$, (b) for $i=7/2$.

field, and the Stern-Gerlach pattern taken at this field will consist of a superposition of the split beam and a beam the same shape as the original beam. (See Fig. 6.) The probability that an atom exist in a state of a given magnetic quantum number $m<i+\frac{1}{2}$ is inversely proportional to twice the statistical weight of that state and is given by $1/(2i+1)$.

The intensity of a beam at its center after passing through an inhomogeneous magnetic field will be the sum of a number of terms each given by the formula:[7]

$$I=2wI_0[e^{-y}(y+1)]_\infty^{s_\alpha/d}, \qquad (3)$$

where I_0 is the intensity of the undeflected beam, d is 1/2 the half-width of the beam, w is the probability of the magnetic state, and s_α takes on a different value for each magnetic moment present at the field, namely,

$$s_\alpha=(F/4kT)(l_1^2+2l_1l_2). \qquad (4)$$

s_α represents the deflection of an atom with the most probable velocity, in traversing a magnetic field of length l_1 and distance l_2 from the end of the field to the detector. It is clear from (3) that the contribution to the intensity due to atoms with nonvanishing moments will be small if s_α is large compared to d; and the intensity will be determined mainly by the atoms with zero moment. The gradient $\partial H/\partial y$ is fixed by the construction of the magnet, consequently d must be made small by using narrow slits and s_α large by using a long beam. If now the field be increased or decreased from one of the values given by (2) all the atoms will have nonvanishing magnetic moments and the value of I will decrease. Therefore the measurement of the variation of intensity in the center of the beam with magnetic field should be expected to show maxima at those fields corresponding to zero moment states. The values of x at which these states occur for different values of the nuclear spin are given in Table I.

The relative values of the fields at which the zero moment states occur taking the highest as unity are given in Table IA.

The interpretation of the results of experiments of this type is very simple if sufficient

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[7] Stern, Zeits. f. Physik **41**, 563 (1927).

TABLE I. *Values of x of zero moment states for various values of nuclear spin.*

i	1/2	2/2	3/2	4/2	5/2	6/2	7/2	8/2	9/2
x	0	.333	.5	.6	.667	.714	.75	.777	.8
			0	.2	.333	.429	.50	.555	.6
					0	.143	.25	.333	.4
							0	.111	.2
									0

TABLE IA.

i	1/2	2/2	3/2	4/2	5/2	6/2	7/2	8/2	9/2
$\frac{H}{H(\text{max})}$	0	1.0	1.0	1.000	1.000	1.00	1.000	1.000	1.000
			0	.333	.500	.60	.667	.714	.75
					0	.20	.333	.428	.50
							0	.143	.25
									0

resolution is attained. If the number of peaks other than at zero field, which always occurs, be N, then the spin is either $(2N+1)/2$ or $2N/2$. The interval in field between the different peaks is constant in each case. However, the interval between zero and the first peak for even spins is 1/2 of that between successive peaks. The spin is thus uniquely fixed by the number of peaks and their relative positions without recourse to the further evidence of the intensity distribution in the deflection pattern. With spins of 1/2, 2/2 and 3/2, such considerations cannot be avoided by this method. Even if all the maxima are not resolved, the ratios of the fields at the observed maxima may be sufficient to determine the spin, as may be seen from Table IA.

The value of the field at any one of the peaks is sufficient to determine the hyperfine structure separation between the two terms $f=i+1/2$ and $f=i-1/2$.

APPARATUS

The apparatus used in this experiment is essentially the same as that described in the previous paper[3] except for minor improvements. However, S_3 which was used originally as a selector slit is used here as a collimator, with width 0.019 mm; S_2 which was used originally as a collimator is considered now as a fore slit, with width 0.01 mm and the oven is used as a source with slit width 0.02 mm. This arrangement serves to eliminate the tails of the beam caused by scattering in the oven chamber, and because of the long distance from fore slit to collimator the half-width of the beam is kept down to 0.09 mm. The magnetic field for the deflection is furnished by the magnet previously used as the analyzer (magnet B only).

Apiezon oil pumps were substituted for the mercury pumps, so that, if the system be allowed to stand over night with caesium deposited on the walls of the oven chamber, mercury will not be absorbed. An ionization gauge is connected to the detecting chamber and registers a pressure of 5×10^{-7} mm Hg during the runs.

The height of the beam was shortened from 6 to 4 mm making the field more nearly uniform over its height.

The FP-54 vacuum tube amplifier used in connection with the surface ionization detector has been increased in current sensitivity to 0.8×10^{-14} amp./cm.

PROCEDURE

The caesium is prepared in vacuum by heating CsCl with freshly turned calcium metal shavings. The pure caesium is driven off at about 500°C. After an additional distillation it is driven into a small bulb and sealed off under high vacuum. This bulb is crushed inside the oven by the oven lid under an atmosphere of helium, after which it is placed in the oven chamber and the system evacuated.

The power input to the oven of five watts raises the temperature at the rate of 1.5 degrees per minute at first and gradually brings the oven to equilibrium at the running temperature of 170 to 190°C in about three hours. The full intensity of the original beam gives a galvanometer deflection of 1 to 6×10^3 cm.

When the beam, as collimated by the fore slit has become steady in intensity, the collimator is turned into place. The magnet current is then turned on to 500 m. a., reversed several times, and then brought up from zero in steps of from 5 to 20 m.a. and the intensity in the center of the beam is measured at each value of the current. At certain fields the distribution of intensity in the beam is measured by keeping the current constant and moving the detector wire across the beam. During the course of taking the points of any one curve the total beam intensity does not vary more than three percent.

MAGNETIC FIELD

A precise knowledge of the absolute value of the field is unnecessary for the determination of the nuclear spin. The only accurate measurement necessary is the proportional change in field with exciting current. For this purpose a flip coil of two turns, about 140×4 mm situated approximately in the plane of the beam is rotated through an angle of 180 degrees, giving a fluxmeter throw proportional to the field. The magnet is calibrated in this way over the entire range over which it is used. These measurements are not in error by more than one percent. The magnet calibration curve is shown in Fig. 2.

An average value of the field over the height of the beam is obtained by rotating the flip coil in a uniform field which in turn is measured with the aid of a second flip coil whose area is accurately known. The precision in the measurement of ΔW, for which the absolute value of the field enters, is limited chiefly by the difficulty in locating the beam with respect to the flip coil. This, however, does not affect the relative values of the field.

RESULTS AND DISCUSSION

A typical curve showing the variation of intensity in the center of the beam with magnetic field is shown in Fig. 3. The peaks at fields B and C are due to atoms having zero moments at these values of the field. The break at A shows up as a slight maximum in some of the runs with a narrower beam width. That there really is a zero moment state at this value of the field, is shown in Fig. 4, the deflection pattern taken at this value of the field. We have here a superposition of a curve having the same form as the direct beam and a curve representing the narrowly split deflection pattern due to the atoms in the other magnetic levels. Fig. 6 is the deflection pattern taken with the much larger value of the field and gradient at C. The high central peak results, again, from the presence of atoms having a zero moment and has the same form as the direct beam. Because of the better resolution with the higher gradient of the field, it now stands quite apart from the rest of the deflection pattern. Since all states have equal statistical weight, the ratio of the intensity at the peak to that of the direct beam should be as $1/(2i+1)$ i.e., 1/8 for a spin of 7/2. The experimental ratios are approximately 1/10. A considerable weakening is to be expected since the field is not constant over the height and width of the beam.

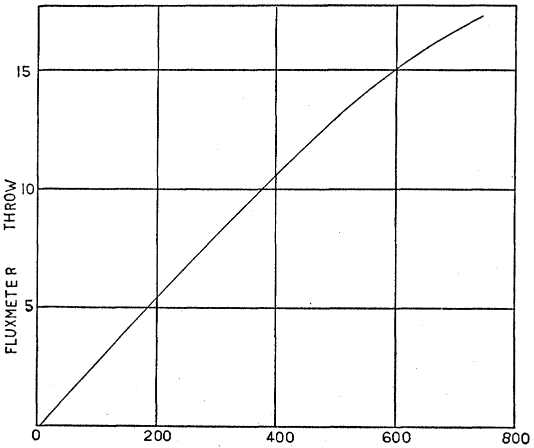

FIG. 2. Magnet calibration curve, fluxmeter throw of 1 cm corresponds to 196 gauss.

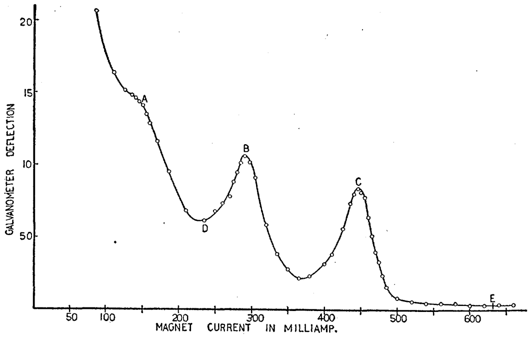

FIG. 3. Experimental curve showing the variation of intensity at the center of the beam with magnet current.

The fact that it is only at particular values of the field that we have components of zero moment is illustrated in Fig. 5, which is a deflection pattern taken at D, where the field and gradient are less than at C. Nevertheless the beam is split in this field with a minimum at the center, proving that all the atoms possess nonvanishing magnetic moments.

The magnet current at which the zero moment state exists is obtained by subtracting the ordinate of an estimated background curve of the intensity due to the atoms of finite moment,

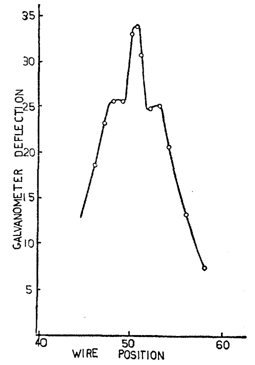

FIG. 4.

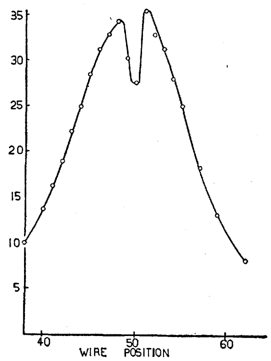

FIG. 5.

FIG. 4. Experimental curve showing the distribution of intensity in the beam at A.
FIG. 5. Distribution at D.

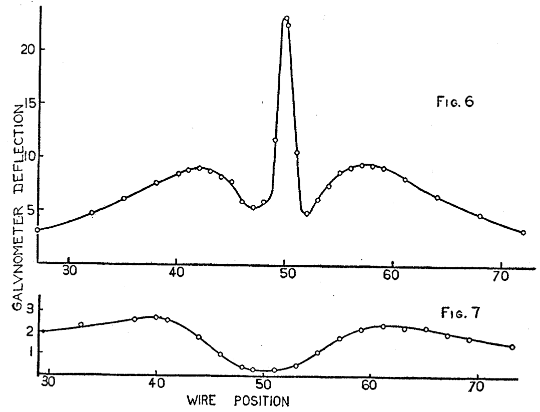

FIG. 6. Distribution at C.
FIG. 7. Distribution at E.

from the corresponding ordinate of the experimental curve. This shifts the maxima slightly to the right. The fields corresponding to these values of the magnet current are then obtained from the magnet calibration curve.

The relative values of the fields at A, B and C, taking the field at C as unity are given in Table II, for five runs.

TABLE II.

Run	I	II	III	IV	V
$H(A)$	.347	.342	.360	.351	not resolved
$H(B)$	.664	.664	.683	.667	.667
$H(C)$	1.000	1.000	1.000	1.000	1.000

The margin of error in locating A is about six percent. The ability to resolve this maximum depends largely upon the beam width. The location of B and C are accurate to one percent. The comparison of the results in Table II with those in IA show that a value of 7/2 for i is the only one consistent with the experimental results. If the spin were 9/2 a fourth maximum should be expected at E (Fig. 3). Fig. 7 shows the distribution of intensity found at this field. If there were present any atoms with moments equal to or close to zero, the pattern would be similar to Fig. 6.

The results show an approximate equality of the intervals in the field between the values at the peaks 0, A, B and C which rules out the possibility of any unresolved peaks on the low field side and shows the spin as odd. The fact that there are three peaks again fixes the spin as 7/2.

For the purpose of obtaining a value of ΔW the peak at C is most suitable. The position of this peak in the two best runs was at 470 m.a. and at 447 m.a. This difference is due to the fact that the beam traversed a slightly different region of the magnetic field during each run. Since $x=(g/\Delta W)ehH/4\pi m_0c)=0.75$ at this field, $\Delta\nu=\Delta W/hc=0.295\pm0.01$ cm^{-1}.

In conclusion the author wishes to thank Professor I. I. Rabi for the many helpful suggestions throughout the progress of this work, and his colleagues in the molecular beam laboratory for their generous assistance in the taking of data.