The Signs of the Nuclear Magnetic Moments of Li^7, Rb^{85}, Rb^{87} and Cs^{133}*

S. MILLMAN** AND J. R. ZACHARIAS
Columbia University, New York, N. Y.
(Received April 22, 1937)

The atomic beam method of nonadiabatic transitions has been applied to the determination of the signs of the nuclear magnetic moments of Li^7, Rb^{85}, Rb^{87} and Cs^{133}. The experiments show that all of these signs are positive and therefore agree with results already known from h.f.s. determinations.

THE atomic beam method of nonadiabatic transitions as developed in this laboratory[1-3] has already been used to determine the signs of the nuclear magnetic moments of the proton, the deuteron, Na^{23} and K^{39}. We wish to report the further application of this method to determine the signs for Li^7, Rb^{85}, Rb^{87} and Cs^{133}.

METHOD

The angular momentum of an atom in a $^2S_{1/2}$ state with nuclear spin I can be characterized in a weak magnetic field by a total quantum number F with values $I+1/2$ and $I-1/2$, and a magnetic quantum number, m, which is the projection of F along the magnetic field direction. If the nuclear magnetic moment is positive, atoms in any of the $2I$ states having an F value of $I-1/2$ have, in strong magnetic field, a positive atomic moment; whereas of all the atoms with $F=I+1/2$, the fraction $(2I+1)/(2I+2)$ have negative atomic moment in strong field and $1/(2I+2)$ have positive moment. On the other hand if the nuclear moment is negative the situation is reversed and the atoms with $F=I-1/2$ have negative atomic moment in strong field. This provides the criterion for determining the sign of the nuclear moment.

The magnetic moment of an atom of any m value except $\pm(I+1/2)$ is a function of the magnetic field, and if $I>1/2$ there are always some states that have zero atomic moment for a definite value of the field. An atom in such a state is not deflected by the inhomogeneous field and a "zero moment peak" is produced in a curve which exhibits the variation of beam intensity with field at the position of zero deflection. With an apparatus of sufficient resolving power the intensity of this peak is made up of atoms of only two states, having the same m but different F. To separate one of these states from the other the field is set at a value sufficiently removed from the peak value to produce a split Stern-Gerlach pattern. A selector slit is then inserted to let atoms of one of these states through, and to obstruct the passage of the others. The selected atoms in passing through a nonadiabatic field can make transitions to states of different m value, but must retain their F quantum number. Therefore if an $I-1/2$ state is selected, transitions can take place only to states that have the same sign of atomic moment in strong field; whereas if an $I+1/2$ state is selected, transitions can take place to $2I$ states of the same sign and to one of the opposite sign. A subsequent strong field analysis enables one to tell whether the selected state has $F=I-1/2$ or $I+1/2$ and therefore to decide the sign of the nuclear moment.

APPARATUS

A schematic diagram of the apparatus is shown in Fig. 1 in which only the longitudinal dimensions are drawn to scale. The first field (75 cm long) is of the usual[4] two-wire type with the collimator slit in the center. The water flow in the wires (copper tubing 4.76 mm o.d.) is sufficient to allow a current of 1400 amperes without undue temperature rise. The transition field was taken from the apparatus used by Kellogg, Rabi and Zacharias[2] in their work on the proton and the deuteron. The second field is of the design used by Torrey.[3] It is placed in the apparatus so that the gradient of its field is in

* Reported at Atlantic City meeting of the American Physical Society, December, 1936.
** Barnard Fellow, Columbia University, 1936–37.
[1] Rabi, Phys. Rev. **49**, 324 (1936).
[2] Kellogg, Rabi and Zacharias, Phys. Rev. **50**, 472 (1936).
[3] Torrey, Phys. Rev. **51**, 501 (1937).
[4] Rabi, Kellogg and Zacharias, Phys. Rev. **46**, 157 (1934).

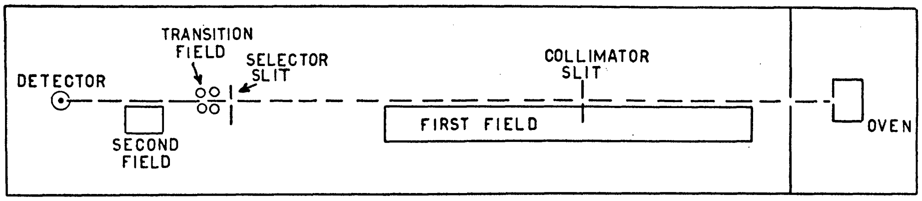

FIG. 1. Schematic diagram of apparatus.

the same direction as that of the first field. Thus atoms that have moment of the same sign in the two fields are deflected in the same direction. Refocusing of the beam is therefore obtained only if the moments of the atoms have different signs in the two fields. The selector slit is mounted on a ground joint and can be moved easily across the beam path. The total beam length is 155 cm.

PROCEDURE

The beam is detected and the current in the first field is varied until a "zero moment peak" is located. As has already been stated the intensity at the position of zero deflection is then made up of contributions from the two "zero moment" states only. We shall designate by the letter A the state that has a positive atomic moment for fields $H<H_0$ and a negative moment for $H>H_0$. The state that has a negative moment for $H<H_0$ we shall call B. It is necessary to separate the two states and to assign the correct F values to them. The current in the first field is now set at a value either higher or lower (8 percent to 25 percent) than H_0. A Stern-Gerlach pattern then shows two peaks about 0.2 mm apart. The tungsten filament detector is set on the positive moment peak (low number readings in our telemicroscope) and the selector slit is then inserted. With no current in the analyzing magnet the presence of the transition field is not noticeable. The current in the second field is now turned on and the detector is moved to analyze the resulting pattern. The gross features of the pattern depend on the F value of the state selected: If $F=I-1/2$ the pattern has only one peak and does not in any way depend on the magnitude of the transition field, since the strong analyzing field cannot differentiate between states of like sign even though the m values are different. On the other hand if $F=I+1/2$, the pattern has two peaks, the relative sizes of which depend on the magnitude of the transition field since transitions to both positive and negative states are possible and the transition probabilities depend on the field. This procedure is then repeated with the detector set on the negative moment peak of the Stern-Gerlach pattern.

RESULTS

Li^7

Li^7 has a nuclear spin of 3/2 and its zero moment peak occurs at 143 gauss.[5] Curve B of Fig. 2 shows the pattern obtained with the selector slit set to pass atoms with positive moment. As the magnitude of the first field is 176 gauss the curve represents a B state. Despite the presence of both the transition field and the analyzing field the pattern has only one peak. Furthermore, this situation is not altered by variations of the transition field, nor does the intensity of the peak vary. The F value of the B state is therefore $I-1/2$ and Li^7 has positive nuclear moment. This finding is corroborated by the data of curve A of Fig. 2 which shows the A state with two peaks.

The analyzed beam of curve B is found farther from the center than the selected beam because the second field produces deflection in the same direction as the first. Similarly, curve A shows one peak partially refocused and the other deflected away from the center position.

Rb^{85}

The nuclear spin of Rb^{85} is 5/2 and its two zero moment peaks[6] occur at 364 gauss and 728 gauss, respectively. The first field is set at 446 gauss and the selected beam on the positive moment side is a B state. Curve B of Fig. 3 shows

[5] Fox and Rabi, Phys. Rev. **48**, 746 (1935).
[6] Millman and Fox, Phys. Rev. **50**, 220 (1936).

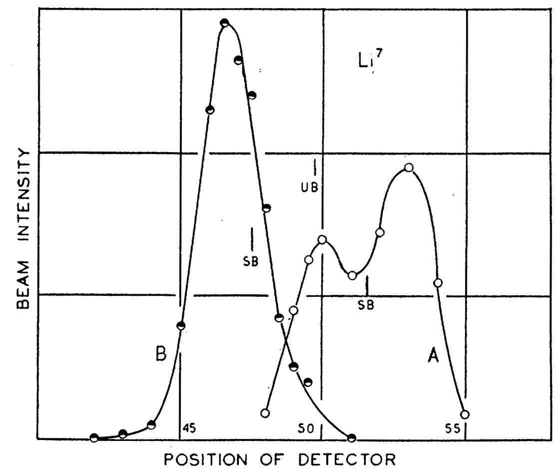

FIG. 2

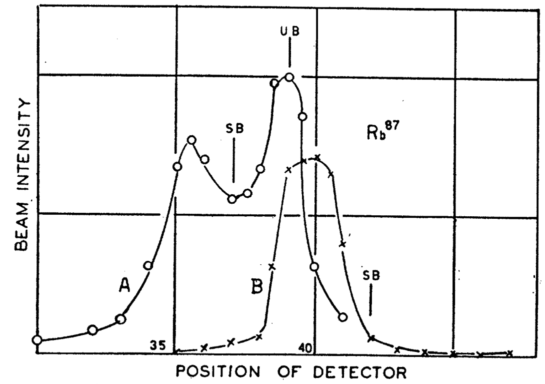

FIG. 4

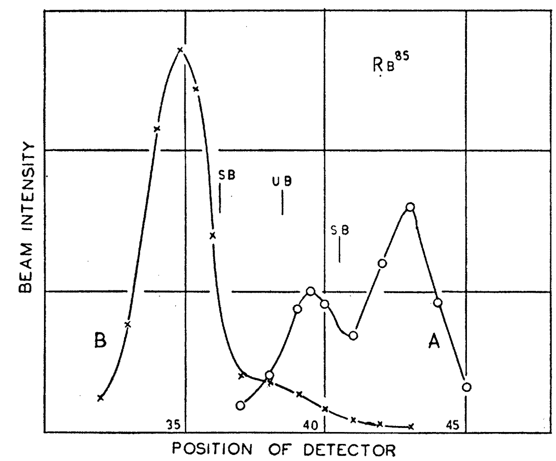

FIG. 3

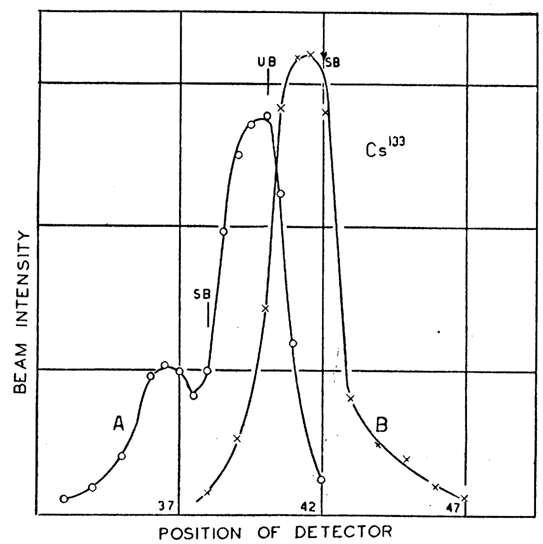

FIG. 5

FIGS. 2, 3, 4 AND 5. Second field analysis of selected beams. *UB* marks center of original undeflected beam. *SB* marks center of selected beam before second field is turned on. Position of detector read on telemicroscope; calibration—22 div. = 1 mm.

only one component for this B state indicating an F value of $I-1/2$ and a positive nuclear moment. The small unresolved peak at position 39 of the detector is due to contamination by some atoms of the A state of the second zero moment peak. Curve A of Fig. 3 shows the pattern for the A state of the first zero moment peak. The presence of two components indicates that the F value is $I+1/2$ and verifies the previous conclusion that the nuclear moment of Rb^{85} is positive.

Rb^{87}

Rb^{87} has a spin of $3/2$ and its zero moment peak[6] occurs at 1230 gauss. Curve A of Fig. 4 shows the pattern obtained when positive moment atoms are selected. Due to the high current required for the zero moment peak it is more convenient to set the first field at a value less than H_0. The selected state is therefore an A state. The presence of two components indicates that its F value is $I+1/2$ and that the nuclear moment is positive. This is verified by the data of curve B of Fig. 4 for the selected B state.

Cs^{133}

Cs with nuclear spin of $7/2$ has three zero moment peaks[7] at 825 gauss,[6] 1650 gauss and 2475 gauss, respectively. The first field is set at 655 gauss for the purpose of selecting the zero

[7] Cohen, Phys. Rev. **46**, 713 (1934).

moment states of the first peak. Curve A of Fig. 5 represents an A state and proves that the nuclear moment is positive. This is verified by the data of curve B of Fig. 5 for the selected B state.

The foregoing results are in agreement with the findings of the workers using the method of hyperfine structure.[8–10]

[8] Granath, Phys. Rev. **42**, 44 (1932).
[9] Kopfermann, Zeits. f. Physik **83**, 417 (1933).
[10] Granath and Stranathan, Phys. Rev. **48**, 726 (1935).

JUNE 15, 1937 PHYSICAL REVIEW VOLUME 51

The Radioactive Isotope of Rubidium

A. HEMMENDINGER AND W. R. SMYTHE
California Institute of Technology, Pasadena, California
(Received April 19, 1937)

By means of a high intensity mass spectrometer we have separated the isotopes of rubidium. Measurements of the radioactivity of the isotopic samples indicate that Rb^{87} is radioactive and that there is no other isotope with an appreciable activity compared to Rb^{87}.

INTRODUCTION

THE history of the radioactivity problem of rubidium is substantially the same as that of potassium, except that there is no record of an attempt to separate the isotopes of rubidium. The early work on the radioactivity of rubidium is recorded by St. Meyer and Schweidler,[1] and more recent data are collected in a paper by Klemperer.[2] There is some evidence that the beta-particles may lie in two bands. The known isotopes are at mass numbers 85 and 87. The best measurement of the abundance ratio is that of Brewer,[3] which gives $Rb^{85}/Rb^{87}=2.59$. Measurements of Nier[4] place an upper limit of the ratio Rb^{85}/Rb^{86} at 1/13,000 and of Rb^{85}/Rb^{88} at 1/22,000.

Klemperer[2] sets forth theoretical arguments for supposing the activity of rubidium to be due to a rare isotope at 86. v. Hevesy[5] also predicts a radioactive isotope at this point. Sitte[6] argues in favor of 87, as does Nier.[4] Quite recently Hahn, Strassmann and Walling,[7] and Mattauch,[8] have shown that the active isotope is Rb^{87}. Hahn and his collaborators separated the strontium from an old mineral rich in rubidium salts and found the strontium to be 99.7 percent pure Sr^{87}. Mattauch checked their measurements of atomic weight with mass spectroscopic data. This evidence is quite conclusive, but since our own measurements were very nearly completed when papers (7) and (8) appeared, we feel justified in presenting them here.

Using the same technique as in the determination of the radioactivity of potassium,[9] we have separated the isotopes of rubidium and measured their activities.

APPARATUS

The Rb^+ emitter was prepared in the same way as the K^+ emitter. For a single charge we used 150 g $Fe(NO_3)_3 \cdot 9H_2O$, 1.5 g RbCl and 1 g Al_2O_3. The fractional difference in atomic weight between the rubidium isotopes is less than half that between the potassium isotopes. To obtain equally accurate results with the former it is necessary therefore to improve the resolving power. Since the entire width of the peaks is due to lack of parallelism of the beam from the source due to the thermal velocity of the ions at right angles to the direction of acceleration, this can be accomplished in two ways, both of which were used. First, the magnet winding was increased from 890 to 2090 turns so that a current of 5 amperes saturated the magnetic circuit with a field of 4200

[1] St. Meyer and E. Schweidler, *Radioactivität* (B. G. Teubner, Berlin, 1927).
[2] O. Klemperer, Proc. Roy. Soc. **A148**, 638 (1935).
[3] A. K. Brewer, Phys. Rev. **49**, 867 (1936).
[4] A. O. Nier, Phys. Rev. **50**, 1041 (1936).
[5] G. v. Hevesy, Naturwiss. **23**, 583 (1935).
[6] K. Sitte, Zeits. f. Physik **96**, 593 (1935).
[7] O. Hahn, F. Strassmann and E. Walling, Naturwiss. **25**, 189 (1937).
[8] J. Mattauch, Naturwiss. **25**, 189 (1937).
[9] W. R. Smythe and A. Hemmendinger, Phys. Rev. **51**, 178 (1937).