The Gyromagnetic Properties of the Hydrogens

J. M. B. KELLOGG, I. I. RABI* AND J. R. ZACHARIAS, *Columbia University*

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The magnitudes of the nuclear moments of the proton and the deuteron are remeasured by the method of atomic beams. The new experimental arrangement is such that the evaluation of the results does not require any information with regard to the velocity distribution of the atoms in the beam. Detection is made objective by the use of a Stern-Pirani detector. The signs of the magnetic moments of the proton and deuteron are determined by the method of nonadiabatic transitions in a weak magnetic field. The results of the experiment are: $\mu_p = 2.85 \pm 0.15$; $\mu_0 = 0.85 \pm 0.03$ nuclear magnetons. Both moments are positive in sign.

THE discovery by Stern[1] and his collaborators that the magnetic moment of the proton is very much larger than the value predicted by the Dirac theory suggests a number of important problems. These include the development of methods for a more precise determination of the magnitude of the moment and the question of the sign. Because of its much smaller moment the same questions arise in more aggravated form for the deuteron.

The question of the sign of the nuclear moments is particularly interesting since the proton is so anomalous that considerations from the Dirac theory do not suffice for its prediction, while the deuteron is the only nucleus of its type (even atomic weight, odd nuclear charge) for which the moment has been measured,[2] and there is therefore no example from which to draw an analogy. This question arises only when the moment is measured by the deflection of molecular or atomic beams,[3] since it is peculiar to these methods that the sign of the nuclear moments does not affect the deflection pattern.

In the experiments to be described we have developed and applied to hydrogen and deuterium a method of determining the sign of the nuclear moments which is based on the use of nonadiabatic transitions between states of space quantization of the atom in weak magnetic fields. We have also developed a method of measuring the hfs separation of the normal state of the atom, on which the evaluation of the nuclear moment depends, which makes the result in principle independent of any assumption as to the velocity distribution of the atoms in the beam. This eliminates an important source of possible error in measurements of this kind.

General Considerations

A hydrogen or deuterium atom in the normal $^2S_{\frac{1}{2}}$ state may have in a magnetic field one of several values of atomic[4] magnetic moment f.[5] For hydrogen these moments are: (in units of μ_0, the Bohr magneton)

$$\begin{aligned} \pm f_1 &= \pm 1, \\ \pm f_2 &= \pm x/(1+x^2)^{\frac{1}{2}}, \end{aligned} \tag{1}$$

and for deuterium the moments are:

$$\begin{aligned} \pm f_1 &= \pm 1, \\ \pm f_2 &= \pm (x+\tfrac{1}{3})/(1+\tfrac{2}{3}x+x^2)^{\frac{1}{2}}, \\ \pm f_3 &= \pm (x-\tfrac{1}{3})/(1-\tfrac{2}{3}x+x^2)^{\frac{1}{2}}. \end{aligned} \tag{2}$$

The moments are plotted against x in Figs. 1A and B. The parameter x is defined by $x = 2\mu_0 H/hc\Delta\nu$, where H is the value of the magnetic field. The quantity $\Delta\nu$ is the separation in cm^{-1} of the two hfs components in zero field and is related to the nuclear magnetic moment μ_N by

$$\Delta\nu = [(2i+1)/i](8/3hc)\mu_N\mu_0\psi^2(0), \tag{3}$$

where i is the nuclear spin and $\psi(0)$ is the value of the Schrödinger eigenfunction at the nucleus which can be calculated exactly. Both from band spectra determinations[6] and, as will be apparent later, from the experiments here described, it is known that the nuclear spin of hydrogen is

* Ernest Kempton Adams Fellow, Columbia University, 1935–36.

[1] Frisch and Stern, Zeits. f. Physik **85**, 4 (1933); Estermann and Stern, Zeits. f. Physik **85**, 17 (1933).

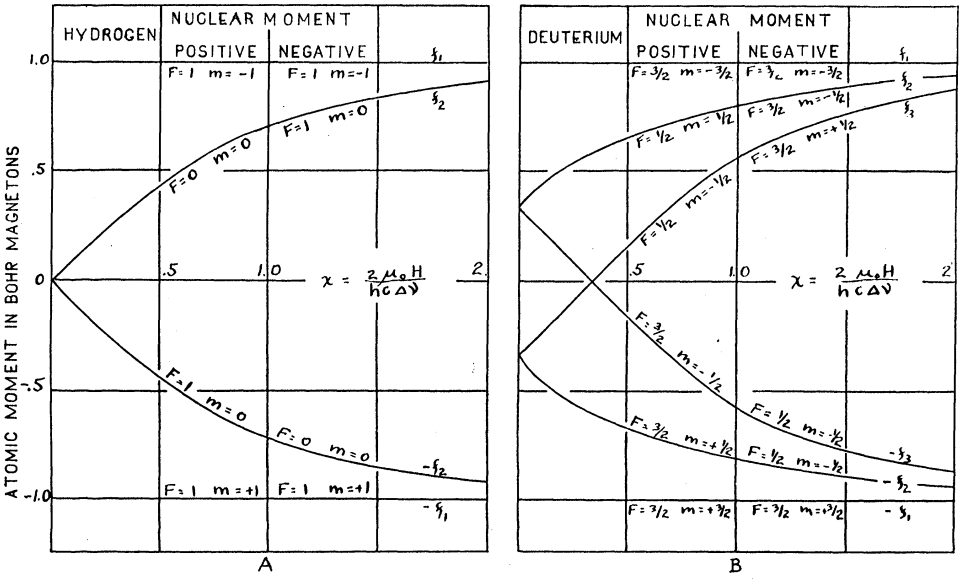
[2] Estermann and Stern, Phys. Rev. **45**, 761 (1934); Rabi, Kellogg and Zacharias, Phys. Rev. **45**, 769 (1934).

[3] Rabi, Kellogg and Zacharias, Phys. Rev. **46**, 157, 163 (1934).

[4] Atomic magnetic moment is not to be confused with nuclear magnetic moment.

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

[6] Murphy and Johnson, Phys. Rev. **45**, 761 (1934).



FIGS. 1A and 1B. Diagram to show quantum numbers associated with the magnetic states assuming the nuclear spin positive or negative.

$\frac{1}{2}$ and the nuclear spin of deuterium is 1. For hydrogen, with nuclear moment μ_P expressed in units of $\mu_0/1838$, the above equation reduces to $\Delta\nu=0.0169\mu_P$, and for deuterium with nuclear magnetic moment μ_D expressed in the same units, to $\Delta\nu=0.0127\mu_D$. Thus if an experimental evaluation of one of those atomic moments which depends upon x can be made while the atom is in a known field H, the magnitude of the nuclear moment can be determined.

The results of a deflection experiment may be made to give both of these quantities. Consider a narrow beam of atoms emerging from the collimating slit of Fig. 3 and passing down the apparatus toward the slit of the Stern-Pirani detector. These atoms pass first through a region A of weak inhomogeneous magnetic field and then through a second field B similar to the first but stronger and arranged to give deflections in the opposite direction to those produced by the field A. This latter condition may easily be satisfied since atoms of positive moment are always deflected into regions of stronger field. The deflection of an atom in the direction y perpendicular to the beam is given by

$$s=(1/4E)\mu(\partial H/\partial y)L, \tag{4}$$

$L=1_1^2+21_11_2$, with E the kinetic energy of the atom, 1_1 the distance the atom moves in the field, and 1_2 the distance the atom traverses from the end of the field to the detector. A suitable choice of H and $\partial H/\partial y$ in the fields A and B will give equality of the deflections produced in these regions, and one can write independently of the value of E and hence of the velocity distribution

$$f'(\partial H/\partial y)'L'=f''(\partial H/\partial y)''L'', \tag{5}$$

where the primes and double primes refer to the values of the various quantities in the fields A and B, respectively. *If the values of H and $\partial H/\partial y$ in the two fields are known, this equation gives immediately the value of the nuclear moment.* In our apparatus the quantities H and $\partial H/\partial y$ are proportional to and can be immediately calculated from the currents used to produce the magnetic fields. With I' and I'' in amperes approximate values of H and $\partial H/\partial y$ for the two fields may be found from $H'=1.34I'$, $H''=1.16I''$ and $(\partial H/\partial y)'=11.1I'$, $(\partial H/\partial y)''=5.95I''$.

A measurement of the atomic moments according to the theory outlined above is sufficient to determine the magnitude of the nuclear magnetic moments, but because of the symmetry of the deflection patterns cannot yield information as to whether this moment is positive or negative, i.e., whether the nuclear magnetic moment is oriented parallel or antiparallel to the

TABLE I. *Transition probabilities for $F=1$.*

m	-1	0	$+1$
-1	c^4	$2c^2s^2$	s^4
0	$2s^2c^2$	$1-4s^2c^2$	$2s^2c^2$
$+1$	s^4	$2c^2s^2$	c^4

TABLE II. *Transition probabilities for $F=3/2$. $c=\cos(\alpha/2)$ $s=\sin(\alpha/2)$.*

m	$-3/2$	$-1/2$	$+1/2$	$+3/2$
$-3/2$	c^6	$3c^4s^2$	$3c^2s^4$	s^6
$-1/2$	$3c^4s^2$	$c^2(c^2-2s^2)^2$	$s^2(2c^2-s^2)^2$	$3c^2s^4$
$+1/2$	$3c^2s^4$	$s^2(2c^2-s^2)^2$	$c^2(c^2-2s^2)^2$	$3c^4s^2$
$+3/2$	s^6	$3c^2s^4$	$3c^4s^2$	c^6

nuclear angular momentum vector. This question has been discussed by Rabi in a paper "On the Process of Space Quantization,"[7] and he there points out that certain nonadiabatic processes may be used to discover the sign of the nuclear moment.

Consider an atom of the beam moving with constant velocity through a magnetic field varying in strength and direction along its path. The atom is equivalent for these questions to an atom at rest and situated in a field varying in time in the same manner. If the angular velocity of rotation of the field, T, is small compared with the Larmor frequency $\omega=2\pi\mu_0 gH/h$ the atom will remain space quantized with respect to the field with the same component m of its total angular momentum F (adiabatic transformability); if the angular velocity is of the same order of magnitude as the Larmor frequency there will be nonadiabatic transitions to states m' not necessarily equal to m but with the same F. The probabilities of such transitions have been calculated by Majorana[8] and are tabulated in Tables I and II for hydrogen and deuterium. The parameter α which occurs in these expressions is obtained from the dynamical theory of the process. Physically α is the angle between the original direction in which the atom is space quantized (direction of the field H) with quantum number m, and the direction after the process with respect to which the atom is quantized with the same quantum number m. Majorana has shown that this process depends only on the Landé g factor and the nature of the process, and is independent of m. Since the two F states have the same g value, the value of α is the same for both for any dynamical process whatsoever.

Since the form of the field T is not known exactly it is not possible to calculate α as a function of the field and of the velocity. There will also be a different value of α for every atomic velocity. We cannot, therefore, begin by setting the field at some particular value and expect to find nonadiabatic transitions. The procedure which we followed was to find experimentally a value of the current in T for which the transitions occurred.

The effective value of α can be calculated from our knowledge of the fraction of the atoms which do not make the transitions and the value of m for the state which has been selected. Since the atoms in the other states pass through the same field and have the same velocity distribution, they have the same effective α. We are thus at liberty to use a field for which the dynamical problem has not been solved. The type of field which we adopted for reasons of convenience is shown in Fig. 2A. This field is neither the Güttinger[9] nor Majorana type although nearer the former. Data obtained in this manner cannot be used to exhibit the quantitative side of the dynamical theory of these transitions. Our purpose, however, is to recognize a qualitative difference in the behavior of the atoms in the two F states under identical conditions.

Reference to Figs. 1A and 1B shows that the assignment of the quantum numbers m and F to atoms in the several magnetic states depends on the sign of the moment of the nucleus. It is this dependence, together with the nonadiabatic transitions made use of in a method to be described, which enables a decision to be formed as to the sign of the nuclear moments.

APPARATUS

The arrangement of the pumps and the slit system (Fig. 3) is almost the same as that described by R. K. Z.[3] In the present apparatus the beam height is 2 mm, and the widths of the various slits are: source sl0t i.03 mm; fore slit, 0.05 mm; collimating slit, 0.02 mm; selector

[7] Rabi, Phys. Rev. **49**, 324 (1936).
[8] Majorana, Nuovo Cim. **9**, 43 (1932).
[9] Güttinger, Zeits. f. Physik **73**, 169 (1931).

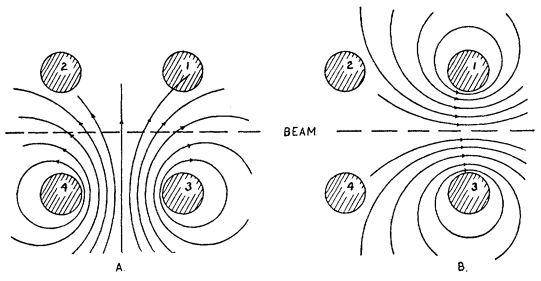


FIG. 2. Diagrams of field near wires T. (A) Nonadiabatic field; (B) Adiabatic field.

slit, 0.5 mm; and detector slit, 0.01 mm. Approximate distances measured from the source slit to the points indicated are: fore slit, 1.0 cm; collimating slit, 17 cm; end of A field, 33 cm; beginning of B field, 38 cm; end of B field, 48 cm; and detector, 50 cm.

The discharge tube: The hydrogen atoms are prepared in a long Wood discharge tube of a design (see Fig. 4) which permits the source slit to be in close proximity to the discharge. The slit is formed by ground edges of thin cover glass held on to the Pyrex tube with picein wax. Water cooling prevents melting of the wax and also seems to keep the temperature of the gas fairly low. With gas pressures of the order of 1 mm the concentration of hydrogen atoms in the beam is between 0.7 and 0.9. In the previous experiment[3] this ratio was only 0.1 to 0.2. The concentration of atoms is taken from measurements of full beam intensity and of the intensity with enough deflecting field on to cast out all atoms.

The ground joint in the threaded collar of Fig. 4 is bored with its axis eccentric and at 5° to the axis of the screw threads. This permits alignment of the source slit parallel to the collimator slit. Motion of the source slit in the horizontal direction is accomplished by moving the brass base plate or by turning the source tube. The canal of the source slit can thus be made to point toward the collimator slit. With the aid of these adjustments it is possible to replace the discharge tube after removing it from the apparatus for cleaning and putting on new slit jaws. This procedure was necessary because Apiezon oil from the diffusion pumps sometimes clogged the source slit.

The magnetic fields: The A and B fields are produced in the manner previously described[3] by current flowing in two horizontal straight tubes parallel to the beam. Great care was exercised both in the construction of the "fields" and in their proper placement with respect to the beam. The B field differs from the A in that it is shorter, capable of carrying more current, and gives a smaller ratio of gradient to field.

Although rheostats, switches, etc., are not worth describing, the leads for the field supply are noteworthy in one regard: in the reduction of stray field. Parallel bus bars of copper placed close together suffice for distances of 20 cm or more from the beam. The insert of Fig. 3 represents a cross section of the leads to the current tubes of the second field in the region near the beam. The cross hatched copper tube is slotted and is soldered to the tube which carries

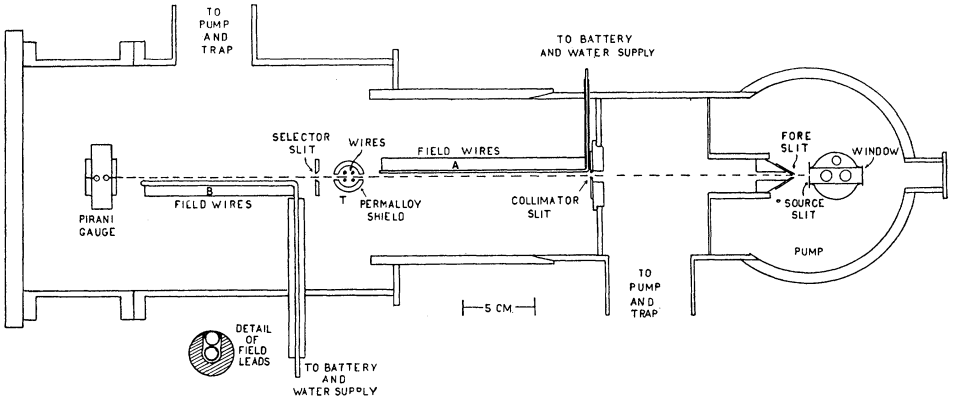


FIG. 3. Diagram of apparatus as used for determination of the sign of the moment for hydrogen and deuterium. The permalloy shield and the wires T were removed from the apparatus for the measurement of the magnitudes of the moments.

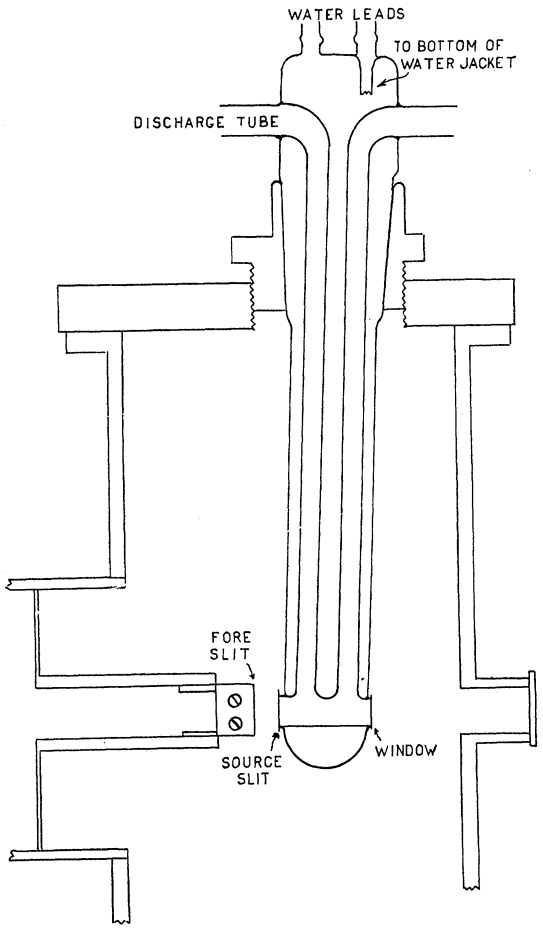


FIG. 4. Section of source chamber to show the construction of discharge tube and of the eccentric brass adjusting collar.

the current in; the central copper tube carries the current out. This arrangement permits simple water connections, simple vacuum seal, good conductivity and small stray field.

A parallel bank of 12 lead storage cells with a capacity of about 1500 amp.-hrs. supplies the first field. For the B field, which requires about 800 amp. continuously, a bank of 6000 amp.-hrs. is maintained. These batteries are charged by a 12-volt, 1200-amp. generator.

The transition field: This field is produced by current flowing in two vertical wires on one side of the beam. It is evident from Fig. 3 that there are four symmetrically disposed copper wires in a region magnetically shielded by permalloy. A system of switches, rheostats, batteries and meters makes it possible to use pairs of wires on either side of the beam as the transition field wires, or to produce an adiabatic field by using one wire on each side of the beam. The forms of these two types of field with respect to the beam direction are shown in Figs. 2A and 2B. Magnetization of the permalloy shield is avoided by running the current in the wires in opposite directions through one hole in the top of the shield.

The detector: The Stern-Pirani detector is of the type designed by Zabel.[10] The detecting gauge and the compensating gauge are enclosed in the same brass block and equipped with slits 2 mm high, 0.01 mm wide, and 4 mm deep. The motions necessary for its proper alignment with the beam are simple screw devices of obvious design. In the early part of the experiment considerable difficulty was encountered in reading the gauge galvanometer while the hydrogen discharge tube was in operation. Unsteadiness of the gauge seemed to be associated with fluctuating pressure in the detecting chamber and with subsidiary electrical effects of the discharge. Therefore the electrical circuit from the gauge wires to the galvanometer was shielded with sheet copper and the backing pressure for the high speed pumps was improved so as to maintain an ion gauge pressure of 10^{-7} mm in the detecting chamber. To avoid electrical and mechanical disturbances by mechanical pumps a three-stage Leybold mercury diffusion pump was inserted in the fore line and the hydrogen gas from the source slit was pumped into an evacuated 30 gal. tank.

METHOD: MAGNITUDE OF THE MOMENTS

The detector slit is set to receive the atoms of the undeflected beam and is left fixed in this position throughout the course of all experiments. The simplest experiment to perform is the determination of the nuclear spin of hydrogen. The current in the B field is turned on and set at such a value as to give an x in the neighborhood of 1.5. With no current in the A field the beam is split in the B field and few atoms enter the gauge. If the A field current, I', is now increased, all atoms in the A field experience a deflecting force proportional to their atomic moments and to

[10] Zabel, Phys. Rev. **46**, 411 (1934).

the current I'. This force is opposite in direction to the force that will act on them when they pass through the B field. At the same time atoms having moments other than $\pm f_1$ are receiving larger deflections in the A field on two counts; first because the larger I' increases H' and hence x and f_2, and second because the force per unit moment is becoming larger due to the increase in $(\partial H/\partial y)'$. These atoms may thus in turn be focused into the detector. Focusing is of course recognized by a maximum of intensity at the detector.

A curve showing the two intensity maxima so obtained for hydrogen is given in Fig. 5. Since four atomic magnetic levels are required to give the two peaks of Fig. 5, and since the number of these levels is given by $(2i+1)(2j+1)$, a nuclear spin of $\frac{1}{2}$ is found for hydrogen.

While the existence of two and only two peaks is sufficient to establish the proton spin, a determination of the position (in current) of the peaks and a more detailed analysis of the operation of the apparatus is necessary before a value can be assigned to the magnitude of the magnetic moment of the proton.

First, the values of H and $\partial H/\partial y$ are neither exactly constant over the height of the beam, nor because of end effects, along the beam. The terms $f(\partial H/\partial y)L$ in Eq. (5) are therefore replaced by a numerical integration over the full path of the beam using values of H and $\partial H/\partial y$ averaged over the height of the beam.

Second, the values of H and $\partial H/\partial y$ are calculated from measured geometry of the apparatus, e.g., the distance between the wires, their diameters, the distance from the wires to the beam, and the lengths of the beam path both in and out of the fields. It is fortunately possible to use the values of the currents required to deflect and focus atoms of constant moment to evaluate directly some of the constants in Eq. (5). If we let $\partial H/\partial y = GI$, then Eq. (5) can be written

$$f'I'/f''I'' = G''L''/G'L' \equiv R. \tag{6}$$

This ratio R can be evaluated in two ways. First it can be calculated directly from the geometry of the apparatus. Second, it can be determined in terms of the currents required to focus hydrogen atoms having $f' = f'' = \mu_0$. A comparison of the values of R obtained in these two ways serves as a check on the geometry used in the calculation of H. The second determination is considered to be more accurate than the first and is used in the evaluation of the ratio f'/f'' for $f' \neq f''$.

Third, consider two atoms emerging from the collimating slit, one with moment $+f$ and the other with moment $-f$. The atom with moment $+f$ is deflected in the A field into regions of stronger field and gradient while that with moment $-f$ is deflected into regions of weaker field and gradient. The result is to give the atom with moment $+f$ a larger deflection than the atom with moment $-f$. The B field which is on the opposite side of the beam from the A field

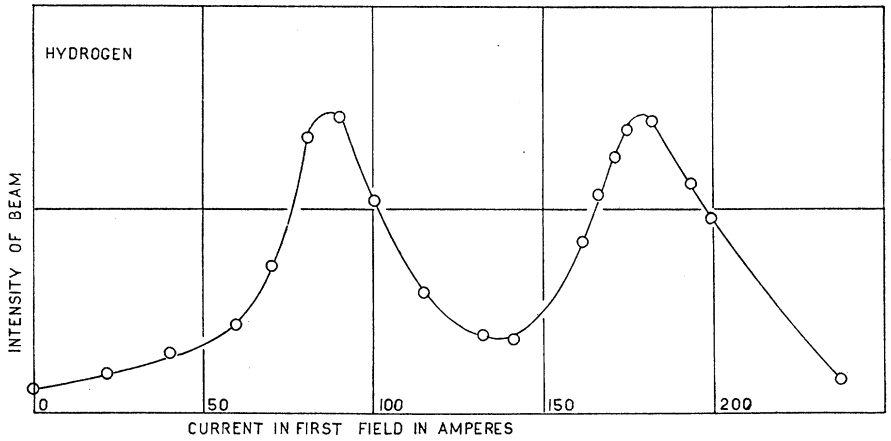


FIG. 5. Intensity at center of beam against field current for hydrogen to show nuclear spin to be $\frac{1}{2}$. The first peak is for $\pm f_1$; the second for $\pm f_2$.

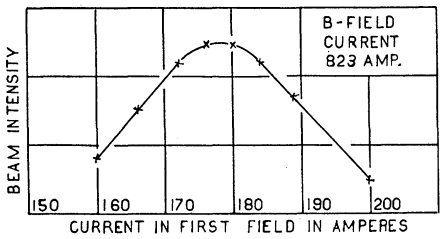


FIG. 6. Intensity of beam against field with selector slit interposed to pass only atoms with negative moments, for hydrogen.

magnifies this effect and $+f$ is underfocused whereas $-f$ is overfocused. Thus instead of a sharp peak a broad maximum is formed by the superposition of the two partially focused beams.

This difficulty is overcome in the following manner. A selector slit is introduced where the beam is split between the two fields. By means of this slit it is possible to cut out of the beam either those atoms with positive or those with negative moments. This slit serves the additional purpose of blocking the undissociated molecules of the direct beam from the detector. Suppose the slit is set to pass only those atoms having positive moment. An intensity-current plot is made for, say, atoms of moment $+f$ (see Fig. 6). The slit is then moved to pass only those atoms having negative moment and an intensity-current plot made for atoms of moment $-f$. If the positive moment peak occurs at current I_+', and the negative moment peak at I_-', then $(I_+'+I_-')/2$ is very closely the current at which the peak would occur in an ideal apparatus, i.e., an apparatus in which the deflecting force on an atom is not a function of the deflection.

Fourth, a method of using the detector is required which will give as accurately as possible the current at which the maximum intensity occurs. A "differential" method of measuring the intensity is adopted. With a given B field current, the current in the A field is set in the neighborhood of the peak. The reading of the detector galvanometer is noted and simultaneously a switch is thrown to vary the A field current by a few percent. After thirty seconds the galvanometer reading is again noted and the switch thrown to give the original A field current. This procedure is continued for six minutes and the readings averaged to eliminate the effect of drift. The difference in the two sets of readings then gives the amount by which the intensity at one current exceeds that at the other. By interrelating two points on the curve so directly one largely eliminates effects of secular changes in the intensity of the beam and changes in the ratio of the number of atoms to molecules. All current-intensity curves were taken in this manner.

METHOD: SIGN OF THE MOMENTS

Hydrogen

The transition field T is fixed in place between fields A and B. The selector slit is set to pass atoms of positive moment and the A and B field currents adjusted to focus the component $+f_2$. According to Fig. 1A this component is either $F=0$, $m=0$, or $F=1$, $m=0$, depending on the sign of the nuclear moment. If the state is $F=1$, $m=0$ (nuclear moment negative), then Table I shows that for a certain value of α, that is, a certain value of the current in the wires of the field T, there will be nonadiabatic transitions to states $F=1$, $m=\pm 1$. If the transition is to $m=+1$, the atom enters the B field region with the sign of its moment changed and is no longer focused. There is therefore a decrease in intensity at the detector. If the transition is to $m=-1$ no decrease in intensity will be observed since the value of x in the second field is so large that all atoms experience approximately the same deflecting force. In any discussion of these experiments, and particularly in the case of deuterium, this equality of atomic moments in the B field must be kept in mind. In the vernacular of the laboratory "only those transitions that cross the diagram (Fig. 1) are counted as 'flop' (nonadiabatic transition)." However, if the state is $F=0$, $m=0$ (positive nuclear moment), no variation in intensity will be observed since changes in F are forbidden. A similar argument may easily be carried out for $-f_2$. The results are summed up in Table III where the expected change in intensity is given for the various possible combinations of nuclear and atomic moment.

While it would seem sufficient to perform an experiment on, say, $+f_2$ and to determine whether this state does or does not make transitions, it is experimentally necessary to show that the result obtained is not due to

extraneous effects of the apparatus. Thus, if it is found that for a particular value of current in the T field wires there *are no* transitions made from the component $+f_2$, it is then necessary to show that for the same value of the T field there *are* transitions made from the component $-f_2$. Furthermore a similar experiment on the components $\pm f_1$ should show that both of these components *do* make transitions. Lastly, to be sure that the asymmetry is not inherent in the position of the beam with respect to the field wires, this whole series of experiments must be performed with the transition wires located on the other side of the beam.

Deuterium

The same apparatus is used as for the sign determination for hydrogen. The selector slit is set to pass atoms of negative moment, and the A and B field currents are adjusted so that only states $-f_2$ and $-f_3$ enter the detector. As is obvious from Fig. 7, when $-f_3$ is focused, the beam is contaminated by $-f_2$. The procedure followed is to focus partially both $-f_3$ and $-f_2$. Suppose the nuclear moment positive. Then transitions are possible to all states with $F=3/2$, and in particular to the state $F=3/2$, $m=-3/2$, i.e., to $+f_1$. Detailed consideration of Table II shows that for an equal mixture of atoms in states $-f_2$ and $-f_3$ this transition probability is a maximum for $\sin^2(\alpha/2)=\frac{1}{2}$. Therefore if the nuclear moment is positive, there will be a value of current in the T field wires which will produce a decrease in the intensity of the beam composed of atoms of moments $-f_2$ and $-f_3$.

On the other hand if the nuclear moment is negative, reference to Fig. 1B shows that the states $-f_2$ and $-f_3$ both have $F=\frac{1}{2}$ and therefore transitions are possible only between these two states. Remembering that the atomic moments in the second field are all practically equal to one Bohr magneton, it follows that the total number of atoms focused into the detector is not changed thereby.

For the atoms with positive moments $+f_2$ and $+f_3$ a similar argument leads to opposite conclusions. The results of this discussion are summed up in Table III.

While current flowing in opposite directions in either wires 1 and 2 or 3 and 4 gives a non-adiabatic field over the region of the beam inside the permalloy shield of the transition field, it is not certain that mere absence of current in these wires gives an adiabatic field in this region. The very existence of the ferromagnetic material of the shield in this space gives rise to the possibility of residual fields which might accidentally fulfill the requirements for a nonadiabatic field. However, with current flowing in opposite directions in wires 1 and 3 the field will be as shown in Fig. 2B and the shield and the region inside the shield will certainly be magnetized in such a manner that there will be no rapid change of direction of the field along the path of the beam. All observations here reported were made by repeatedly switching from configuration B to configuration A of Fig. 2.

If this procedure is not followed, the results are essentially the same. However, there were slight increases of intensity on switching from no current to configuration B which would indicate the presence of this accidental nonadiabatic field.

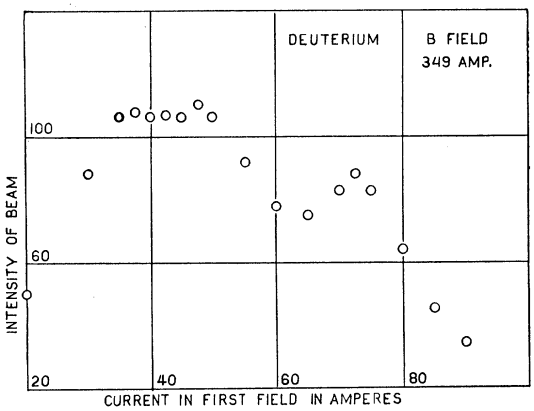


FIG. 7. Intensity of beam against field with selector slit set to pass only atoms with negative moment.

TABLE III. *The qualitative expected change of focused beam intensity for nuclear moment assumed positive and negative; and the observed change in intensity.*

	Component Focused	Expected Change of Intensity		Observed Change of Intensity
		Positive Nuclear Moment	Negative Nuclear Moment	
Hydrogen	$\pm f_1$	Decrease	Decrease	Decrease
	$+f_2$	None	Decrease	None
	$-f_2$	Decrease	None	Decrease
Deuterium	$\pm f_1$	Decrease	Decrease	Decrease
	$+f_2$ & $+f_3$	None	Decrease	None
	$-f_2$ & $-f_3$	Decrease	None	Decrease

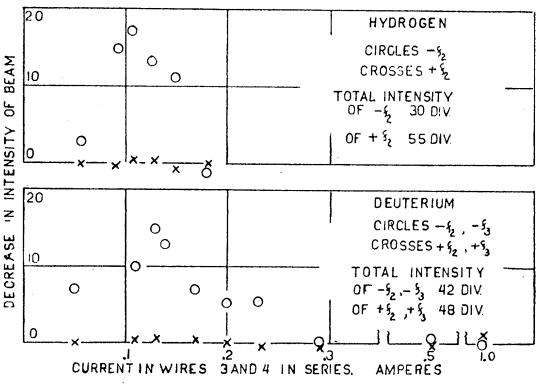


FIG. 8. Nonadiabatic transitions.

RESULTS

The sign of the nuclear moments: Typical experimental results are given in Fig. 8. They show the change in intensity on the introduction of the nonadiabatic field. The striking differences between the behavior of the states with positive atomic moments and those of negative atomic moments is very apparent. This difference is not due to a geometric asymmetry because the same behavior is obtained with either pair of wires 1 and 2 or 3 and 4. Consultation of Table III shows that the experiments establish the signs of the nuclear moments of hydrogen and deuterium to be positive.

The magnitudes of the nuclear moments: Figs. 6 and 7 show typical experimental curves from which the intensity-current maxima were obtained. Table IV gives the results of a series of measurements of the quantity R of Eq. (6) for different values of the B field current and the corresponding values of the A field current for the low current peak. They fall within one percent of constancy and seem to show no trend with current. This table shows the precision of the determination of the maximum of intensity with current. The value of R calculated from the geometrical measurement of field wire distances etc. is 11.05 as compared with 11.09 which is the average of the values of Table IV. This check permits us to place confidence in the values of the moment as calculated from the currents in the A field necessary to focus the atomic moments $\pm f_2$.

Table V gives the results of a series of measurements of these quantities and the proton moments calculated from them. Table VI gives the

TABLE IV. *Hydrogen.* I_+' is the current to focus $+f_1$, and I_-' is the current to focus $-f_1$. $I_A=(I_+'+I_-')/2$. Currents in amperes.

B Field Current I''	A Field Current I_+'	I_-'	I_A	$R=I''/I_A$
400	32.1	40.1	36.1	11.08
500	39.5	50.3	44.9	11.13
627	50.8	62.5	56.7	11.06
648	52.0	65.5	58.7	11.03
648	50.9	65.5	58.2	11.13

TABLE V. *Hydrogen.* I_+' is the current to focus $+f_2$, and I_-' is the current to focus $-f_2$. $I_A=(I_+'+I_-')/2$. Currents in amperes.

B Field Current I''	A Field Current I_+'	I_-'	I_A	μ_P
601	121.7	142.7	132.2	2.79
732.5	140.0	166.0	153.0	2.87
732.5	141.5	164.5	153.0	2.87
773	145.7	170.0	157.7	2.81
783	148.0	172.0	160.0	2.85
823	150.7	178.0	164.3	2.87

TABLE VI. *Deuterium.* I_+' is the current to focus $+f_3$, and I_-' is the current to focus $-f_3$. $I_A=(I_+'+I_-')/2$. Currents in amperes.

B Field Current I''	A Field Current I_+'	I_-'	I_A	μ_D
349	66.3	73.2	69.7	0.854
400	68.2	78.8	73.5	.841
440	72.4	82.4	77.4	.848

results of similar measurements with deuterium.

The final results do not have a precision as high as would appear from these tables. First because an error in the determination of the peak current is magnified in the calculation of the moment. Second because of the possibility that the check between the value of R as measured by the ratio of currents and as calculated from the geometry may be partly the result of fortuitous compensation of errors in the very difficult geometrical measurements.

These measurements yield for the proton moment a value of 2.85 ± 0.15 nuclear magnetons; and for the deuteron a value of 0.85 ± 0.03 nuclear magnetons. Our judgment of the precision comes from a discussion of the possible errors in the determination of the geometry.

DISCUSSION

The deuteron value should be somewhat more precise than that of the proton since the geometry

does not enter as importantly. This circumstance arises from the fact that the hfs separation for deuterium is so small that the moment in the B field is practically independent of the field. The ratio of the proton moment to the deuteron moment is 3.35. This value should be somewhat more accurate than that of those for the individual moments since systematic errors should effect both values in the same direction. It is to be noted that this value differs considerably from the value 4 obtained by Farkas and Farkas[11] from the rates of the para-ortho conversion for hydrogen and deuterium.

The value of the proton moment which we previously obtained by the use of atomic beams, 3.25 ± 10 percent is considerably higher than our present results. The cause of this discrepancy is rather obscure but may lie in our previous assumption that the temperature of the beam was the same as the temperature of the source slit.

With the sign of the moments established one can deduce an approximate value of the neutron moment on the naive assumption that the deuteron moment is the algebraic sum of the proton and neutron moments with the additional assumption that the spin of the neutron is $\frac{1}{2}$. The neutron moment is thus -2 nuclear magnetons.

In conclusion we wish to express our appreciation of the aid of a grant from the Carnegie Institution of Washington. Also, we wish to thank Professor H. C. Urey for the generous gift of the heavy water used in these experiments.

[11] Farkas and Farkas, Proc. Roy. Soc. **A152**, 152 (1935).

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The Photoelectric Properties of Zinc

CHARLES F. DEVOE, *University of Wisconsin*

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The work function of a vacuum distilled surface of zinc was found to be 4.24 volts at 1.5×10^{-8} mm pressure; as the pressure of air was increased the work function decreased to a minimum at about 10^{-6} mm pressure and then increased. Helium had no effect to a pressure of 3 mm. Nitrogen had no effect to a pressure of 10^{-3} mm.

EXPERIMENTS on the photoelectric properties of high melting point metals have shown that the metals must be heated at high temperatures for hundreds of hours before reproducible values for the long wave limits are obtained. Since this technique cannot be applied to zinc, several methods have been used to produce a gas-free surface rather than attempt to outgas a contaminated one.[1–9] The values for the long wave limit of zinc obtained in these experiments ranged between 2940A and 4000A.

[1] Richardson and Compton, Phil. Mag. **24**, 575 (1912).
[2] Hennings, Phys. Rev. **4**, 228 (1914).
[3] Küstner, Ann. d. Physik **46**, 893 (1915).
[4] Hennings and Kadesch, Phys. Rev. **8**, 209 (1916).
[5] Welch, Phys. Rev. **32**, 657 (1928).
[6] Werner, Zeits. f. Physik **67**, 207 (1928).
[7] Hughes, Phil. Trans. Roy. Soc. London **212**, 205 (1912).
[8] Dillon, Phys. Rev. **38**, 408 (1931).
[9] Rentschler, Henry and Smith, Rev. Sci. Inst. **3**, 794 (1932).

Hughes[7] measured the long wave limit of a vacuum distilled surface of zinc but the vacuum he used was low compared to that available now. The purpose of this experiment was to study zinc surfaces prepared by Hughes' method under the best possible vacuum conditions.

APPARATUS

The experimental tube is shown in Fig. 1. The thin molybdenum strip A, spotwelded to a tungsten wire yoke and shaft, could be moved into the molybdenum collecting cylinder G, or in front of a tungsten filament E from which the strip could be heated by electron bombardment, or could be placed horizontally over either of the two quartz crucibles Z containing the zinc by means of an electromagnet acting on the soft iron bar C. The collecting cylinder G was sup-