MAGNETIC MOMENTS OF THE ALKALI METAL ATOMS

By John B. Taylor.[1]

Abstract

The work of Stern and Gerlach in which they determined the magnetic moments of certain atoms and at the same time furnished direct evidence of the theory of space quantization, by deflection of rays of the atoms in an inhomogeneous magnetic field, has been repeated for silver atoms. A simplified apparatus is described, using a silver plated tungsten coil as source of atoms, rather than the furnace used by Stern and Gerlach, which gives trouble in outgassing.

The magnetic moment of sodium and potassium. The apparatus was further modified for use with the alkali metals by construction of a liquid air cooled target for receiving the atomic rays and a Pyrex glass device for holding the molten metal during evaporation. The images of the rays on the glass target were made visible by immersing in hydrochloric acid gas, which "fixed" them as the opaque and visible chloride. Distinct images of the separated rays resulting from the action of the magnetic field on the oriented atoms have been obtained and are reproduced. Measurements of the separations show that, within the experimental error, sodium and potassium possess magnetic moments equal to one Bohr magneton, in accord with spectroscopic predictions.

THE experiments of Stern and Gerlach,[2] in which they determined the magnetic moments of certain atoms by deflection of a ray of the atoms in an inhomogeneous magnetic field, have introduced a method of research of great interest. Measurements of susceptibilities and observations on magneto-mechanical systems both deal with matter in bulk, where the effects of the solvent and of neighboring atoms cloud the results. The "atomic ray" is a uni-directional narrow beam of atoms in which there is little or no inter-collision effect. This allows investigation of the action of individual atoms, and it is with such rays that Stern and Gerlach have secured direct evidence of space quantization and a direct measure of the unit of magnetic moment so far accepted,—the Bohr magneton.

The equation relating the amount of deflection of the atomic ray to the magnetic moment of the atom is:

[1] This communication is an abstract of a thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Chemistry at the University of Illinois.

[2] O. Stern, Zeits. f. Physik., **7**, 249 (1921); W. Gerlach and O. Stern, Zeits. f. Physik. **8**, 110 (1921); **9**, 349, 353 (1922); Ann. d. Phys., **74**, 673 (1924); **76**, 163 (1925).

$$\frac{1}{M} = \frac{1}{2s}\left(\frac{\partial H}{\partial s}\right)_0 \frac{l^2}{3.5RT}\left\{1 + \frac{l^2 M}{12\times 3.5RT\times s}\left[\left(\frac{\partial H}{\partial s}\right)_l - \left(\frac{\partial H}{\partial s}\right)_0\right]\right\}$$

Here s is the amount of deflection measured as shown later; M is the magnetic moment (gauss cm per mol.); l is the length of the pole pieces of the magnet, the distance the atomic ray must travel through the magnetic field; $(\partial H/\partial s)_o$ is the value of the inhomogeneity of the field at the point where the ray enters the field; $(\partial H/\partial s)_l$ is the corresponding inhomogeneity at the end of the field, after the deflection of the ray. This is not equal to $(\partial H/\partial s)_o$ since $\partial H/\partial s$ changes in value from point to point across the field between the pole pieces, being greatest next to the knife edged pole piece. (See below.) The values of $\partial H/\partial s$ are obtained for any distance of the ray from the knife edge by a preliminary mapping of the field. The 3.5 RT term comes from the expression which Stern[3] found in his direct measure of the velocity of the silver atom.

Since the work of Stern and Gerlach appears to be of such fundamental importance, it was thought desirable to repeat it in way of confirmation, and if possible to extend it. Their initial experiments in which they found the normal silver atom to possess a magnetic moment equal to one Bohr magneton have been repeated in a simplified apparatus. Following this, the alkali metal atoms, sodium and potassium, have been investigated.

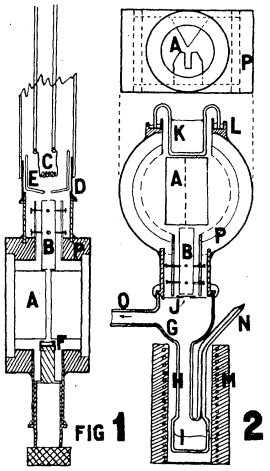
Experimental

A large Dubois type magnet, possibly a duplicate of Stern and Gerlach's, was used to produce the magnetic field. The apparatus for formation, deflection, and detection of the atomic rays was suspended between the flat pole pieces of this magnet. It was a vacuum tight brass box with end tubes, as shown in three sections at P, in Figs. 1 and 2. The auxiliary pole pieces for producing the inhomogeneous field were of soft iron, shaped as at A and held on soft iron plates set in and soldered to shoulders on the brass box. One pole piece was a 60° knife edge, the other slotted as shown in the upper view of Fig. 2. Magnetic measurements showed the field produced and the inhomogeneity of the field to be closely that used by Stern and Gerlach. (See also below.)

Fig. 1 gives one section of the brass box P, and the arrangement for silver. Fig. 2 gives other sections of P, but the arrangement is for the alkali metals as will be described later. In Fig. 1, C is a silver plated tungsten coil which was a source of silver atoms when heated by passage of current. The silvered coil gives less trouble in outgassing than does a

[3] O. Stern, Zeits. f. Physik., **2**, 49 (1920).

small furnace of the type used by Stern and Gerlach. It was suspended on long copper leads sealed out through copper tubes, which in turn were sealed through a Pyrex head piece (not shown). A ground joint allowed removal of this head piece with the coil for replating with silver. It also carried a plane glass plate to allow control of the temperature with an optical pyrometer. This temperature was held at approximately 1200°K. The Pyrex glass tube supporting the coil holder was sealed to a short thin walled copper tube *D*, which was soldered to the brass box.



Figs. 1 and 2. Diagram of apparatus.

The slits, which form the ray, were made in thin copper disks held on a framework and adjusted by a set of screws as shown at *B*. The slits used in the experiments with silver were both .1 mm wide, 2mm long, and held 3 cm apart. The slits must be adjusted so that the path of the atoms, after leaving them, will be exactly parallel and at the desired distance from the knife edged pole piece. Between the coil and the first slit a glass diaphragm *E* was inserted to prevent silvering the whole interior of the apparatus.

The ray of silver atoms was received on tiny glass plates held under a cap on the plate holder, as shown at *F* in Fig. 1. The surface of the plate was less than a millimeter from the end of the pole pieces. The time of run was usually about one hour, during which time a vacuum of $3-5 \times 10^{-5}$ mm was maintained in the apparatus. At the end of the run the plate holder was removed and the glass plate, bearing an invisible image of the silver atoms on its face, was immersed in a dilute (one percent)

hydroquinone-silver nitrate intensifying bath.[4] This deposited more silver upon the trace already there and made the image visible for measurement.

The images obtained for silver did not show a splitting or separation into two lines as obtained by Stern and Gerlach. This was undoubtedly because the slits were too wide in proportion to the amount of deflection to show more than a decided broadening of the ray in the magnetic field. A trace of division was noticed in some of the runs. These results indicated that the apparatus was in working order and the investigation of the alkali metals was begun.

The apparatus was modified as shown in Fig. 2. A Pyrex container G held the alkali metal. This container consisted of a pot I, short tube H for limiting the evaporation of the metal from I, and an enlargement above H for sealing with de Khotinskey cement to the brass box P. The box is shown inverted in this figure, since the alkali metals were evaporated from below,—not from above as for silver in Fig. 1. The capillary N is for filling. O leads to liquid air trap, McLeod gage and pumps.

After a preliminary test of the apparatus by pumping to a high vacuum, the capillary was blown out at N, and the filling device sealed on. This was a series of small bulbs connected by tubes or short lengths of capillary, and allowed successive distillation and filtration of the alkali metal completely in vacuum. The metal reached I in a mirror like condition and after a short heating was practically gas free. A residual gas pressure averaging 4×10^{-5} mm was held during the runs. M is a copper tube furnace for heating the metal in I and the tube H. Temperatures were read with a chromel alumel couple calibrated under the conditions of the experiment. J is a copper diaphragm which prevented alkali metal from entering the pole piece box and carried a small iron shutter which closed the opening of the diaphragm during outgassing, to avoid unnecessary clogging of the fine slits.

A run was started by applying the magnetic field. This opened the iron shutter, which had been suitably oriented, and the slits were thus exposed to the stream of atoms. The atomic rays were in this case received on a Pyrex target K whose face was cooled by liquid air. Definite images could not be secured on uncooled targets. The use of this target necessitated a change, as shown, in this end of the box P. The tube and plate holder F were replaced by the Pyrex target K and the circular brass channel L, which allowed easy insertion and sealing of the target with beeswax rosin mixture.

[4] J. Esterman and O. Stern, Zeits. f. Phys. Chem., **106,** 399 (1923).

The images, sodium or potassium, were made visible by immersing the target in hydrochloric acid gas. This "fixed" the images as the opaque and visible chloride.

The first slits used were 0.1 mm×2 mm, and as for silver gave only broadened images. (See Plate I.) Then in a series of runs and adjustments the slits were narrowed gradually to a width of .03 mm, when images as shown in Plates II, III, and IV were obtained.

Sodium was evaporated at 345°C and potassium at 245°C.

Discussion of the Images and Calculations of the Magnetic Moments

The Plates I–IV are photomicrographs of the original tiny images. Plate I (16×) for sodium, shows only the broadening and is unsuitable for measurement.

Plates II and III (16×), show the divided rays finally obtained for sodium and potassium. Plate II was unfortunately formed on a target streaked with bubbles in the glass. Under the microscope it was almost as clearly defined as III. Plate IV is a photomicrograph (32×) of the splitting shown in III.

Fig. 3 is a diagram of Plate III with dimensions. The distance s is the quantity used in the calculation of M, the magnetic moment. The location of the outer limit of s, at the most dense point in the branch of

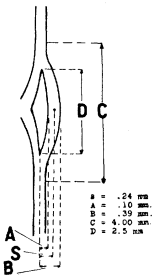


Fig. 3. Diagrammatic sketch of Plate III.

S = .24 mm
A = .10 mm
B = .39 mm
C = 4.00 mm
D = 2.5 mm

the split, is easily seen under the microscope. The measurements were made with an eye piece micrometer. At X the image (see also III) appears to be pulled out and flattened. This is the side toward the knife edge and has actually been drawn against the pole piece by the greater

$\partial H/\partial s$ at the edge. For this reason the more uniformly deflected branch of the split is chosen for measurement of s.

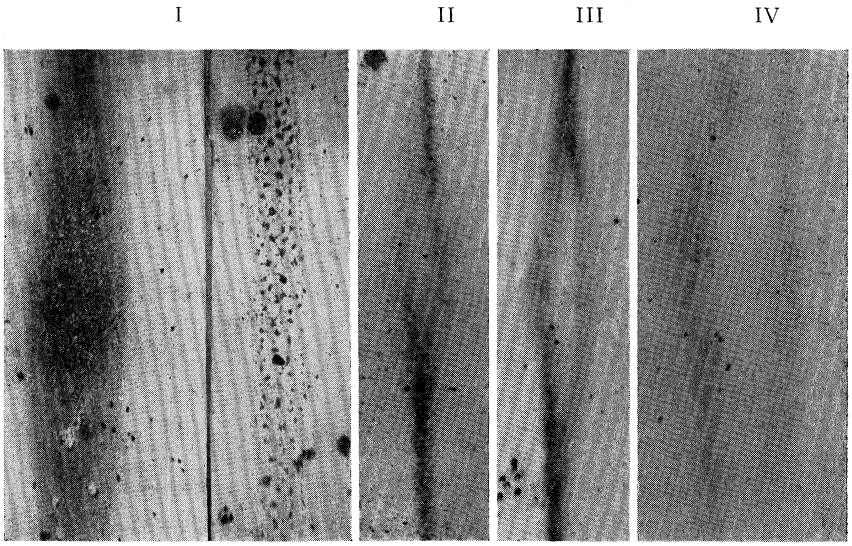


Plate I. Sodium. (A) without field; (B) with field, broadened only.
Plate II. Sodium. Plate III. Potassium. Plate IV. Potassium.

The data for calculation of M from these images are as follows: Slits, $.03\times 2.5$ mm; pole piece, length, 3.0 cm; distance, middle of slits from knife edge, 0.26 mm; giving $(\partial H/\partial s)_o$ a value of 160,000 gauss per cm.

Sodium $s=0.20$ mm $(\partial H/\partial s)_l=105{,}000$. $T=620°\text{K}$

Potassium $s=0.24$ mm $(\partial H/\partial s)_l=94{,}000$. $T=520°\text{K}$

By inserting these values of s $(\partial H/\partial s)_o$, $(\partial H/\partial s)_l$, l and T in the equation given above, there results for the magnetic moments:

$M=5350$ gauss cm, from the data on sodium.

$M=5380$ gauss cm, from the data on potassium.

This is about a four percent difference from 5584, the Bohr unit magneton value, and warrants the conclusion that normal atoms of sodium and potassium both possess a magnetic moment equal to one Bohr magneton.

An examination of the equation shows that the deflection s is independent of the atomic weight of the element and that elements of equal magnetic moment should have s related inversely as the absolute temperatures of evaporation.

$$s_{\text{Na}}/s_{\text{K}}=.20/24=.833; \qquad T_{\text{K}}/T_{\text{Na}}=520/620=.838$$

The single magneton value for the alkali metals is in accord with the spectroscopic prediction made possible by use of Landé's[5] classification of the anomalous Zeeman effect, as referred to the neutral unexcited atom.

Accuracy

As in Stern and Gerlach's experiments the possible error is close to ten percent. The largest source is the measurement of s, which on account of the diffuseness of the lines and the difficulty in judging the exact points of reference, can be measured only to .01 mm, a possible error of five percent. The values of $(\partial H/\partial s)_o$ and $(\partial H/\partial s)_l$ are large and do not vary rapidly, yet the measurements of Stern and Gerlach may be in error by a few percent. The values of $\partial H/\partial s$ are taken from the table given by Stern and Gerlach. This is justified by several circumstances. As mentioned before the magnets are of the same type and capacity. The pole pieces are the same. Also by using the temperature relationship and allowing for the ratio of $\partial H/\partial s$ used in the two cases, Stern and Gerlach's deflection for silver was reproduced by calculation. Moreover, the close agreement with the single magneton value 5584, supports the validity of the value chosen. Precise measurements of the inhomogeneity are now being made but will be of no advantage until the large error in the measurement of s is removed. It is important to note that this error in $\partial H/\partial s$ can be practically eliminated by choice of a reference substance giving a certain s under set conditions of the slit system. Temperatures were read to within one percent.

It is seen that the reduction of the possible error in these experiments is an important matter, and that the detection and measurement of s are the chief difficulties. In consequence of the Maxwellian distribution of velocities, the s for individual atoms is spread over a range of values and the resulting branches of the split are broader and more diffuse than the original ray. This can be remedied by any method producing a ray of single or narrow range velocity atoms. Any error in the velocity factor ($3.5\ RT$) will be reduced at the same time. Narrowing of the original ray also helps but increases difficulties in detection of the ray by any means. The actual measurement may be made more certainly by any method which takes accurate account of the variation of intensity in the ray, that is, a method which picks out the s of the majority of the atoms. This is not done of course when actual images are received on plates. Resort must be had to detecting devices such as delicate pressure gauges, ionization gauges, etc., the application of which is very doubtful at present.

[5] Sommerfeld, Atombau and Spektrallinien.—4th ed.

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LABORATORY OF PHYSICAL CHEMISTRY,
UNIVERSITY OF ILLINOIS.
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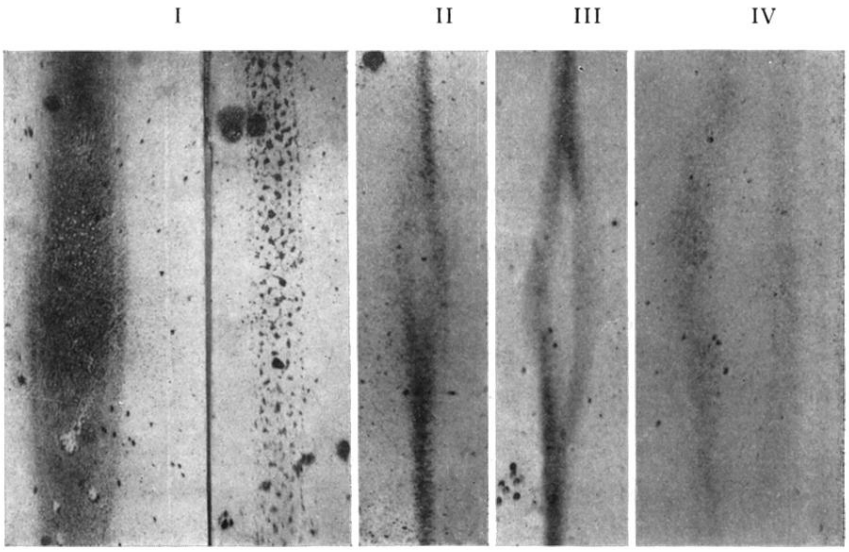

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