THE RICE INSTITUTE

MAGNETIZATION

IN

SINGLE CRYSTALS OF KI AND LIF

by

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INTRODUCTION

In recent years The Rice Institute has been engaged in basic research concerning the Nuclear Magnetic Resonance in Single Crystals of the Alkali Halides. One of the more important parameters in such studies is $T_1$, the spin-lattice relaxation time, particularly at low temperature. The reason $T_1$ is important is that it is the time parameter which determines the exponential approach to equilibrium of the nuclear spins and the lattice. It is also called the longitudinal relaxation time, since it is the time constant associated with the exponential growth or decay of the nuclear magnetization of the sample in the direction of the externally applied field. Hence the solid state physicist is interested in $T_1$, for it gives him a measure of the interaction of the individual nuclei with the local fields in which they find themselves. Also, studies of $T_1$ can indicate the coupling of the spin system to the lattice thereby giving insight into the structural bonds of the sample and lattice vibrations.

The early theory (1) of nuclear spin-lattice relaxation was based on the interaction of the nuclear magnetic dipole moment with the lattice. Nuclei without electric quadrupole moments would have quite long $T_1$'s, on the order of years. Paramagnetic impurities however can drastically shorten such times according to the work of F. J. Low and C. F. Squire (2) on LiF. The more recent theory of nuclear spin-lattice relaxation due to the interaction of the nuclear electric quadrupole moment with the crystalline electric field
gradients was worked out by Van Kranendonk (3). It was then seen
that a nucleus like I$^{127}$ in KI which has such a large quadrupole
moment ($-0.75 \times 10^{-24} \text{ cm}^2$) might have a relaxation time at 4.2° K
which is of the order of ten hours. This stimulated the measurement
of $T_1$ of I$^{127}$ in samples of KI here at Rice.

The first work at Rice on spin-lattice relaxation studies of
I$^{127}$ in KI were conducted by C. V. Briscoe and C. F. Squire (4).
Their results showed excellent agreement with J. Van Kranendonk's
theory from 300 °K down to 10° K. In the temperature range between
1 and 4° K their results indicated that $T_1$ was about 4 hours and
was temperature independent instead of the predicted $T^{-7}$ temperature
dependence. It was therefore decided to perform further studies of
$T_1$ in the liquid helium range.

For the past two years S. M. Day has been working on additional
measurement of $T_1$ of I$^{127}$ looking not only at temperature dependence
but also at orientation effects. His early work showed an apparent
difference in $T_1$ depending on whether it was measured for growth or
decay of the magnetization. In fact the gross magnetization seemed
to be different, (5) depending upon initial conditions, and some
confusion existed.

It was therefore decided that an entirely different method should
be tried whereby the gross magnetization of substances such as Alkali
Halides could be measured directly. It is well known that B. Lasarev
and L. Schubnikow (6) had made static susceptibility measurements on
solid hydrogen at 4° K. They utilized the Classical Gouy method to
measure the total force due to the proton's nuclear moments when placed in an inhomogeneous magnetic field and showed that the proton was not simply a nuclear Bohr magneton. Realizing that extreme sensitivity was needed for measuring the force obtained, the problem was discussed with Mr. Sam Worden of Worden Laboratories, Houston. A relatively sturdy, yet quite sensitive analytical balance, was fabricated by Mr. Worden out of quartz. The size of the balance is of the order of two centimeters across and some four and a half centimeters high. Weighing a two gram sample, the balance has a sensitivity in the ten microgram range. Thus with such a sensitive balance the force due to diamagnetism and even the force caused by paramagnetic impurity ions in a crystal could be measured. In fact with sufficiently high magnetic field gradients paramagnetic forces due to the nuclei themselves should be large enough to be measured at low temperatures. Therefore the task was to incorporate this quartz balance into an experimental setup so as to utilize all its sensitivity. Many problems arose most of which have already been solved, all of them shall be discussed in this thesis.

Results of the gross magnetization of a single crystal of KI from 295 °K down to 2.5 °K and gross magnetization of a single crystal of LiF from 295 °K to 1.49 °K are given. From these results estimates are made of the concentration of paramagnetic impurities in these crystals. Thus the role of such impurities on nuclear spin lattice relaxation time, $T_1$, can be subject to quantitative theory.
A. The Quartz Balance

The fact that, in addition to being very strong, quartz has an exceptionally low coefficient of thermal expansion makes it ideal for use in the construction of measuring devices of high sensitivity. One of the most common means of determining small forces accurately is that of measuring the elongation of a quartz spring. Thus a quartz spring was actually installed in a glass tube above the sample chamber so that the sample was hung directly from the end of the spring. However, the thermal expansion caused by room temperature changes as well as trouble from vibration from the pumps and the boil off from the helium bath prevented any consistent measurements. At this point Mr. Samuel Worden, an outstanding expert in quartz fabrication, was consulted. He suggested the use of a small analytical balance made entirely of quartz. Mr. Worden then made a balance for us which has a sensitivity in the 10 microgram range yet was more than able to support a 2 gram sample (Mr. Worden has since constructed several quartz balances which are many times more sensitive; in fact his greatest difficulty in making the balance we used was to keep its sensitivity down in the range of usefulness under our conditions).

The compactness of the balance allowed it to be easily installed in a brass housing at the top of the sample chamber. The delicate fineness of the quartz fiber used makes direct measurements of the balance's parts rather difficult. The general dimensions however
can be seen from the drawing in figure 1. Perhaps the relative size of the balance can be best realized in figure 2 by noting that the vertical brass rod on the left is only 4 3/8 inches long. It should be noted that the balance has two separate guards, or stops (e and f) so that its workings will not be damaged if too great a force is placed on it.

The balance mechanism pivots on two hinges (a and b) which are carefully constructed so that the swinging action is uniform. Both arms of the balance are finely drawn at points c and d so as to provide a bending action in the arms themselves. Thus the direction of the force on the arms is vertical thereby reducing unwanted torques on the hinges. The pointer p is skillfully braced to the cross arm so that it exactly follows any motion of the cross arm. Because of the stops, the pointer never swings more than 6 degrees from the true vertical position.

The balance is suspended by means of a diamond shaped loop which fits directly into the V-shaped brass hook as shown in figure 2. Thus by using such a suspension design, any shifting of the zero due to motion of the entire balance has been practically eliminated. Careful calibrations have been done and the balance has been found linear over the entire range measured (see the section of Results). The sturdiness of the delicate quartz is exceptional, the balance has held a 1.85 gram specimen and its counter weight continuously for periods of over 6 weeks without any observable changes in the sensitivity. The primary danger of breakage is due to the compressional forces placed on the balance arms when loading or
THE QUARTZ BALANCE

FIGURE 1
unloading the arms. It must be remarked that the arms have been snapped off a few times and Mr. Worden has been able to repair the balance. Of course the sensitivity must be recalibrated after any such repair.

B. Cryogenics

To obtain the various low temperatures used in the experiment, the sample was suspended in a glass tube inside the inner dewar of a two dewar assembly. The outer dewar contained liquid air and the inner dewar contained liquid helium. For the 81°K measurement the inner dewar contained an atmosphere of helium as an exchange gas. When lower temperatures than the normal 4.2°K boiling point of the helium bath were required, they obtained by pumping on the bath vapors with a mechanical pump. Measurement of the vapor pressure above the bath with a manometer made it possible to determine the temperature of the bath. Since these techniques are conventional in low temperature work, further details will not be given.

A diagram of the sample chamber is given in figure 3. It was a glass tube (G) of 1 inch outer diameter and 110.5 centimeters in length. The sample chamber was attached to the lower face of the 1/2 inch thick brass flange (A) over the top of the inner dewar, the connection was made by using a small brass flange and a housekeeper’s seal (H). The sample (S) was suspended from the balance by a nylon thread (N).
The quartz balance (c) was hung from a small brass hook which was 4 3/8 inches above flange (b). The hook was fastened on a small horizontal cross bar so that its position could be adjusted by means of a set screw (see figure 2). The entire balance was enclosed in a vacuum tight brass housing (c), which was fastened by means of a flange to the brass plate (b). This cover was 5 1/2 inches high with an inner diameter of 1 1/4 inches. It has three windows (w), all of which were 1 inch in diameter and wax sealed to the brass cover. Two of the windows were used to view the pointer arm of the balance, the third was in the top of the housing so that one could sight down the tube and check that the sample was swinging freely.

The pressure in the sample chamber could be measured and adjusted through a 1/8 inch pump line. For this a hole was drilled through a radius of the brass plate (b) and a thermocouple gauge (t) and a veeco valve (v) were then placed in the pump line.

The pointer of the balance was viewed by a traveling telescope (e) which had 18.5 divisions per millimeter of horizontal displacement of the cross hairs. Each division is itself divided into a 100 subdivision by a vernier on the drive shaft of the cross hairs. The telescope was mounted directly on the large brass flange plate (b) by means of two set screws so that the field of view could be adjusted as needed for the various magnetic fields used. The relative position of the telescope can be seen in figure 4; also in this picture the vernier can be noted, it is the wheel near the left end of the telescope.
PROCEDURE

The Gouy method itself is discussed in the Appendix A but a brief outline of the general procedure is in order.

The sample was suspended by a nylon thread which was attached directly to the specimen. This was done by drilling a very small hole some two millimeters deep in the center of an end of the cylindrical sample, then a slightly larger hole on the order of 1/2 millimeter diameter was drilled along a diameter of the specimen so as to perpendicularly intersect the first hole. The nylon thread was then pulled down through the top hole and a small knot tied in the end of the thread so that it could not slip through the center hole. The sample was hung from the balance arm. The length of the thread being chosen so as to place the specimen's lower end just between the upper edge of the magnet's pole faces.

The quartz balance was then carefully balanced by use of a glass counter weight and small copper wire riders as needed. Next the brass housing was carefully placed over the balance. It was at this point that the lateral position of the sample was checked to be sure it was swinging freely. This was periodically checked since the slightest touching of the sample against the wall of the chamber would completely destroy the accuracy of any measurement taken.

After this the sample chamber was leak tested and then carefully flushed with helium gas several times so as to remove any adsorbed
gases in the system. Finally the sample chamber was sealed off leaving a pressure of only a few thousand microns of helium in the chamber as an exchange gas.

Readings of the pointer's position were taken with the field off. The field was then brought to the desired value and the new position of the pointer recorded. The stability of the magnetic field for the different readings was checked by means of a rotating coil fluxmeter; current adjustments were made as needed so that the same field was used for all measurements.

Hence having calibrated the balance with known weights, the apparent change in weight of the specimen due to the magnetic field was calculated. Now by assuming that at room temperature all the force was due to the diamagnetic susceptibility, which is well known, the field gradient could be calculated. The diamagnetism is also assumed temperature constant. This then gave field values which could be used at lower temperatures where paramagnetic forces begin to affect the total force value. The equation used is (7) in Appendix A. The effect of impurities could be seen by taking the difference of the initial deflections from the several temperatures studied. From this an estimate of the paramagnetic impurity concentration was made.

Previous work with alkali halides has shown the paramagnetic impurity usually to be members of the iron group, mostly Fe$^{+++}$ ion. The susceptibility for ions of this group is given by Van Vleck as:

$$\chi = \frac{N G^2 q^2 S(S+1) J}{3 \beta k T}$$  \quad (1)
where

\( \Theta \) is the Bohr magneton

S is the spin quantum number

g is the spectroscopic splitting factor, or so called gyromagnetic ratio

k is the Boltzmann's constant

and T is the absolute temperature

For Fe\(^{3+} \) ions S is 5/2 and g is taken to be 2.

Hence by equating the paramagnetic force observed with the force calculated by using this expression for the susceptibility, the paramagnetic impurity concentration can be evaluated. The expression obtained by using equation (1) in the force equation (7) is:

\[
N = \frac{6 F_{ob} \kappa T}{\beta^2 [g^2 S(S+1)] A [H^2 + H_0^2]}
\]

(2)

where \( F_{ob} \) is the observed paramagnetic force, the other terms are defined either above or in the Appendix A. This gives at least an order of magnitude results.
RESULTS

A. A Calibration of Balance

The quartz balance was calibrated at room temperature by carefully adding riders of known weight and measuring the deflection due to them. This of course was repeated several times and the average taken. The calibration used in the calculations on the KI specimen was made using a standard 2 milligram weight.

Mr. Worden then replaced the arms and extended the pointer of the balance and thus increased the sensitivity. Then to get more precise measurement of the sensitivity and especially to check the linearity of the quartz balance, several weights were calibrated with a semi-micro balance.

The results are given in the following chart.
**TABLE 1**

Sensitivity of Quartz Balance

<table>
<thead>
<tr>
<th>Weight Milligrams</th>
<th>Deflection Verniers</th>
<th>Verniers per Milligram</th>
<th>Average Verniers/milligram</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 ± 0.08</td>
<td>680</td>
<td>340</td>
<td>340</td>
</tr>
</tbody>
</table>

Sensitivity was then increased as noted

<table>
<thead>
<tr>
<th>Weight Milligrams</th>
<th>Deflection Verniers</th>
<th>Verniers per Milligram</th>
<th>Average Verniers/milligram</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.96 ± 0.03</td>
<td>1368</td>
<td>1430</td>
<td>1430</td>
</tr>
<tr>
<td>1.76 ± 0.03</td>
<td>2490</td>
<td>1415</td>
<td>1415</td>
</tr>
<tr>
<td>2.69 ± 0.03</td>
<td>3862</td>
<td>1435</td>
<td>1435</td>
</tr>
</tbody>
</table>

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B. KI Single Crystal

The total deflections were recorded for the various temperatures used. Taking room temperature readings as being due solely to the diamagnetism, the change in deflection at the lower temperatures could be attributed to paramagnetic impurities. These deflection changes are plotted versus the reciprocal of the temperature (figure 6); the points in the helium range lie on a straight line. Since the nylon thread contracts as the temperature is lowered, the specimen changes its position in the magnetic field. Hence the field gradient changes which explains why the higher temperature points do not lie on this same straight line. By taking the slope line in the helium range where the nylon thread's length is constant a straight line is drawn to include the origin. These adjusted values of the deflection are then used to calculate the impurity concentration.
TABLE 2

Gross Magnetization of a Single Crystal of KI

<table>
<thead>
<tr>
<th>Temperature (T) °K</th>
<th>1/T °K⁻¹</th>
<th>Total Deflection verniers</th>
<th>Change in Deflection verniers</th>
</tr>
</thead>
<tbody>
<tr>
<td>295</td>
<td>.003</td>
<td>1698</td>
<td>0</td>
</tr>
<tr>
<td>81</td>
<td>.012</td>
<td>1684</td>
<td>14</td>
</tr>
<tr>
<td>4.2</td>
<td>.238</td>
<td>1581</td>
<td>117</td>
</tr>
<tr>
<td>2.7</td>
<td>.370</td>
<td>1485</td>
<td>213</td>
</tr>
<tr>
<td>2.5</td>
<td>.400</td>
<td>1465</td>
<td>233</td>
</tr>
</tbody>
</table>
CHANGE IN DEFLECTION
VS
RECIPIROCAL OF TEMPERATURE
FOR
KI CRYSTAL

VERNERS

1/T IN (°K)^-1

FIGURE 6
C. LiF Single Crystal

The total deflection measured at several temperatures are listed. As with the results on KI, the change in deflections as compared to the room temperature deflection are plotted versus the reciprocal of the temperature. Figure 7 shows that the points in the helium range lie on a straight line, with the exception of the point at 2.7°K. However this point was taken as the bath temperature was being lowered so it is quite possible that the sample's temperature was still slightly higher and a temperature of 2.9°K, which would fall on the line, is quite likely.

Again the straight line of the helium range is shifted so as to include the origin. The impurity concentration is calculated with these adjusted values.
### TABLE 3

Gross Magnetization of a Single Crystal of LiF

<table>
<thead>
<tr>
<th>Temperature (T) °K</th>
<th>$1/T$ (°K)$^{-1}$</th>
<th>Total Deflection verniers</th>
<th>Change in Deflection verniers</th>
</tr>
</thead>
<tbody>
<tr>
<td>295</td>
<td>.003</td>
<td>2993</td>
<td>0</td>
</tr>
<tr>
<td>81</td>
<td>.012</td>
<td>2968</td>
<td>30</td>
</tr>
<tr>
<td>4.2</td>
<td>.238</td>
<td>2878</td>
<td>120</td>
</tr>
<tr>
<td>2.7</td>
<td>.370</td>
<td>2850</td>
<td>148</td>
</tr>
<tr>
<td>2.4</td>
<td>.417</td>
<td>2830</td>
<td>168</td>
</tr>
<tr>
<td>1.49</td>
<td>.670</td>
<td>2761</td>
<td>237</td>
</tr>
</tbody>
</table>
CHANGE IN DEFLECTION
VS
RECIPIROCAL OF TEMPERATURE
FOR
LiF CRYSTAL

VERNIERS

\[ \frac{1}{T} \text{ in } \text{('K)}^{-1} \]

FIGURE 7
DISCUSSION

The $1/T$ dependence of the observed paramagnetism, as shown in figures 6 and 7 are in accordance with the Curie Law. Considering the paramagnetic impurity to be Fe$^{+++}$ions, the impurity concentration would be $7.4 \times 10^{16}$ ions per cc. in the KI crystal, and $1.3 \times 10^{16}$ ions per cc. in the LiF crystal. These calculations assume a $g$ value of 2 but we note that a $g$ value of 4.27 for Fe$^{+++}$ions as a paramagnetic impurity in glass has recently been reported $^{10}$. These higher values are said to be due to spin orbit effects whereby the spin may prefer to align itself parallel to certain crystal directions. Though in the Alkali Halides such effects would not be expected $^{11}$. It is hoped that electron resonance studies will be done on these specimens in the near future here at Rice.

If $S$ is taken to be the nuclear spin and $\beta$ is a nuclear Bohr magneton then equation (1) can be used to calculate the expected nuclear paramagnetic susceptibility $^{12}$. From this it is possible to compute the paramagnetic deflections which one should expect. It was found that with the relatively low fields used, the deflections should be of the order of 33 vernier divisions for I$^{127}$ at 4.2°K.

The deflections expected for Li$^{7}$ at 4.2°K is some 41 vernier divisions. It should be noted that though in this latter case the spin is smaller the sensitivity of the balance had been improved by a factor of over 4. At present the relative error is too large to make these measurable, however several improvements are being made which should allow these nuclear deflections to be observable.
As with most new experimental systems many problems were encountered, some were quickly solved, others were more difficult to eliminate and a few still remain. The first difficulty arose from air condensing on the specimen at low temperatures whenever the brass cover was removed for rebalancing. It was realized that the cover could only be removed at room temperature. Moreover, the sample chamber was sealed off from the helium bath to keep air from condensing on the sample during liquid helium transfers, and also to control the buoyancy force by adjusting the pressure of the exchange gas. For some time we were plagued with leaks in the sample chamber several of which only appeared in the helium range. However by using the housekeeper seal with a flange and O-ring the leaks were finally eliminated.

Then came the problem of attaching a nylon thread to the specimen. At first attempts were made using various stopcock greases to glue a nylon button to the top of the sample, but none of the greases would hold throughout the entire temperature range needed. Next a glass cradle was made for the crystal. Not only was it relatively heavy but the glass was very paramagnetic and was washing out any effects of the sample itself. Then the previously described (see experimental procedure) method of directly attaching the thread was tried and found quite satisfactory.

One of the worse problems has been vibrations due to pumps, diesel and general background due to machinery about the building. They cause the sensitive pointer to oscillate and render measurements quite hard to obtain. Much work has been done to eliminate
this, shock mounts were tried. For a time a section of the pump out line was replaced with a heavy rubber hose so as to uncouple vibrations from the system, however these things did not appreciably help. At present if great care is taken by the observer so as not to shake the platform above the magnet, then much of the vibrations are removed.

By considering the thermal expansion of nylon (13) it is seen that the thread contracts some 7 millimeters in going from room temperature down to helium temperature, thus shifting the sample's position in the magnetic field. It is realized that in the future a quartz fiber must be used to attach the specimen to the balance. Another real problem for some time has been the inconsistency of the zero readings. It was suggested by Mr. Worden that if the hook on the counter weight was not fine enough then the position of the weight could change thereby changing the zero point. Making the hook much finer may well eliminate this difficulty.

At first an unusual exponential growth of apparent paramagnetism was observed. The force was much too large to be caused by any nuclear effects moreover its time constant was some $10^4$ times too long for electronic systems. It just simply did not correspond to any expected forces. Immediately the magnet's current values were checked but they seemed constant. However upon closer observation it was found that the magnetic field was indeed undergoing a slow consistent decrease which changed the field gradient over the sample. This relatively small field change
decreased the diamagnetic force such that the net deflection indicated the presence of paramagnetism. The problem was lessened by carefully monitoring the magnet's field with a rotating coil fluxmeter. But this is by no means the final solution since with such high sensitivity a field change of one hundred gauss will cause a corresponding deflection change of about 32 verniers. Hence a more accurate method for measuring the field is needed, perhaps a NMR probe. The magnet's controls are too coarse to allow fine adjustments on the current which makes the need for very exact field measurements essential. This is by far the greatest problem remaining since as higher fields are used the field gradient becomes more sensitive to small field fluctuations.

The fact that the quartz balance gives a linear response to changes in forces is very important. This removes any worry of inconsistency due to structural changes in the balance. The balance has from the first been remarkably strong yet agile. The uses of such a sensitive instrument are unlimited, its applications in solid state research alone are vast. Certainly this fine research tool will open the way for many projects in the future.
CONCLUSIONS

The paramagnetic impurity concentrations of the two crystals studied are within the range previously reported for alkali halides \(^{(8)}\) \(^{(14)}\). The outstanding point of these experiments is not the values obtained for the impurity concentration but rather the fact that a direct quantitative measure of the impurity could be made. The utilization of the Gouy method to make such measurements indicates the sensitivity of the system. The quartz balance has proven itself a true research instrument. Of course several refinements need yet to be made in order to use the full sensitivity of the balance.

Replacing the nylon thread with a fine quartz fiber will greatly eliminate the changing of the sample's position in the magnetic field. Slight modifications may be necessary in the brass hook to further lessen the shifting of the zero position of the pointer. In the future the specimens should be longer so as to get higher field gradients across the length of the sample. However the primary difficulty at present is the instability of the magnetic field. The rotating coil fluxmeter does not give sufficient accuracy in the field measurements. In addition the magnet's controls are too coarse, rendering fine adjustments extremely hard. At present the force due to nuclear magnetization is no larger than the maximum errors. But with these further improvements the full sensitivity of the quartz balance should enable nuclear magnetization forces to be easily measured.
The applications of such a sensitive research instrument is unlimited, the quartz balance will not only advance an entirely new method of studying nuclear magnetization of materials, but also open a completely new means of studying solids.
The Gouy Method

In the Gouy method (15) for measuring the susceptibility the substance being studied must be in the form of a rod of uniform cross section. The specimen is suspended vertically from one of the arms of a balance, in this case the sensitive quartz balance. The sample is suspended so that the lower end is in a region of high magnetic field intensity, while the upper end is in a considerably lower field intensity region, thus giving a large field gradient along the sample. Now the magnetic force $dF$, acting on an element of a solid specimen of length $dx$ and volume $dv$ is given by

$$dF = \frac{K_2 - K_1}{2} \left( \frac{dH_x^2}{dx} + \frac{dH_y^2}{dx} + \frac{dH_z^2}{dx} \right) dv$$

where $K_2$ and $K_1$ are the respective volume susceptibilities of the specimen and the surrounding exchange gas, $H_x, H_y,$ and $H_z$ are the components of the field in the region lying between $X$ and $X + dx$. Considering symmetry it is seen that $H_x, H_y, H_z$ and $\frac{dH_x^2}{dx}, \frac{dH_y^2}{dx}, \frac{dH_z^2}{dx}$ must be very small, thus

$$dF = \frac{K_2 - K_1}{2} \frac{dH_x^2}{dx} dv = \frac{K_2 - K_1}{2} \frac{dH_x^2}{dx} A \, dx$$

where $A$ is the area of cross-section of the specimen.

Hence the total magnetic force acting on the whole sample is

$$F = \frac{K_2 - K_1}{2} A \int_{H_0}^{H_0 + H} \frac{dH_x^2}{dx} dx = \frac{K_2 - K_1}{2} A \left[ H^2 - H_0^2 \right]$$

By using helium for the surrounding exchange gas, $K_1$ may be made negligible.
Now this force $F = g \Delta W$ (6) where $g$ is the gravitational constant and $\Delta W$ is the apparent change in the weight of the sample on turning on the magnetic field, hence the final form of the equation is

$$g \Delta W = \frac{K_2}{2} A [H^2 - H_0^2] \quad (7)$$

Thus the value of $K_2$ is experimentally determined; moreover, knowing the density $\rho$ and Molecular weight $M$ of the specimen, the molar susceptibility may be computed by

$$\chi_m = \frac{KM}{\rho} \quad (8)$$
It was decided that a brief note on buoyancy force should be included. Of course anytime a substance is suspended in a medium it experiences a buoyancy force equal to the weight of the medium it has displaced i.e. Archimedes Principle. Realizing that this could be important especially at lower temperatures where the density becomes large, some preliminary calculations were done as follows:

\[ f = \rho V \]  \hspace{1cm} (9)

where \( f \) is the buoyancy force due to the exchange gas in the sample chamber

\( \rho \)  is the density of the exchange gas

\( V \)  is the volume of the sample

Since the pressures used are low one can assume that the exchange gas obeys the ideal gas law and thus equation (9) becomes:

\[ f = \frac{PMV}{RT} \]  \hspace{1cm} (10)

where \( p \) is the pressure of the gas

\( M \) is the molecular weight of the gas

\( R \) is the universal gas constant

and \( T \) is the absolute temperature of the exchange gas

In this experiment the exchange gas was helium and at 4.2°K the pressure was some 120 microns in the sample chamber. Thus equation (10) gives a value of 1.09 micrograms for the buoyancy force.
Considering the present sensitivity of the system it can be seen the buoyancy force may be neglected. However after further improvements are made this force will certainly become important.
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