

i.e. their magnetic susceptibilities are inversely proportional to the abs. temp.

$$\chi = C/T$$

where C is a const. called the Curie const. I shall briefly indicate how this inverse dependence on temp. is explained

Let us take some magnetic salt, ~~say~~ Manganese ~~say~~ sulphate. It is of the Mn^{++} ion type contributes to the magnetism. There are two ways in which

this magnetism may arise. As we all know the Mn^{++} ion must consist of a large no. of electrons, relative in 1. orbit; each electron, being having a spin relative to a spin

in an orbit is equivalent to a current circulating in the orbit. Opp. direction, and will therefore behave as an elementary magnet. But it so happens that the different electrons' orbits are coupled in such a manner as to exactly neutralize one another's effect, so that the magnetism one can say is zero

and an angular momentum of $\sqrt{5/2}$ units.

These actual values for the magnetic moment ~~are not~~ do not interest.

For the present we will merely use the fact that the M_{n++} has a certain magnetic moment, which is half

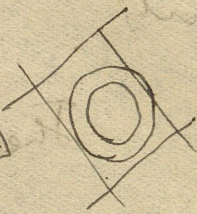
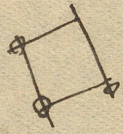
the for the spins of some of its electrons. If now we place a

magnesian salt in a magnetic field, these elements, magnets will tend to

place themselves along the field. This will however be hampered by thermal agitation, which will be greater

~~the higher the temp.~~ At A

statistical equilibrium will be restored, in which there will be more proportion of most spins along the field than along the other direction. The result is that



disturbing its neighbours. But - in any
 case the exptal observation that ~~the~~
 the manganese salts do obey, nearly
 the Curie law, shows that the
 magnetic moments are ^{practically} free to ~~orient~~ ^{turn round} ~~themselves~~,
 and this freedom persists even ~~at~~
~~at~~ ~~low~~ ~~temp~~ ~~to~~ the lower ~~1-~~
 temperatures ~~attained~~ viz $1^\circ A$, since the
 Curie law is obeyed. ~~This is a~~

~~case~~ i.e. at $1^\circ A$ even though our
 degrees of freedom, eg. lattice oscillations,
~~the~~ rotation of the atoms as a whole,
 etc are more or less completely
 frozen, there is still ~~some~~ freedom
 for the electrons to orient themselves.

~~Suppose now~~ In the absence of a
 mag. field (i.e. spin axis will be chaotic
 i.e. ~~chaotic~~ ^{orientations} ~~random~~ (i.e. why
 be oriented at random,
~~there is no~~ ~~orient~~ magnetization in the
 the salt of ~~has~~ no permanent magnetism)
 salt is ~~supported~~ ^{is kept} in a helix ~~at~~ $1^\circ A$.

when the field is put on, the ~~order~~
spin align themselves along the field.
(since the temp is small the disturbance
~~will be~~ due to thermal agitation will
also be very small). i.e. we will

produce a regularity ~~from~~ of orientation
in a chaotic

producing a certain regularity ~~of~~ orientation

starting ~~from~~ a chaotic state: The physicists
would say that we are lowering
the entropy; ~~the result~~ whatever

~~the~~ phraseology we adopt, the
result should be a ~~rise~~ ^{momentary} rise in the temp.

of the salt. Momentarily it may reach even as high a value

as 7 or 8. Suppose now with the aid of ~~the~~
we have a ~~large~~ ^{small} amount of liquid helium at -1°

in a helium bath at -1° , the
temp. will be low put back

with the help ~~of~~ which and the heat will be conducted

away by the bath. The surrounding
bath will have the temp back to

1°. That is, starting with the manganese salt at 1° A, with its spins oriented chaotically, we have managed with the help of the magnetic field and the surrounding bath, to produce a regular alignment of the spins, ^{at 1°} and maintain the temp. at ^{1°} original value, viz 1°.

The physical world we have to do with is a mixture of order and disorder. The spins are in a state of disorder. The magnetic field is a means of creating order. The bath is a means of maintaining the temperature. The result is a lower entropy state. The entropy of the salt is heat-insulated. The amount of heat abstracted for the salt is the

If now the bath is removed, ^{now} ~~evacuated~~ it out ~~completely~~ and into a pump, and ~~suddenly~~ remove the salt is heat-insulated. If now the ^{magnetic} field is removed suddenly, the spins ~~moments~~ are disoriented, and will ^{soon} reach a chaotic ^{state of} orientation; The result will be a lowering in temp. ^{Since the salt is heat-insulated its entropy is said to be adiabatic. The entropy remains the same.} The amount of heat abstracted for the salt is the

of heat

Spinis is quite small, but - when the
 sp. heat of the salt at the low
 temp is also extremely small. (obv. is
 an inverse T^3 law), and so
 the fall in temp will be appreciable.

4 cal.
 10 per gram
 per gm.

By this method Giauque and
 Mc D. in Am. de Haas + Westra in
 Leyden have been able to reach
 temps as low as $.005^\circ$ Abs.
 I shall ^{postpone} discuss ~~the~~ ~~significance~~
 of these temps. to a later ~~part~~.
 part of the lecture.

We have seen that at 1° abs.
 the spinis is ~~entirely~~ ^{practically} free. But
 we have no reason to suppose that
~~the~~ this freedom is with persist-
 unaffected right up to absolute
 zero. If it were so, then when we
~~measured~~ ⁱⁿ the above ~~adiabatic~~ ^{diamagnetic}
 expt. we should have reached

abs. zero, which is impossible. We should suppose that at some low temp. θ , ^{or lower} than $\frac{1}{2}$, between 0° and 1° , the natural freedom of ~~rotation~~ ^{orientation} of the spin axes should

be considerably ~~less~~ hampered*) It is easy to picture a mechanism which will bring about this reduction of freedom at low temp. ~~It~~

It is in the crystal, the Mn ion should be surrounded by a ~~large~~ ^{and div.} ~~no. ions~~ ~~number~~ the sulfate ions ~~and water molecules~~ which are all electrically charged. Due to these charges there will be a strong electric field, and this at ordinary temps, in fact even at 1°A , the ~~spin~~ ^{spin} influence of these electric fields on the

random orientation \sqrt{me} spin is negligible
 when we go to a sufficiently low
 temp θ , the ~~for~~ electric part will
 exert ~~a strong~~ ^{an} ~~influence~~ ^{orientation} influence. This temp.
 θ , which would be a characteristic of
 the particular crystal will therefore
 determine ~~what low value of~~ temp.

RA will be
 a measure
 of the
 order

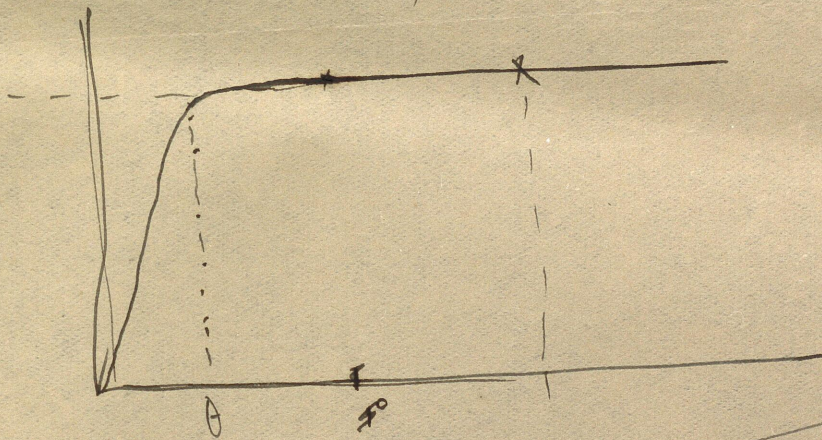
that can be reached of order
 degree. The lower the value of
 θ , the lower the temp. that can
 be reached of demagnetization.

It is not difficult to
 make the discussion more
 quantitative. For this purpose I
 will have to use the conception
 of entropy, which I have already
 mentioned. For the present purpose
 you may take it as a measure

of the degree of disorderliness present in the system, and would need to be a sufficiently good definition for our purpose. Consider again the manganese salt, and restriction of ourselves to the spins ^{orientations of} ~~magnets~~ of,

the as long as the spins are entirely free, the entropy will have the highest ~~max.~~ value, which is the

R



can ~~at all~~ temp. it up to 1°C, as we know especially

~~We do not~~

We further know that at some lower temp. θ , the freedom of orientation of the spins should be ~~off~~ restricted by the ~~system~~ equal elect fields in the crystal, until it be zero (complete restriction) at absolute zero. ~~ie. in this~~ the diagram of the entropy

diff- temp. will be more wheel like
this. (diag.) We can further visualize

~~initially can even go further~~ Suppose the
help of this diagram in whole process
of stirring ~~the~~ low temps. by the
magnetic method. Initially at 1° ;

↓ we start at this pt., and magnetize
Salt- initially we are lowering the
entropy to some low value, depend
on the field used + the ~~no degree~~
~~of magnetization~~ of the salt. We now
merely demagnetize the salt and remove
the mag. field. i.e. the entropy
should remain constant, and ~~should~~
~~reach a value~~ the temp. will have
to fall down to a value T_f , for
which the entropy at zero external
field is the same as ~~that at~~ the value
at 1° ~~at~~ the ~~initial~~
We can now see while the lower
the val of θ , the lower would be the
temp T_f .

We can proceed still further and get a quantitative estimate relation between various quantities involved. I have already discussed in a general way the ~~more~~ effect of a magnetic field, ~~and the~~ on the salt, and the Curie law of suscept. I have ~~assumed that~~ Sel is consider the mechanism in slightly greater detail. The Mn^{++} has an ~~more~~ $\mu = \frac{5}{2}$ angular momentum $5/2$, and a neg. mag. mom. of $\sqrt{5}$. In the presence of a magnetic field, as we have seen, this will be a key for the spin axis to orient along the field. ~~That is~~ ~~the~~ ~~existence~~ of the ~~orbital~~ ~~moment~~ ~~is~~ ~~not~~ ~~completely~~ ~~absent~~.

~~to be~~ To be sure that will
be various orientations

There are only ~~the~~ certain discrete
orientations possible, viz. when m_l
resolves itself into m_l \checkmark must

= $5/2, 3/2, 1/2, -1/2, -3/2, -5/2$

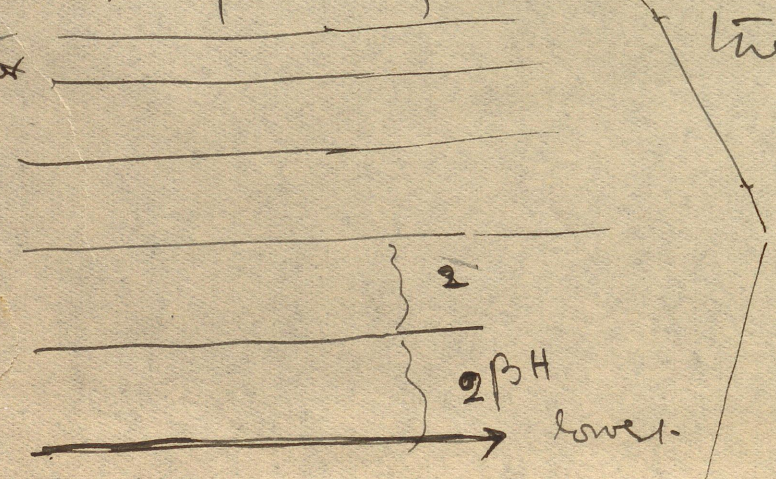
~~There are not at a given temp.~~

~~there there is however~~ a large number
of ions will be oriented
at $1/2$ transition, a slightly smaller no.
At the temp is lower,

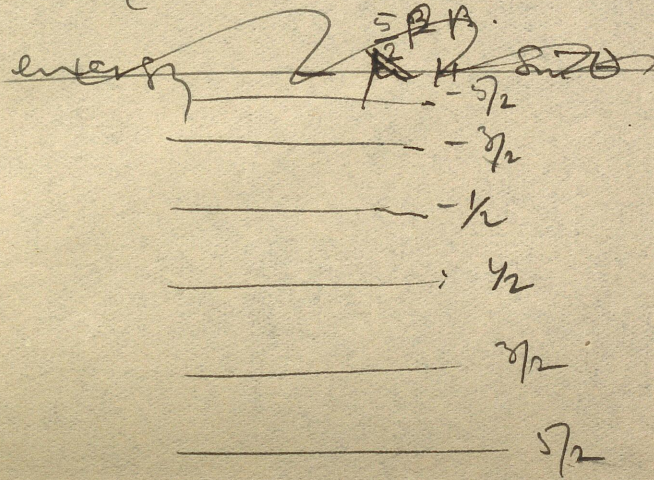
and the thermal disturbance become less

~~the~~ the $5/2$ orientations will ~~be~~ ~~more~~
energy will ~~be~~ ~~more~~ ~~likely~~ to be more

more probable, at the expense of
the other levels.



This is visualised better into the help of an energy level diagram. There will be six energy levels, at equally spaced. These ions have moments, and all are along the field will have a potential



the common interval being equal to $2\beta H_0 = E_1$

∴ The population among the

of these different levels, can be readily calculated from the

The distribution of ions among the different energy levels, at any given temp, will be given by the Maxwell Boltzmann law, and is well known.

If n_0 is the no of ions in the lowest level, then the consequent higher levels will be given by $n_0 e^{-E_i/kT}$, $n_0 e^{-2E_i/kT}$, etc.

The entropy can be readily

Calculated: I will ~~come to~~ ^{take up} the calculation
 a little later. But ^{at this stage} one can see
 introduce a calculation that the entropy
 should be much a fn of E/RT .
 where E is the energy difference between
 successive levels, $= 2\beta H$.

Let us assume ~~in~~ ~~250~~
~~external~~ ~~field~~ when we go to
 sufficiently low temperatures, the
 effects of the crystal field ~~will~~ on
 the orientation of the spins will
 be of a similar nature. i.e. there
 will be six ^{equally spaced} ~~orientations~~ energy levels,
 corresponding to the diff. possible orientations
 of the spins in the crystalline
 field. ~~Since~~ We have assumed the
 the restriction to freedom
 of orientation of the
 spins occurs at a
 certain temp. θ . i.e.
 the energy of ~~separation~~

bands; ~~between~~ the spin and the crystal
forces must be of the order of $k\theta$.

~~We have not yet defined θ precisely,
and we may ~~for convenience~~ define~~

In this ~~work~~. the ~~energy~~ separations E_s between the
successive energy levels in the above
diagram should be of the order of $k\theta$

Since we have not yet defined θ
~~rigorously~~ ~~precisely~~, we may ~~very~~ ~~indistinctly~~

~~any loss of rigour~~ ~~define~~ ~~take~~
~~take~~ ~~define~~ θ ~~take~~ this ^{relation} ~~take~~

$E_s = k\theta$, as ~~a~~ ~~definition~~ ~~of~~ θ
~~precisely~~ ~~precisely~~.

It can easily be seen that
the entropy at the final temperature
attained in the adiabatic experiment

say T_f ,

is ~~not~~ ~~large~~ corresponding a set of k equally
spaced levels, at intervals of $k\theta$; whereas

at the ~~begin~~ initial temp T_i and
when the magnetic field was incident, we

entropy was, ^{as} ~~the~~ correspond to
a space of interval of $2\beta H$.

$$S_i = f \left(\frac{2\beta H}{kT_i} \right)$$

$$S_f = F \left(\frac{k\theta}{kT_f} \right)$$

Since the two entropies should
be equal we have the extremely
simple relation

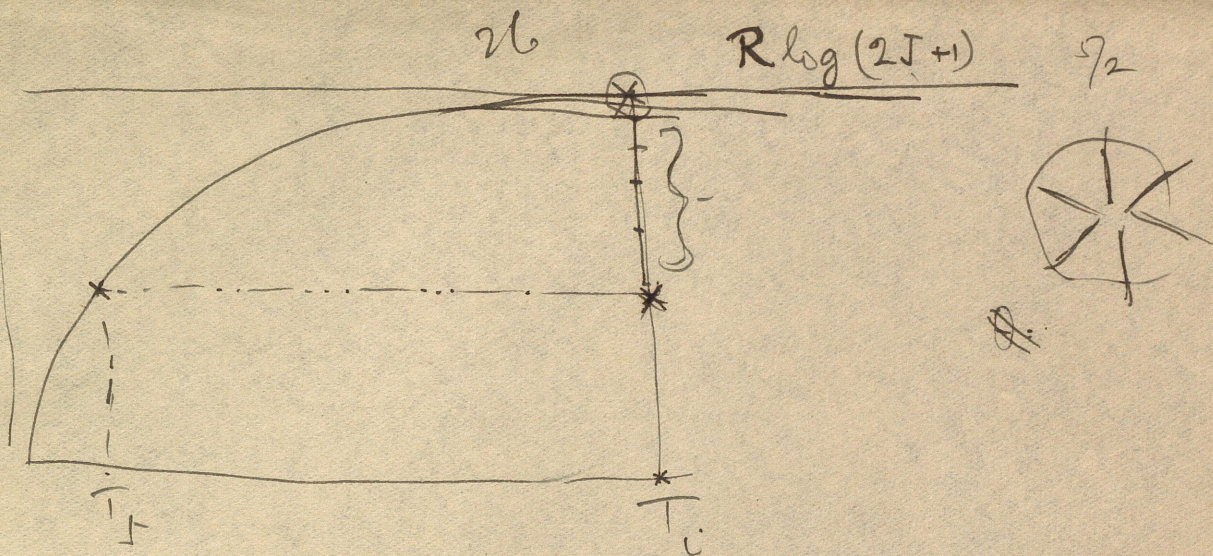
$$\frac{2\beta H}{kT_i} = \frac{k\theta}{kT_f}$$

$$\text{or } \frac{T_f}{T_i} = \frac{k\theta}{2\beta H}$$

The final temperature reached should
be ^{only} related to initial temp., & inversely
to the field H .

~~This relation has been~~ ~~verified~~
~~starting with~~ various initial
temperatures, and fields, the final temp
can be determined; and this relation
has been fully verified.

From Boltzmann's
 proportionalities
 we can
 calculate
 in case of
 $\frac{k_B}{2J}$



We have till now avoided the ~~area~~
 actual calculation of entropy; by adopting
 a very useful dodge. The calculation
 however is very simple. ~~On the~~
~~assumption~~ we ~~take~~ the ~~only~~ entropies
 we need to know about ~~are~~
^{external.}

- (1) the entropy ~~at the~~ in ^{external.} zero field
 at different temps. ~~(which is the~~
 i.e. the calculation of the curve
 drawn here. ~~the~~
- (2) the entropy at the initial temp.
 under different ~~at~~ fields.

the calculation of ^{under} ~~the~~ entropies
 in both cases ~~it reduces~~ reduces to
 calculating the entropy ~~corresponding~~ a
 system of 6 equally spaced ~~spaced~~

levels at a given temp. T .
 Let E be the separation.
 We can do it in two ways. We

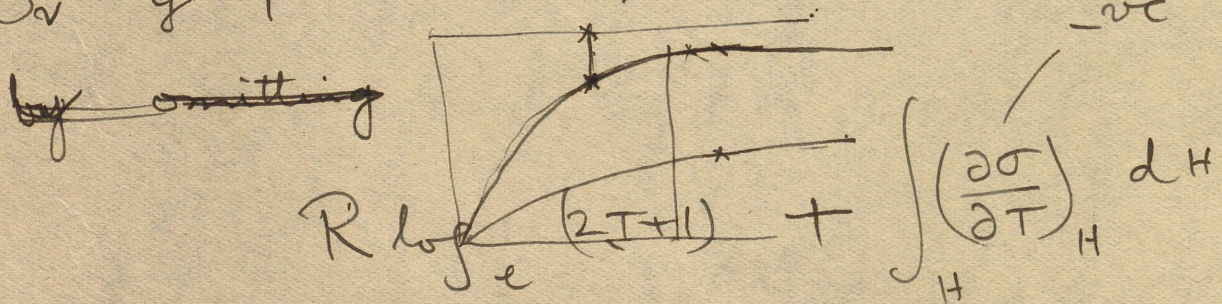
~~can treat each of the separation~~
~~We can either from the known~~
 distribution of the vis amount
 the different levels, when we obtain

When there is no splitting, when $E = 0$ the
 entropy should be equal
 to $R \log(2^{\frac{5}{2}} + 1)$

$$S = R \left[\log_e Q + T \frac{d}{dT} \log_e Q \right]$$

$$Q = 1 + e^{-E/RT} + e^{-2E/RT} + e^{-5E/RT}$$

Or if you are physicist you can calculate
~~by omitting~~



Both ^{me} methods yield ^{of} course ~~the~~ similar results.

We have neglected lattice effects etc.

Before proceeding further I shall describe some of the results obtained. Much of the work has been done in this laboratory. By G. A. & his coll. in America, de Haas in Leyden, Simon ^(now at -) & Oxford. The results obtained are given in the following table

Subs.	
Fe in alim	.061
Al in Am. sulph.	.11
Sp sulph.	.22
Ti Co. alim	.013

Lowest temp. reached was with Ti Co. alim.

and was $.005^{\circ}K$ with a $T_c = H =$
 I am giving here only the char. temps θ , since θ ~~is~~ we have seen completely defines the entrop. temp. curve at ~~the~~ low temp for 0° to $1^{\circ} Abs.$

Before proceeding further I should make some remarks concerning the measurement of these low temps. ~~The gas temp~~ ^{to} about -1°

some day when ~~we~~ we may suppose
 of any part has been studied using
 all-diff-~~temp~~ ~~turning~~ temps or
 the thermodynamic scale, it should
 be easy to reduce the present
 experimental data to the new scale.

$$T = \left(\frac{\partial U}{\partial T^*} \right)_{H=0} \div \left(\frac{\partial S}{\partial T^*} \right)_{H=0}$$

~~When we have mentioned that~~
 In the preceding discussion

~~there is / We have~~ have neglected

the entropy due to the lattice vibrations.

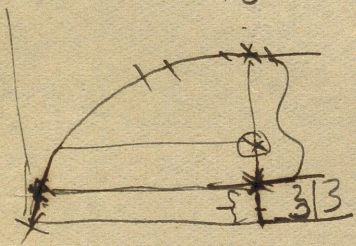
But because the magnetic entropy
 is much larger in comparison.

But - when we go to very low

temps, the mag. entropy being
 small the saturation, ~~we~~

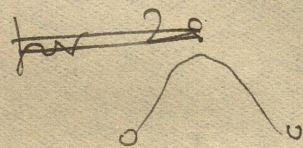
even in an ~~infinite~~ infinite field, we
 can not reach an entropy zero but a value

2×10^{-5} per c.c., which would correspond to
 an entropy under zero field at a temp
 0.005, even under favourable conditions.

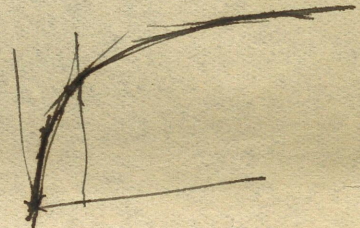


~~But~~ We have seen that knowing the
 value of the heat temp θ we ~~can~~ can
 construct the whole (temp-entropy) curve
 in the neighborhood of θ . That
 means we can predict all the thermal
 properties of the substance. e.g. sp. heat-
 \therefore we have merely to calculate for the

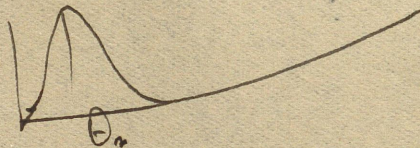
curve



$$T \frac{\partial S}{\partial T}$$

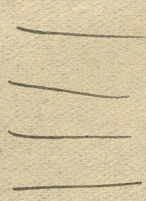


At very low temps very ~~to~~ small



There should be an anomaly near
 above the region $T = \theta$.
 This is ^{also} otherwise obvious
 with 200° etc.

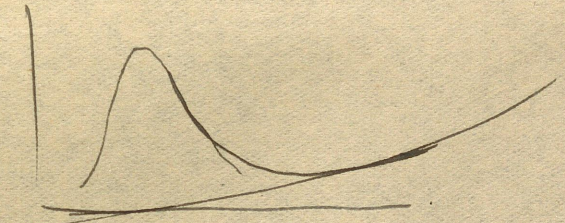
We have ³² here ~~det.~~ θ is the demagnetization ~~exp~~
~~therefore~~ we can get at this
 characteristic temp θ , which refers to



splitting of the energy levels
 under the crystal field,
 we can ~~get~~ predict all the
 various quantities ~~at~~
 in the neighborhood of

abs. zero, ~~intense~~ a shell ~~and~~ the
 demagnetization

~~The sp. heat~~



One is the theoretical
~~data~~ method of calculation
 the mag. and the
 asymmetry of crystal
 field ~~Results~~

gives ~~of~~ no practical help

show his
 two figures.

sp. heat anomaly extends further

Prediction of Simon }
 to help. 26 }
 22. }

i.e. for moments at about 3×10^5 it is possible to predict θ .

If we ~~can predict~~ μ can have some other method it would naturally be of great interest. We have one such in the magnetic anisotropy of hex crystals.

Taking for example Mn Am sulph. ~~it will~~ ^{it will} have 3 prin, which will be practically the same, since

Usual for a crystal the 3 principal axes are different. For example in cobalt salt α/χ

about 25%, for Cu salt about the same amount.

But if the magnetism is due solely to the ^{spin} electrons since they are free,

in which we direction the field is applied χ should be the same. i.e. to say the

crystal should be isotropic; this is of course the st approximation.

But as we have seen there is a χ ~~field~~ ^{restriction} due to the crystal field; this one to which the three principal axes.

~~any~~ any such ~~measurement~~ measurement can not-
give us a higher accuracy than 1/2%,

Because
over
measures
fields
or not
accurate

whereas the deviation from the Curie
law value viz $\frac{C}{T}$ is of the order
of $\frac{1}{T}$ i.e. $\frac{.1}{300}$ or 1 in 3000.
0.03%.

The deviation of this order can not-
be measured even when we go to liquid
air temps. $\frac{1}{T} \sim \frac{.1}{100}$ or 1/10%
which is too small to be measured.
accurately.

We ~~have~~ can however ~~measure~~ ^{sustain}
at the quantities Θ_1, \dots , by the
following dodge. Suppose we ~~have~~ have

a direct method of measuring the
difference betw χ_1 and χ_2 and χ_1 and χ_3

then we obtain $\frac{C}{T} [\Theta_1 - \Theta_2]$

~~$\frac{C}{T} [\Theta_1 - \Theta_2]$~~

$$\frac{\chi_1 - \chi_2}{\chi} \times T = \Theta_1 - \Theta_2$$

$$\frac{\chi_1 - \chi_3}{\chi} \times T = \Theta_1 - \Theta_3$$

since we know χ to a good approximation

we know $\Theta_1 - \Theta_2$ and $\Theta_1 - \Theta_3$, and
from the relation $\sum \Theta_i = 0$, we obtain
the individual Θ_i 's

The calculation of Θ from Θ is simple.

If we take the exp. for the largest
suscep.

$$\chi_1 = \frac{C}{T} \left(1 + \frac{\Theta_1}{T} \right)$$

it can be rewritten, in view of the definition

of Θ/T , in the form

$$\chi_1 = \frac{C}{T - \Theta_1}$$

i.e. the form of this relation, ~~shows that~~
 Θ used in place of T , we get $T - \Theta_1$,
shows that the effect of the crystal field
which gives rise to the term Θ_1 , is
in effect equivalent to a magnetic
field whose magnitude H_s can be
readily calculated from Θ_1 .

~~When we~~
~~know H_s , we~~ i.e. the splitting of
the levels under the crystal field
is into n equally spaced ones,

2
50-10

in which is exactly the approximation we showed
 into. The energy difference between successive levels
 which we arrived to be equal to $R\theta$,
 is now seen, ~~to be equal to~~ from the
 above consideration to be equal to separation
 i.e. = $2\beta H_s$.

in a field H_s ,
 $\therefore \theta = \frac{2\beta H_s}{R}$,
 and knowing H_s , θ is known.

i.e. for the moment \checkmark
 $\chi_1 - \chi_2 / \chi$, and $\frac{\chi_1 - \chi_3}{\chi}$ at room temp
 we can predict θ , and \therefore all the
 thermal properties of the ~~system~~ χ
 in the neighborhood of abs. zero.

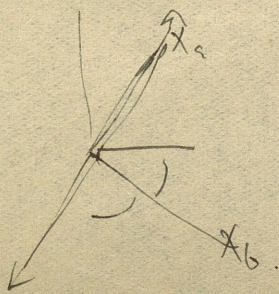
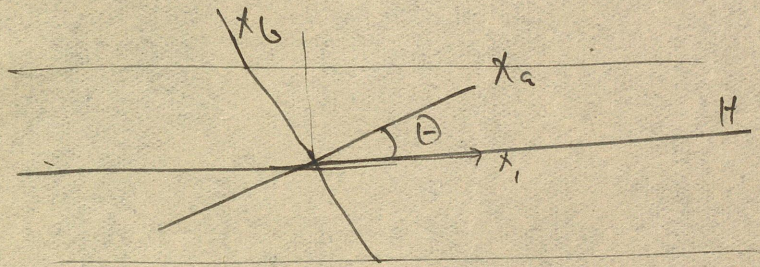
We now come to the experimental
 determination when a crystal



suspended in a mag. field, ~~the~~ in the
 horz. plane there will be two directions
 at right angles to each other which the force is = max
 for one of them the suscept is a min.
 = χ_0 and for the other the suscept is = $\chi_0 + \chi_1$.

~~the former set the for.~~

the crystal will tend to set itself in the X_a axis along field. If rotated from the position the crystal tends to restore it.



$$= c \frac{1}{2} (\chi_1 - \chi_2) \sim \frac{1}{2} (\chi_a - \chi_b) H \sin 2\theta$$

and has a max. value when

$$\theta = 45^\circ$$

10×10^{-6}
per gm.

On this may be based an elec. method

of measuring $\Delta \chi$.

Disturbing effect due to asymmetri

shape, and the surface distribution of magn.

changes. Elimination.

Abs. value:—

~~various~~ diamagnetic correction:

Residual values.

θ nearly same as obtained by Kurtz & S.

50
3 x 10⁻⁶
35
105
10⁻⁸

We shall come back now to the question of the lowest temperature ~~can be~~ attainable by ~~in this method~~ this method.

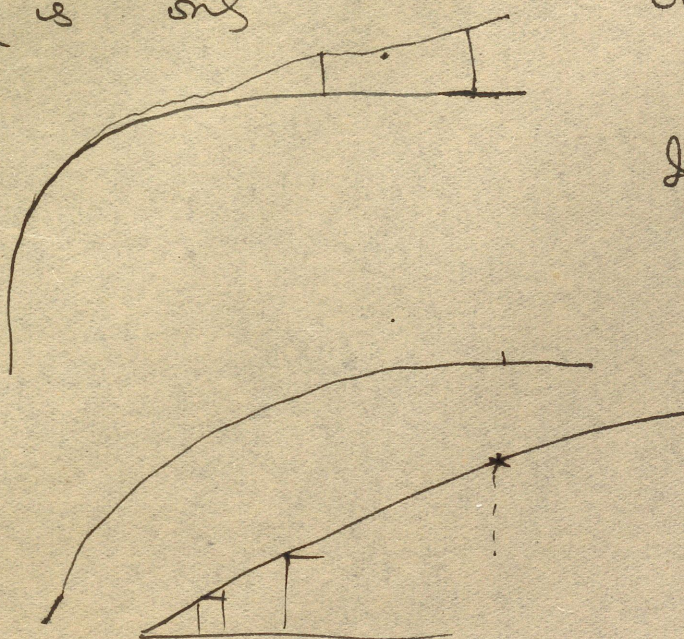
~~In the first we found~~ We found a substance in only one spot ~~mount-~~ substance. Starting

with 1° abs., we found that the lower limit attainable even ~~in the~~ ^{with an} ~~influence of~~ ~~the~~ ~~gas~~ ~~space~~ substance, a substance in ~~the~~ ~~gas~~ ~~space~~

cryst fields on the ~~gas~~ ~~space~~ is a mini,

~~eg. NaCl~~ eg. Ti Salt .
even in infinite fields k is only

the lowest temp. attainable 1.005° . This has already been obtained in practice



If we start ~~in the~~ ~~initial~~ ~~temp~~, we can of course go ~~to~~ ~~lower~~. But ~~we~~ ~~still~~ a lower limit. ~~Some~~ If the initial ~~temp~~ is so low

~~that the elec.~~ ~~is~~ ~~of~~ ~~the~~ ~~order~~ ~~of~~ θ , the ~~electrons~~ ~~are~~ ~~already~~ ~~in~~ ~~the~~ ~~orbital~~ ~~and~~ ~~the~~ ~~ext.~~ ~~field~~

In the spring of 1823 Faraday had the
misfortune to injure ~~one of~~ his eyes as the result
of an explosion. The records were "It was
from one of my tubes, and was so powerful as
to drive pieces of glass like pistol shot through
the window. However I am getting better and
expect to see as well as ever"

Dr Paris's account of the liquefaction of chlorine
L. F. Reads like a bit out of Pepys's diary.

"I had been invited to dine with
Sir Humphrey Davy on Wednesday, the 5th
Mar 1823, for the purpose of meeting the
Rev. Uriah Tonkin, the heir of his last
friend and Benefactor of that name.
On quitting my house for that purpose,
I perceived that I had time to spare,
and I accordingly called on my way
at the Royal Instn. Upon descending into
the laboratory I found Mr Faraday engaged
in expt on chlorine and its hydrate
in closed tubes. It appeared to me
that the tube in which he was

operating upon this substance contained
some oily matter, and I rallied him
upon the carelessness of employing sealed
vessels. Mr F, upon inspecting the tube,
acknowledged the justice of my remark,
and expressed his surprise at the circum-
stances; in consequence of which he immedi-
ately proceeded to file off the sealed end
when, to our great astonishment, the
contents suddenly exploded and the
oily matter vanished.

Mr F was completely at a loss to
explain the occurrence and proceeded to
repeat the expt. in a view to its
elucidation. I was unable, however, to
remain and witness the result.

Upon mentioning the circumstances
to Sir H Davy after dinner he appeared
much surprised; and after a few minutes
of apparent abstraction, he said
"I shall enquire about this expt -
~~to-morrow~~ to-morrow."