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The magnetization of pure iron and nickel

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The saturation magnetizations of very pure iron and nickel have been measured absolutely by a force method at room temperature. The values are 217.6 and 55.1 emu/g (217.6 and 55.1 J T^{-1} kg^{-1}) respectively. The theory and reliability of the force method are investigated and discussed. New measurements have also been made by a relative method on the same materials at temperatures ranging from 4 K to above the respective Curie temperatures of iron and nickel. Reduced magnetization, temperature data have been derived and are compared with those already available for face centred cubic cobalt.

1. Introduction

Measurements on the magnetization of ferromagnetic or ferrimagnetic solids and its dependence on magnetic field and temperature give valuable information leading to knowledge relating to electronic structure in the solids. In the past, many sets of such measurements have been made, particularly on alloys (see, for example, Sadron 1932; Ahern, Martin & Sucksmith 1958; Crangle & Hallam 1963; Crangle, Kuznietz, Lander & Baskin 1969, for a wide variety of materials). Almost entirely, these measurements have been made not by absolute methods but relatively to the absolute measurements on iron and nickel made by Weiss & Forrer (1926, 1929). There has been for some years a need to repeat the work of Weiss and Forrer and to check its accuracy with the purer materials now available. This has been met to a large extent by the recent measurements of Danan and others (see Danan, Herr & Meyer 1968), who used the same experimental method, the transient induction method, as Weiss & Forrer.

However, a great majority of the work on metallic alloys and compounds has been and continues to be done by the so-called 'force' method first used on ferromagnets by Sucksmith (1939). There are several variations of the method, but they all depend on measuring the translational force experienced by a small magnetized sample when placed in a non-uniform magnetic field. Previous measurements have been relative because hitherto it has not been possible to measure a magnetic field gradient independently and absolutely with sufficient accuracy. The force method is particularly convenient because it is very easy to use and because it requires small samples. Metallurgical uniformity throughout the sample, control of specimen temperature and strong effective magnetic fields are then more easily achieved. One disadvantage of the method is that the relevant theory is not very clearly and reliably understood.

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For these reasons it seemed highly desirable to design an experiment to obtain a new standard of magnetization by the force method using the purest materials available and to compare the results with the most recent measurement by the induction method. This paper reports the results of such an experiment.

At the same time, the temperature dependence of the magnetization of pure iron and nickel, from 4 K to above their respective Curie temperatures, was investigated afresh, using the same specimens. This is particularly necessary in view of the recent measurements by Maglic & Shull (1969) on the temperature dependence of the thermal neutron magnetic scattering amplitudes of iron and nickel. These give information on the temperature dependence of the d-like component of the magnetization. The neutron measurements may be compared with data on bulk magnetization with a view to obtaining the s-like component by difference, but the bulk magnetizations must be known with sufficient accuracy for the difference to be of value.

2. Theory of the force method for measuring magnetization

The force acting on a magnetizable specimen situated in a (non-uniform) magnetic field may be calculated from the variation of its free energy with position. Stoner (1937) and Guggenheim (1936a, b) have discussed in detail the factors on which the free energy depends.

We consider the specimen to be a small isotropic ellipsoid. Stoner (1937) showed that for a single inductively magnetizable body, the magnetic contribution W to the total energy of the body in an external field H_e is

$$W = -\int_0^{H_e} I \,.\, \mathrm{d}H_e \text{ per unit volume of the body.} \tag{1}$$

This has been shown (Stoner, 1937) to be equivalent to the sum of three terms W_e, W_d and W_m which may be identified as follows:

external field energy $\qquad W_e = -\int \mathrm{d}(I \,.\, H_e),$ $\qquad\qquad$ (2)

demagnetization energy $\qquad W_d = -\dfrac{1}{2}\int \mathrm{d}(I \,.\, H_d),$ $\qquad\qquad$ (3)

self-magnetization energy $\quad W_m = \int H \,.\, \mathrm{d}I,$ $\qquad\qquad\qquad$ (4)

all are referred to unit volume of the body.

I is the magnetization of the specimen, per unit volume.

H_e is the field applied externally. In the present case it is a function of position.

H_d is the field produced by the pole density set up on the surface of the specimen due to the fact that it is magnetized. H_d is taken as being equal to $-DI$, where D is a constant called the demagnetizing factor and depends on the geometry of the specimen,
$$H = H_e + H_d.$$

The change in magnetic energy when there is an incremental change in specimen position is

$$\delta W = -\delta(\boldsymbol{I}.\boldsymbol{H}_e) - \tfrac{1}{2}\delta(\boldsymbol{I}.\boldsymbol{H}_d) + \boldsymbol{H}.\delta \boldsymbol{I}. \tag{5}$$

If we substitute for $\boldsymbol{H}$ and $\boldsymbol{H}_d$ in terms of $\boldsymbol{H}_e$ and $\boldsymbol{I}$ equation (5) becomes

$$\delta W = -\boldsymbol{I}.\delta \boldsymbol{H}_e \text{ per unit volume.}$$

It is assumed that the magnetization $\boldsymbol{I}$ is uniform throughout the specimen. If it were not so an integral over the specimen volume would be necessary.

Since the force acting on the specimen is given by the gradient of the free energy, we now write for the total force

$$\boldsymbol{F} = -\boldsymbol{M}.\nabla \boldsymbol{H}_e, \tag{6}$$

where $\boldsymbol{M}$ is the vector magnetization moment of the whole specimen. Writing equation (6) in its cartesian component form we have (neglecting the negative sign):

$$\left.\begin{aligned}
|F_x| &= M_x \frac{\partial H_x}{\partial x} + M_y \frac{\partial H_y}{\partial x} + M_z \frac{\partial H_z}{\partial x}, \\
|F_y| &= M_x \frac{\partial H_x}{\partial y} + M_y \frac{\partial H_y}{\partial y} + M_z \frac{\partial H_z}{\partial y}, \\
|F_z| &= M_x \frac{\partial H_x}{\partial z} + M_y \frac{\partial H_y}{\partial z} + M_z \frac{\partial H_z}{\partial z}.
\end{aligned}\right\} \tag{7}$$

The aim of the experiment was to derive $\boldsymbol{M}$ (and to relate it to unit mass of specimen) from measurements of $\boldsymbol{F}$ and $\nabla \boldsymbol{H}_e$.

These equations refer to the specific condition that the magnetization $\boldsymbol{I}$ is uniform throughout the specimen. It is not clear to what extent this condition might be violated in the case of a strongly magnetizable prolate ellipsoid situated in a transverse field gradient, and whether a variation in external field will be reflected in a like variation in magnetization. In any case, if the specimen is fully saturated and the magnetization is independent of field, no error should arise. Where magnetization depends linearly on field no error would be expected to first order, because of the symmetry of the specimen. If the dependence of magnetization on field has a strong curvature, some error might be expected but its magnitude is uncertain. In an actual experiment the extent of this possible error is usually limited by using small specimens, so that the applied field varies little over their thickness.

2.1. *Design of the experiment*

It is possible to simplify equations (7) considerably by suitable experimental design.

Let the x direction be horizontal and defined by the direction of the main magnet flux; and let the z direction be vertical.

Considerable care was taken to ensure that the boxed term in equation (7) strongly predominated over all the others. To this end the following were arranged:

The faces of the pole caps of the magnet were accurately flat over a large area and inclined to one another by a small angle only in the vertical direction, causing $\partial H_x/\partial z$ to be the largest gradient at the specimen position, which was the centre of the magnet.

The balance used for measuring the force was made about ten times more sensitive in the z direction (vertical) than in the other directions.

The experimental specimens were prolate ellipsoids freely resting on their holder, that would automatically aline themselves in the direction of the magnetic field, making $M = M_x$ and $M_y = M_z = 0$.

3. EXPERIMENTAL DETAILS

3.1. Absolute measurements

3.1.1. Determination of the gradient of the field

The electromagnet used was of high quality, made by Varian Associates. The pole faces were of diameter 30 cm and the gap between them was about 6 cm. The faces were optically flat and inclined to each other at an angle of 11.5′ in the vertical direction and accurately parallel horizontally. Under these conditions the maximum field gradient produced was about 5 Oe/cm, when the main field strength was about 10 500 Oe.

The magnetic field was stabilized to one part in 10^7. A temperature-compensated Hall-effect field sensor was situated in the magnetic field and this controlled the power supply of the magnet automatically. A field-dial field setting control permitted quick and accurate setting of field.

Field gradients were determined by point-by-point field plotting with a nuclear magnetic resonance (n.m.r.) field probe mounted on a micrometer carriage. Since small gradients were employed, good resonance signals were obtained. A natural water sample was used for resonance in fields up to 8 kOe, and deuterated water between 8 and 10.5 kOe. The nuclear factors for water and deuterium are known accurately (see Laukien 1958), and the conversion from resonance frequencies to field strengths could be made precisely. The factors employed were:

field/Oe = frequency/MHz × 234.88 for protons in natural water

field/Oe = frequency/MHz × 1530.1 for deuterium in D_2O.

The probe receiver coil was 5 mm in diameter, and the resonance signal was associated with its centre point.

An example of the variation of field with vertical position is given in figure 1.

The gradient $\partial H_x/\partial z$ was determined by observing the change in the n.m.r. frequency when the probe was moved exactly 1 cm in the vertical direction, and its value was assigned to the mid-point of the range. The gradient was slightly inhomogeneous and this procedure was repeated for three points around the specimen position. From these results, the value of $\partial H_x/\partial z$ at the position of the specimen was determined by interpolation, as shown in figure 2. The frequency meter used to measure the resonance frequency was calibrated against the very accurate 200 kHz
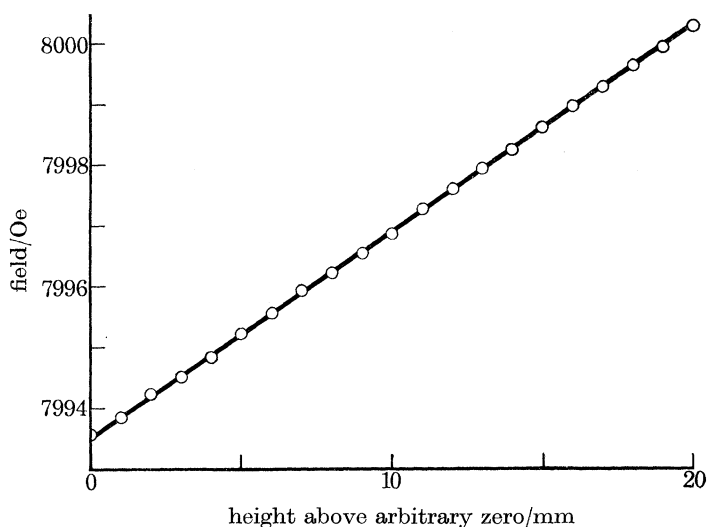
FIGURE 1. Magnetic field intensity plotted against vertical position along a central line within the gap of the magnet, for constant energization of the magnet.
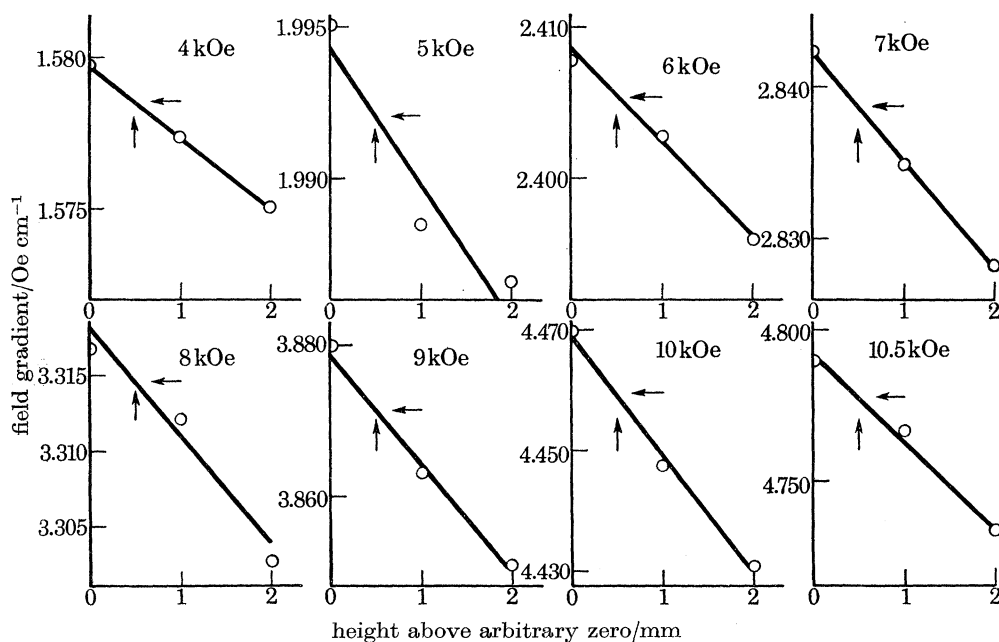

FIGURE 2. Measured field gradient in the vertical direction (dH_x/dz) shown as a function of position around the specimen location (indicated by arrows) for various settings of the magnet.

broadcast standard available in England. Under the most sensitive conditions, when the field strength was 8 kOe, a change of 0.002 Oe could be detected. Gradients were determined at eight fields between 4 and 10.5 kOe to an accuracy of about 0.1 %. It was the usual practice to check field setting of the magnet by use of the n.m.r. probe.

It was found that when the magnet was adjusted and its controls reset to restore the original field, the central field intensity was reproduced exactly. However, accurate gradient reproduction could only be accomplished by following a specific field cycling procedure prior to setting the field. This involved demagnetizing the magnet by reversing the direction of the field, increasing its magnitude to 10 kOe and reducing it to zero before then setting the required value in the original direction.

3.1.2. *Force determination*

A ring balance (Sucksmith 1939) in a modified form similar to that of Pepper & Smith (1965) was used to measure the force on specimens. The modified balance, which doubles the magnification of the original system, employs two plane mirrors attached to the ring, and a concave mirror on a separate fixed mount. The light beam passes through the moving mirrors twice. All reflecting surfaces were accurately figured. A force experienced by a specimen distorts the balance ring, which results in the deflexion of a light beam that is focused into a travelling microscope by the mirror system. The deflexion for a force of 1 dyn was about 0.30 mm and a change in force of $\frac{1}{30}$ dyn could be detected by the balance. The sensitivity was limited by the quality of the optical surfaces that could be achieved, and by the mechanical interference from vibrations in the building. That part of the force acting on the balance that was due to the action of the field gradient on the experimental specimen was found by difference after carrying out blank measurements with specimen absent and with field absent. The balance was calibrated in terms of known weights placed on a pan attached to the specimen support. The calibration was repeated many times throughout the course of the experiment, and its variation was small. The deflexion as a function of force was linear to better than 0.1 %. Weights were converted to forces, by assuming the acceleration due to gravity in the Sheffield area to be 981.3 cm s^{-2}.

The balance was made insensitive to any lateral forces on the specimen (x and y directions) by constraining the specimen holder with two flat spirals of the kind used by Sucksmith (1939). In any case it was established in a separate experiment that the lateral forces acting on an iron ellipsoid at the specimen position were certainly less than 0.02 % of the main force (F_z), and were therefore entirely negligible.

In the general case, where the magnetic axis of an ellipsoidal specimen is inclined to the field direction the specimen experiences a torque which will tend to reduce this inclination to zero. A collinear condition was realized by allowing the ellipsoidal specimen to rest in a slightly oversize coaxial horizontal hole in its holder.

The holder was alined into the field direction as accurately as possible and the specimen was allowed to complete the alinement automatically by moving slightly in the holder. In this way the balance experienced no torque, to which it could have been slightly sensitive; and as well the specimen became accurately alined in the x-direction.

The use of small pole gaps in a conventional magnet produces a reaction, the so-called image effect, between the specimen and the pole-pieces. This varies directly with the permeability of the pole faces and so depends on the state of saturation of the magnet. In their induction experiments Weiss & Forrer (1929) found that the flux due to images was sometimes as much as 50 % of that from the specimen alone.

In the present work no image effect was expected. The image forces are directed very nearly perpendicularly to the direction of the forces being measured and are almost completely self-cancelling for a central specimen position, when the reactions to each pole are compounded. The absence of the effect was verified experimentally by measuring forces under identical conditions on different specimens of the same material. The force per unit mass was constant to within 0.1 % for a considerable range of masses.

3.2. *Materials used*

Nickel I

Metals Research Ltd grade 1 single crystal nickel, 99.995 % pure. The largest single impurity in this specimen was carbon (0.0035 %).

Nickel II

Johnson, Matthey Ltd spectrographically pure polycrystalline nickel, 99.95 % pure. The chief impurities were carbon (0.03 %), oxygen (0.01 %) and nitrogen (0.01 %).

Iron I

Metals Research Ltd grade 1 polycrystalline iron, 99.994 % pure. The chief impurities were carbon (0.0035 %) and oxygen (0.002 %).

Iron II

Johnson, Matthey Ltd spectrographically pure polycrystalline iron, 99.95 % pure. The chief impurities were carbon (0.03 %), oxygen (0.01 %) and nitrogen (0.01 %).

All the specimens were fashioned into prolate ellipsoids, about 4 mm long and 2 mm in diameter. The nickel single crystal specimen was cut with its (111) 'easy direction' along the major axis.

3.3. *Measurement of magnetization above and below room temperature*

The measurements made above and below room temperature were not absolute but relative. The forces were measured by a method similar in principle but different in detail, and the balance was calibrated at room temperature by use of the absolute measurements already described. The maximum field strength available here was about 19 kOe.

For working above room temperature a small evacuated furnace was placed inside the gap of the magnet and surrounding the specimen. Temperatures well in excess of the Curie temperature of iron could easily be reached and maintained steadily. The junction of a calibrated Pt, PtRh thermocouple was embedded in the specimen support, in good thermal contact with the specimen itself. Below room temperature a conventional helium cryostat was used. Temperatures were measured in the usual way by resistance thermometers placed in good thermal contact with the sample.

4. Results and discussion

4.1. *Absolute measurements at room temperature*

The results of independent absolute measurements of magnetization made at 293 K in a range of field strengths for two samples or iron and two of nickel are shown in table 1. No significant variation with field was apparent at this temperature once technical saturation had been reached. The relative measurements of Foner et al. (1969) in strong fields suggest that the differential susceptibilities of iron and nickel, when beyond technical saturation, are too small to be observed in the present absolute measurements. The mean values given in table 1 for each element are for all fields beyond technical saturation and for both specimens.

TABLE 1. ABSOLUTE VALUES OF THE MAGNETIZATION OF TWO SPECIMENS OF NICKEL
AND TWO OF IRON MEASURED AT 293 K IN EXTERNAL MAGNETIC FIELDS
BETWEEN 4 AND 10.5 kOe

In taking averages, the measurements on iron at 4 kOe have been excluded. Absolute magnetizations are in emu/g measured at 293 K.

specimen	external field/kOe								mean
	4	5	6	7	8	9	10	10.5	
Ni I	55.10	55.00	55.04	55.11	55.13	55.14	55.14	55.05	55.11 ± 0.06
Ni II	55.20	55.15	55.15	55.10	55.06	55.08	55.20	55.16	
Fe I	(214.0)	217.6	217.8	217.7	217.5	217.8	217.6	217.8	217.6 ± 0.12
Fe II	(213.0)	217.4	217.5	217.7	217.6	217.7	217.6	217.6	

4.2. *Relative measurements below room temperature*

4.2.1. *Iron*

Magnetizations were measured at temperature intervals of about 50 K from room temperature downwards. Interpolated values are shown in tables 2 and 3.

TABLE 2. SUMMARY OF EXISTING ABSOLUTE MEASUREMENTS
ON THE MAGNETIZATION OF NICKEL AND IRON

Data for nickel below 300 K are derived from Kaul & Thompson (1969).
Magnetization/emu g^{-1}.

	temperature/K		
authors	293	77	0 (or 4)
nickel			
Weiss & Forrer (1929)	54.3	—	57.6
			(extrapolated)
Danan (1958)	55.2	—	—
Danan, Herr & Meyer (1968)	—	—	58.57 ± 0.03
present work	55.1 ± 0.1	58.4 ± 0.1	58.6 ± 0.1
Iron			
Weiss & Forrer (1929)	217.61	—	221.74
			(extrapolated)
Danan (1958) (same specimen as above)	217.35	—	—
Danan, Herr & Meyer (1968)	—	—	221.71 ± 0.08
present work	217.6 ± 0.1	221.4 ± 0.1	221.7 ± 0.1

4.2.2. *Nickel*

Very good relative measurements of the magnetization of nickel between 4 and 300 K have been published recently by Kaul & Thompson (1969). The data given in tables 2 and 3 for nickel below room temperature are the relative measurements of Kaul & Thompson standardized at 293 K against the present absolute measurements at that temperature. In the present work measurements on nickel at 4 and 77 K agree well with the data derived from Kaul & Thompson (1969).

4.3. *Summary of measurements of low-temperature magnetization*

The results of the present work are summarized and compared with previous work in table 2. Previous room temperature values for 288 K have been converted to refer to 293 K.

With the exception of Weiss & Forrer's original work on nickel there seems to be good agreement between the various determinations. We conclude that all the magnetizations given by Weiss and Forrer for nickel are too low by about 1.6 %.

The best values for the saturation magnetizations at zero temperature for the two elements, expressed in Bohr magnetons per atom are:

$$\text{iron} \quad 2.217 \pm 0.001,$$
$$\text{nickel} \quad 0.616 \pm 0.001.$$

4.4. *Measurements made above room temperature*

The spontaneous magnetization σ_{0T} of a ferromagnet is the value of its intrinsic, or domain, magnetization in zero applied field. Because of complications associated

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Values of reduced magnetization for f.c.c. cobalt taken from Crangle (1955) and similarly interpolated are included. Data for nickel below 300 K are derived from Kaul & Thompson (1969).

reduced temp. (T/θ)	reduced magnetization ($\sigma_{0,T}/\sigma_{0,0}$)			nickel		iron	
	Ni	Fe	Co	$T(\mathrm{K})$	$\sigma_{0,T}$ emu g^{-1}	$T(\mathrm{K})$	$\sigma_{0,T}$ emu g^{-1}
0.00	1.0000	1.0000	——	0.0	58.58	0.0	221.7
0.02	0.9997	1.0000	——	12.6	58.56	20.9	221.7
0.04	0.9990	0.9995	——	25.2	58.52	41.8	221.6
0.06	0.9983	0.9991	——	37.9	58.48	62.6	221.5
0.08	0.9974	0.9982	——	50.5	58.43	83.5	221.3
0.10	0.9962	0.9973	——	63.1	58.36	104.4	221.1
0.12	0.9952	0.9964	——	75.7	58.30	125.3	220.9
0.14	0.9939	0.9950	——	88.3	58.22	146.2	220.6
0.16	0.9925	0.9937	——	101.0	58.14	167.0	220.3
0.18	0.9911	0.9919	——	113.6	58.06	187.9	219.9
0.20	0.9892	0.9905	——	126.2	57.95	208.8	219.6
0.22	0.9870	0.9883	——	138.8	57.82	229.7	219.1
0.24	0.9846	0.9865	——	151.4	57.68	250.6	218.7
0.26	0.9822	0.9842	——	164.1	57.54	271.4	218.2
0.28	0.9797	0.9815	——	176.7	57.39	292.3	217.6
0.30	0.9768	0.9797	——	189.3	57.22	313.2	217.2
0.32	0.9737	0.9774	——	201.9	57.04	334.1	216.7
0.34	0.9703	0.9747	——	214.5	56.84	355.0	216.1
0.36	0.9664	0.9720	——	227.2	56.61	375.8	215.5
0.38	0.9624	0.9684	——	239.8	56.38	396.7	214.7
0.40	0.9578	0.9644	——	252.4	56.11	417.6	213.8
0.42	0.9527	0.9603	——	265.0	55.81	438.5	212.9
0.44	0.9476	0.9562	——	277.6	55.51	459.4	212.0
0.46	0.9420	0.9513	——	290.3	55.18	480.2	210.9
0.48	0.9334	0.9463	——	302.9	54.68	501.1	209.8
0.50	0.9268	0.9400	0.9320	315.5	54.29	522.0	208.4
0.52	0.9201	0.9341	0.9247	328.1	53.90	542.9	207.1
0.54	0.9123	0.9278	0.9169	340.7	53.44	563.8	205.7
0.56	0.9046	0.9211	0.9085	353.4	52.99	584.6	204.2
0.58	0.8966	0.9138	0.8995	366.0	52.52	605.5	202.6
0.60	0.8882	0.9057	0.8898	378.6	52.03	626.4	200.8
0.62	0.8802	0.8976	0.8808	391.2	51.56	647.3	199.0
0.64	0.8720	0.8881	0.8706	403.8	51.08	668.2	196.9
0.66	0.8633	0.8796	0.8579	416.5	50.57	689.0	195.0
0.68	0.8539	0.8692	0.8441	429.1	50.02	709.9	192.7
0.70	0.8419	0.8584	0.8302	441.7	49.32	730.8	190.3
0.72	0.8284	0.8462	0.8110	454.3	48.53	751.7	187.6
0.74	0.8129	0.8336	0.7989	466.9	47.62	772.6	184.8
0.76	0.7938	0.8187	0.7803	479.6	46.50	793.4	181.5
0.78	0.7711	0.8024	0.7616	492.2	45.17	814.3	177.9

TABLE 3 (*cont.*)

reduced temp. (T/θ)	reduced magnetization $(\sigma_{0,T}/\sigma_{0,0})$			nickel		iron	
	Ni	Fe	Co	T(K)	$\sigma_{0,T}$ emu g^{-1}	T(K)	$\sigma_{0,T}$ emu g^{-1}
0.80	0.7462	0.7844	0.7405	504.8	43.71	835.2	173.9
0.82	0.7200	0.7636	0.7158	517.4	42.18	856.1	169.3
0.84	0.6897	0.7406	0.6893	530.0	40.40	877.0	164.2
0.86	0.6603	0.7149	0.6616	542.7	38.68	897.8	158.5
0.88	0.6299	0.6852	0.6291	555.3	36.90	918.7	151.9
0.90	0.5964	0.6486	0.5924	567.9	34.94	939.6	143.8
0.92	0.5437	0.6013	0.5485	580.5	31.85	960.5	133.3
0.94	0.5142	0.5548	0.4949	593.1	30.12	981.4	123.0
0.96	0.4461	0.4948	0.4244	605.8	26.13	1002.2	109.7
0.98	0.3303	0.4078	0.3323	618.4	19.35	1023.1	90.4

	nickel	iron	cobalt
Curie temperature/K	631.0	1044.0	1390.0
$\sigma_{0,0}$/emu g^{-1}	58.58	221.7	166.1

with the domain structure, it is not possible to measure this quantity directly. It must be obtained by suitable extrapolation of magnetization measured in strong fields. At temperatures removed from the region of the Curie point, where the magnetic isothermals are linear, σ_{0T} may be estimated by extrapolation of the isothermals to zero field. For temperatures approaching that of the Curie point, however, this is not possible because of curvature of the isothermals. The extrapolation technique of Weiss & Forrer (1926), involving the use of curves of constant magnetization, was therefore adopted for this region. Thus, values of the spontaneous magnetization σ_{0T} at temperatures T up to the Curie temperature were obtained. Of the methods available for defining Curie temperature two were chosen. In the first, a graph of σ_{0T}^2 was plotted against T and the part of it having the steepest slope was extrapolated to the temperature axis. The second was the one described by Belov & Goryaga (1956) and by Arrott (1957). Graphs of H/σ_{HT} were plotted against σ_{HT}^2 for various constant temperatures. The temperature at which the linear graph of H/σ_{HT} against σ_{HT}^2 passed through the origin was taken to be the Curie temperature.

4.4.1. *Nickel*

A selection of magnetic isothermals for nickel 1 at the temperatures nearest to the Curie temperature is shown in figure 3. No differences could be found between specimens of nickel from the two sources. The values of the Curie temperature derived from the two methods are 631 ± 2 and 632 ± 2 K, respectively, agreeing well with the value of 631 K obtained by Weiss & Forrer but differing slightly from the value 627 ± 1 K given by Arajs (1965). However, Arajs defined the Curie temperature differently.

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Spontaneous magnetizations interpolated between the experimental points at regular values of T/θ are given in table 3. The values are all higher than those given by Weiss & Forrer. However, if all Weiss & Forrer's spontaneous magnetizations are scaled up by 1.6 %, there is good agreement between the two sets of data. In the region where the (σ_{HT}, H) curves show the most curvature, from about 490
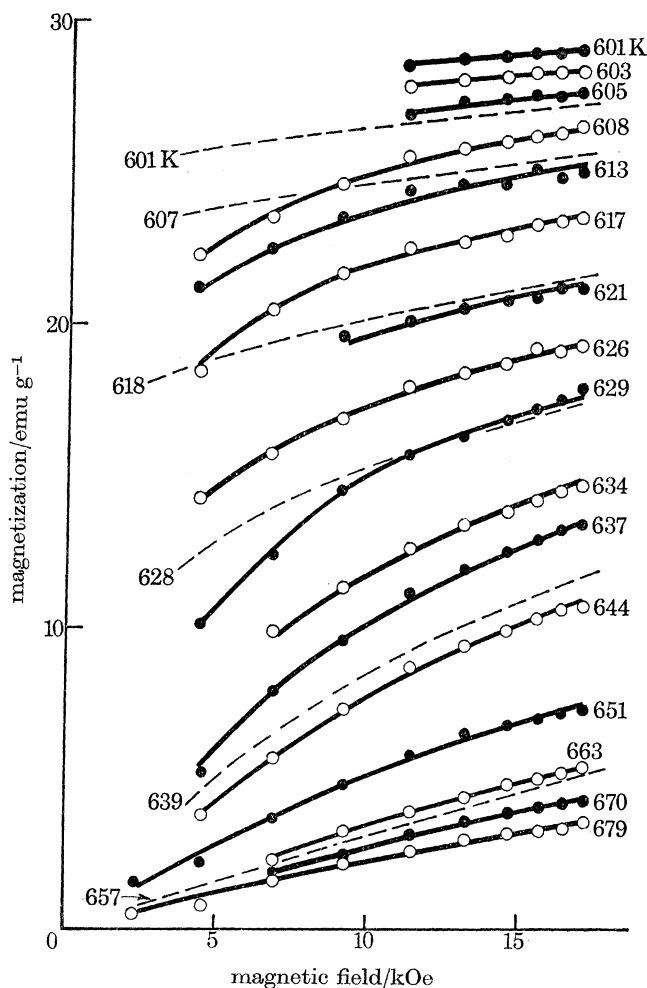

FIGURE 3. Magnetic isothermals for nickel measured at temperatures near the Curie temperature. The broken lines give a selection of data from Weiss & Forrer (1929).

to 630 K ($T/\theta = 0.94$ to 1), there is a difference in the shapes of the curves between the present work and Weiss & Forrer. The present curves agree at high fields with the scaled version of Weiss & Forrer's, but at lower fields (below $H = 10\,000$) they lie lower by several units of magnetization. It is to be expected from the theory given in § 2 that any doubts about the reliability of the force method will be strongest just where the differences occur. However, an estimate of the maximum possible

error suggests something much smaller than the difference found between the two investigations. As a precaution, data referring to the region of the difference were treated tentatively. They were used neither in this determination of the Curie point nor for the spontaneous magnetizations given in table 3.
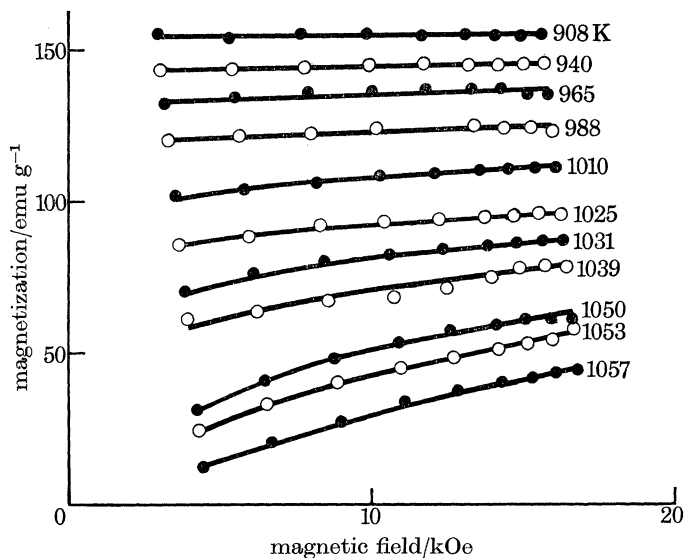

FIGURE 4. Magnetic isothermals for iron measured at temperatures near the Curie temperature.

4.2.2. *Iron*

Similarly, magnetic isothermals for iron near its Curie temperature are given in figure 4. Again, no differences could be detected between specimens of iron from the two sources. The data given are for iron I. The Curie temperature derived from the data was 1045 ± 3 K from the $(H/\sigma, \sigma^2)$ procedure and 1046 ± 3 K from the curves of constant magnetization. This result agrees with the value of 1044 ± 2 K given by Arajs & Colvin (1964). Potter (1934) quotes two values for specimens of iron from different sources. One, 1042 K, agrees with the present work but the other is 1035 K. Careful examination of the data given by Potter for the magnetization as a function of field and temperature shows that these data refer to the material with the lower Curie temperature. We are therefore doubtful about whether they refer to sufficiently pure iron.

Table 3 gives the new measurements of spontaneous magnetization for iron interpolated at regular values of T/θ.

We have examined the data given by Potter (1934) in detail and have found that if the temperatures given there are converted to the Kelvin scale and multiplied in the ratio of the Curie temperatures given respectively by Potter and by the present work, then the two sets of spontaneous magnetizations agree well. Also, having made these corrections to Potter's temperatures we found there to be

excellent agreement between the shapes of his (σ_{HT}, H) isothermals and ours. The method used by Potter to measure magnetizations was a force method different from that used at present. The important difference is that Potter's specimen was placed in an essentially uniform magnetic field and the measurement would seem to be largely immune from the slight uncertainties we have referred to that are associated with conditions where magnetization changes rapidly with field. This observation lends support to the view that the differences in isothermals referred to in the section on nickel are too large to be accounted for by possible errors in the force method.

4.4.3. *Law of corresponding states for iron and nickel*

Numerical values for the reduced magnetization $(\sigma_{0T}/\sigma_{00})$ of nickel and iron at regular intervals of the reduced temperature (T/θ) are given in table 3. The values given here are very similar to those which may be derived for nickel from the work of Weiss & Forrer (1926) and for part of the range for iron from Potter (1934). This is largely because in each case the errors apparent in the earlier work in the actual magnetizations for nickel and in the temperatures for iron disappear when reduced values are calculated. The differences in the reduced curves between iron and nickel remain and they appear to be real.

These data and similar information on other materials (see, for instance, Myers & Sucksmith 1951; Crangle 1955, for cobalt) should be explicable in terms of a basic theory of the magnetism of the materials. The measurements could be used to test such a theory. However, no such theory exists which is sufficiently detailed or which covers a significant proportion of the temperature range for which the material is ferromagnetic. The limiting cases of a completely localized Heisenberg ferromagnet (see, Van Vleck 1932) on the one hand and the simple band ferromagnet (see, Stoner 1951) on the other, both produce theoretical laws of corresponding states which do not fit the present experimental curves very well.

For purposes of comparison, reduced magnetizations for face-centred cubic cobalt have been included in table 3. These have been derived from the data of Crangle (1955) and interpolated for the same values of T/θ as for iron and nickel. Cubic cobalt is not stable in bulk form below about 690 K. There appears to be a close similarity between the reduced curves for f.c.c. cobalt and nickel.

Note on the conversion of the magnetic measurements from cgs to SI units

In translating to the SI system it is very convenient to consider the induction B which is related to the field strength H by

$$B = \mu_0 H,$$

where μ_0 is the permeability of free space.

Instead of a field of 10^4 oersted in the cgs (emu) system we write an induction (*in vacuo*) of 1 tesla in the SI system.

Similarly, specific magnetizations in emu g^{-1} (more exactly erg $Oe^{-1} g^{-1}$) translate into joule tesla^{-1} kilogram^{-1} in the SI system, without change in numerical value.

Mass susceptibility in emu g^{-1} (i.e. erg $Oe^{-2} g^{-1}$) becomes $J\, T^{-2}\, kg^{-1}$ in the SI system, with 1 emu g^{-1} changing to $10^4\, J\, T^{-2}\, kg^{-1}$.

In summary we have:

specific magnetization: 1 emu g^{-1} becomes $1\, J\, T^{-1}\, kg^{-1}$

mass susceptibility: 1×10^{-6} emu g^{-1} becomes $1 \times 10^{-2}\, J\, T^{-2}\, kg^{-1}$

field (meaning induction in free space): 10^4 Oe becomes 1 T.

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