

MAGNETISM AND THE STRUCTURE OF MATTER*

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THE first attempts at an explanation of magnetic phenomena were mainly concerned with the problem of action at a distance, but later the centre of interest shifted to the mechanism within the magnetized body which came into action under the influence of the external field. After the discovery by Oersted of the magnetic effect of an electric current, Ampère suggested in 1825 that a hypothesis of molecular currents might explain induced and permanent magnetization. At the time, only ferromagnetic phenomena were known, but the design of powerful electromagnets enabled Faraday to make the fundamental discovery that all matter is affected to a greater or less degree in a magnetic field. There are two broad types of behaviour: diamagnetic substances tend to move from the stronger to the weaker part of a non-uniform field and to set their longest dimension at right angles to the lines of force; paramagnetic substances move from the weaker to the stronger part of a field and set their length along the lines of force. Faraday showed that the resultant flux (lines of force per square centimetre) within a diamagnetic body must be less, while the flux within a paramagnetic body must be greater, than that in the external field. That means that the induced magnetization within a diamagnetic body opposes the inducing field, while that within a paramagnetic body reinforces the field.

Weber suggested in 1854 that if electric currents could exist within molecules, then substances might be divided into two classes according as to whether their molecules had a resultant magnetic moment due to circulating currents or not. Only the former could show paramagnetism. This is the basis of the Langevin theory. The atom is now known to be built up of particles of a certain mass and charge, the velocity and distribution of which can be varied under certain conditions. Magnetism is a property of these ultimate particles, because a moving charged particle is equivalent to a current in a circuit and therefore possesses a magnetic moment.

DIAMAGNETISM

Diamagnetism is due to induced currents within the atom, these induced currents taking the form of a modification of the existing motion of the electrons. The orbits precess about the field direction, and this extra electronic motion gives

rise to a magnetic moment the value of which depends on the field strength, the electronic mass and charge, and the projected areas of the electronic orbits. The gram atomic susceptibility (ratio of the intensity of magnetization per gram atom to the inducing field) is entirely governed therefore by the distribution of electron density in the atom. All atoms show diamagnetism, but unless the resultant angular momentum of the atom is zero in the absence of a field, paramagnetism or ferromagnetism will also be present and the diamagnetism is relatively unimportant.

The susceptibilities of the inert gases have been measured and compared with those calculated from spectroscopic knowledge of the electron density distribution. Other atoms or groups of atoms may attain zero resultant angular momentum in three principal ways. In *ionic compounds* the component atoms may give or accept electrons, so that the external shells of each are completed. This occurs, for example, in the alkali halides. The susceptibilities of such polar compounds are additive, but when the compounds are dissolved in water, only dilute solutions show additivity. In concentrated solutions the ions not only depolymerize the water, but also form hydrates and other complexes. The electronic structure both of the ions and of the water molecules is deformed, with a consequent change of susceptibility. The structures of light and heavy water and of water of crystallization are also being studied by measurements of susceptibility.

In *homopolar compounds* the atoms share electrons, thus completing their electron shells or pairing off their odd electron spins. The diatomic molecules H_2 , Cl_2 , Br_2 , etc., are diamagnetic because the electron spin of one atom is anti-parallel to that of the other. In O_2 , however, the electron spins are parallel, giving rise to a strong paramagnetism. Nearly all organic compounds are diamagnetic, and Pascal has shown that their molecular susceptibilities obey an additive rule $\chi_M = \sum \chi_A + \lambda$, where λ is a factor which makes allowance for the different kinds of valency bonds. This rule can be used for the determination of chemical constitution in doubtful cases, and for the study of polymerization. Complex compounds are frequently diamagnetic because the effective atomic number of the complex group is equal to that of an inert gas, but this alone is not a sufficient criterion. The state of the electrons taking part in the formation of chemical bonds

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is important. Measurements of susceptibility are now being used to investigate the constituents of natural products, including blood.

In *metallic compounds* the valency electrons become free electrons having a small resultant paramagnetism, while the positive metallic ions will be diamagnetic if their outer shell is closed. Thus many metals are weakly paramagnetic or diamagnetic. In some semi-metals such as bismuth, antimony and graphitic carbon, the binding electrons are not really free; their energy states bear a definite relation to the crystal structure and this results in high diamagnetism and large anisotropy, both of which disappear on melting or can be radically changed by the solution in the solid of small quantities of other elements.

Normally, diamagnetism is independent of temperature and of change of state, but a metal which becomes superconducting at very low temperatures always becomes also strongly diamagnetic. Except for a very small surface region, no flux can penetrate an ideal superconductor, the permeability being zero throughout the interior of the metal and changing from zero to unity in a region of about 1000 Å. width below the surface. The supercurrent, which exists only in this surface region, is according to the theory of London a stationary current dependent upon the presence of a magnetic field, similar to that in a large diamagnetic atom. In wires, films or particles of dimensions comparable with 1000 Å., the susceptibility is only a fraction of that of the bulk superconductor. Slater has suggested a molecular model for the theory of London on the basis of semi-bound electrons with very large wavefunctions, and explains the 'threshold field' as that value at which the Larmor precession energy becomes comparable with the 'atomic' energy.

In aromatic organic compounds there are electrons which occupy large plane orbits, and this results in a large molecular anisotropy. From the principal susceptibilities of single crystals of such substances, it is sometimes possible to determine the orientations of the molecules, or if the crystal structure is known to deduce the electron distribution in the molecule.

PARAMAGNETISM AND FERROMAGNETISM

Any atom or ion will be paramagnetic that does not succeed in completing its outer shell or in pairing off its electrons. The inner closed shells contribute only to a correcting diamagnetism. The resultant magnetic moment of the atom is measured in Bohr magnetons (μ_B) and is dependent upon the motion and distribution of the odd electrons, that is, upon their momenta. Electrons can have orbital (L) and spin (S) momenta, which combine to give a resultant angular momentum (J). All

of these are quantized, that is, they can only have certain values. The angle between the resultant angular momentum and the magnetic field direction can also only have $(2J + 1)$ discrete values. The gyromagnetic ratio, which is the ratio of angular momentum to magnetic moment, is $2m/e$ for orbital motion, m/e for spin motion and $2m/ge$ for the whole atom, where g , the Landé splitting factor, is dependent only on L , S and J .

In the Gerlach-Stern experiment a stream of free atoms from an electric oven passes through an inhomogeneous magnetic field and is received on a cold glass plate, the vapour pressure in the apparatus being low so that no collisions take place. Paramagnetic atoms will be both orientated and deflected, giving $(2J + 1)$ separate traces, the separation of which depends upon g . Hence the one experiment gives both angular momentum and magnetic moment of free atoms. Data so obtained agree well with those determined from spectroscopic measurements. A modification of the method can give the spin momentum and magnetic moment of the nucleus. Even for large atoms containing many protons and neutrons the largest nuclear spin observed is $9/2$, indicating that the nucleus itself may have a shell structure, only uncompensated particles contributing to the resultant momentum. The magnetic moment of the proton is 2.85 nuclear magnetons ($\mu_N = \frac{1}{1840} \mu_B$), from which it appears that the proton itself may not be a single particle.

When the effective magnetic moments of bulk substances containing paramagnetic ions are measured, it is found that the rare earth salts give results which agree well with theory, whereas salts of the transition series have susceptibilities considerably lower than theoretical values. This is due to quenching of the orbital moments in the latter by electric fields due to neighbouring atoms; this effect may introduce asymmetry in the case of crystalline fields. The incomplete group in rare earth ions is largely shielded from such interaction by an outer completed shell.

Paramagnetic saturation can only be approached at very low temperatures using enormous fields and substances of large magnetic moment. At ordinary temperatures the susceptibility varies inversely with absolute temperature (Curie's law) or with the excess temperature above a critical value θ (Curie-Weiss law). In the latter case it appears as if, within the substance, there were an extra field adding to the effect of the external field. This inner field is much too large to be of purely magnetic origin and is attributed to exchange interaction between electrons of neighbouring atoms.

Below the Curie point, θ , it is possible for a spontaneous magnetization to exist in certain cases

even in the absence of an external field. This magnetization, which varies from complete saturation at 0° A. to zero at the Curie point, is identified with the 'saturation' intensity of ferromagnetic substances appropriate to each temperature. Above their Curie points, all ferromagnetic substances are paramagnetic and obey the Curie-Weiss law. The intrinsic magnetization of a ferromagnetic is uniform in direction only throughout small regions or domains the average size of which is about 10^{-8} c.c., containing some 10^{15} atoms. The directions of magnetization of the various domains may be random and their resultant nil, but a small field is usually sufficient to align moments of individual domains. Single crystals have certain axes of easy magnetization which would appear to be the natural directions of spontaneous magnetization. Measurements of the gyromagnetic ratio prove that the elementary magnetic carrier is the electron spin. Heisenberg showed that intrinsic fields of the right order of size could arise from exchange interaction between electron spins. The condition for a large-scale alignment of spins is that the ratio of the distance between

neighbouring atoms to the radius of the energy shell in which uncompensated electron spins exist shall lie within certain limits. The ratio has the right value for iron, cobalt, nickel, and for some of the rare earth metals; chromium and manganese lie just outside the range, but certain compounds and alloys containing these elements (notably the Heusler alloys) are ferromagnetic.

The first few atoms of an impurity do not markedly affect polycrystalline ferromagnetic materials, but if the number of dissolved atoms becomes larger than the number of domains, then even very small percentages of carbon, oxygen or sulphur can greatly lower permeability and increase hysteresis. The addition of silicon has the effect of causing these impurities to crystallize out in forms in which they are relatively less harmful. Much work has been done on the technical side in these directions, and in the preparation of 'soft' and 'hard' magnetic materials. Recent X-ray work has revealed why it is that alloys prepared under certain conditions of heat treatment make excellent permanent magnet material.

OBITUARY

Mr. Wilfred Trotter, F.R.S.

IN the recent autumn the Royal Society has suffered the loss of both of its fellows whose work lay in surgery, Harvey Cushing of America, who died on October 7, 1939, and Wilfred Trotter of London, who died on November 25 at the age of sixty-seven. Each had done conspicuous work in the surgery of the brain, approaching their problems with physiological thought, and Cushing's name will always be remembered for the studies by himself and his pupils on the pituitary gland and on the microscopic structure of brain tumours in reference to their ways of malignant growth. He was a pioneer in cerebral surgery in America, and his supreme powers both as an operator and as a scientific thinker soon gathered around him at Harvard a school of workers who will assuredly maintain the energetic influence left by Harvey Cushing's mind. The possibility of this broadly based success was a reward of the changes deliberately planned in American universities in order to enable a leader in medicine or surgery to receive all such laboratory and other advantages as a professor of physiology would expect in his department for the progress of scientific work and teaching.

Trotter was too early in England for such an opportunity, and much of his life was therefore spent in individualistic effort as a consulting surgeon. At University College Hospital he inherited the field of Sir Victor Horsley's work and soon proved himself

to be a master of the surgery of the brain and of the thyroid gland. He wrote a general analysis of the physiological processes involved in cerebral concussion which influenced surgical thought widely. A new approach to the difficult tumours of the pharynx was devised by him, and in this and equally in all the familiar operations of surgery he worked with such technical perfection and delicate care of every detail for the welfare of both wound and patient that none could surpass his results. Practice as a London consultant grew rapidly, and from 1932 onwards Trotter had the honour of being sergeant surgeon in succession to three kings of England. But at that zenith of individual success he made a choice which to ordinary ambition seemed utterly paradoxical. His health was becoming unequal to the fullest strain of work, and so about 1934 he withdrew, not from unpaid hospital duties at his medical school, but from all private practice. He wished, while he still could, to teach the young men.

Trotter's influence on those around him at University College Hospital had at all times been profound. The fine lines of his face and the quiet perfection of everything said or done by him were united with a keenness of intellect that was stirringly eager to aid the minds of others and never stood aloof. His method was like that ascribed to Socrates, a conversation in which he would relentlessly, yet never with courtesy or overbearing force, compel those sharing it to think afresh, to see