Magnetism from B.C. to 21st Century

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Magnetism - From B.C. to 21st Century

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In this article, the readers will feel like travelling into the world of magnetism from ancient to modern times.

1. Introduction

Magnets and magnetism have mystified human beings right from their discovery. Even today when a magnet is in hand, irrespective of age one would like to play with it. Ever since its discovery, science and technology of magnetism has been continuously expanding. At present, magnets and magnetism are woven in our life. Fans, grinders, computers, CD players, credit and debit cards, magnetic key-cards, bank cheques, currency and a large number of many such facilities exist, thanks to magnetism and magnetic materials. Thus, to discuss fully intricacies of magnetism one needs several volumes of books. So, we shall limit ourselves only to certain important features. Some of these may not be available in standard text books and are described presently.

History

In almost all the books on magnetism and history of magnetism it is credited that Greeks and Chinese were the first to realise attractive power of a rock stone called *load stone* which was found in a region called magnetia. Aristotle (384-322 B.C.) credited Thales of Miletus (624-545 B.C.) for scientifically discussing attractive power of the load stone. But it is rarely noticed that the power of the load stone now called magnet, was known to Indian surgeon Sushruta who used this power to extract iron arrow from wounded soldiers. He lived in the same period as Thales of Miletus. Sushruta called this rock *'ayas kanta'* means iron loving. During 27-29 AD, Gai us Plinius secundus, better known as Pling the Elder, wrote in his encyclopedic work, that a hill near river Indus was full of stones that attracted iron.

Let us begin with a resume of magnetic facts discovered from early periods, down the time line.

- Using a compass, P. de Maricourt discovered that a magnet (load stone) has two poles namely north and south poles. This was in 12th century.
- In the 1600's William Gilbert, a physician, concluded that Earth itself is a giant magnet.
- In 18th century Danish scientist Hans Christian Oersted observed that a compass needle in the vicinity of a wire carrying electrical current was deflected. So a connection between electric and magnetic fields was discovered.
- In 1831, Michael Faraday discovered that a momentary current existed in a circuit when the current in a nearby circuit was started or stopped. Shortly thereafter, he discovered that motion of a magnet toward or away from a circuit could produce the same effect.

- In the 19th century James Clerk Maxwell gave his famous equations in which he unified the electric and magnetic forces. He also proposed that light was electromagnetic radiation.
- In the late 19th century Pierre Curie discovered that magnets lose their magnetism above a certain temperature, and later on it came to be known as the Curie point.
- In the 1900's scientists discovered superconductivity. Superconductors are materials that have a zero resistance to a current flowing through them when they are at a very low temperature. They also exclude magnetic field lines (the Meissner effect) which makes magnetic levitation possible.
- Recall that an electric dipole consists of two equal but opposite charges separated by some distance, such as in a polar molecule. Every magnet is a magnetic dipole. A bar magnet is a simple example. Note how the *E* field due an electric dipole is like the magnetic field (*B* field) of a bar magnet. Fields emanate from the + or N pole and re-enter the – or S pole. Although they appear to be the same, they are different kinds of fields. *E* fields affect any charge nearby, but a *B* field only affects moving charges. As with charges, opposite poles attract and like poles repel.
- We have studied electric fields due to isolated + or – charges, but as far as we know, magnetic monopole does not exist, meaning that it is impossible to isolate a N or S pole. When we try to separate the two poles by breaking the magnet, we only succeed in producing two distinct dipoles.

Magnetic monopole

We know that an electric dipole has positive charge on one side and negative charge on the other. The positive charge is made of protons and the negative charge is made of electrons. Existence of these two types of charges are experimentally verified. On the other hand, a magnetic dipole does not have different types of matter yielding the north pole and south pole. An electric dipole and magnetic dipole are fundamentally quite different. In an electric dipole made of ordinary matter, the positive charge arises from protons and the negative charge is made of electrons, but a magnetic dipole does not have different types of matter creating the north pole and south pole. Instead, the two poles arise simultaneously from the combined effect of all the currents and intrinsic moments throughout the magnet. Hence the two poles of a magnetic dipole must always have equal and opposite strength, and the two poles cannot be separated from each other. In fact Gauss law of magnetism in terms of the Maxwell's equation asserts that the monopoles do not exist.

In 1932, P.A.M. Dirac proposed his quantum theory of magnetic charge which showed that if any magnetic monopole exists in the universe then electric charge in the universe will be quantised. But we know that electric charge is quantized so magnetic monopole must exist in the universe. Many attempts were made but they proved to be inconclusive. Recent advances suggest that magnetic monopoles should exist. This is a hot topic.

For us who would like to test rich taste of magnetism, let us not worry about this problem. When pudding is sweet why to worry about its ingredients !

2. Theory of Magnetism

Weber was the first who tried to explain the phenomenon of magnetism on the basis of molecular alignment in a material. This theory assumes that all magnetic substances are composed of tiny molecular magnets. Any unmagnetized material has the magnetic forces of its molecular magnets neutralized by adjacent molecular magnets, thereby eleminating any magnetic effect. A magnetized material will have most of its molecular magnets lined up so that the north pole of each molecule points in one direction, and the south pole faces the opposite direction. A material with its molecules thus aligned will then have one effective north pole, and one effective south pole. Classical theory of magnetism was well developed before modern theory of magnetism. According to a law discovered by Lenz, when a substance is placed within a magnetic field H, the field within the substance, -B-differs from H- by the induced field, $4\pi I$, which is proportional to the intensity of magnetization, I. that is;

$$B = H + 4\pi I$$

where, B = the magnetic field within the substance; H = the applied magnetic field

I = the intensity of magnetisation.

Thus $B/H = 1+4\pi I = k$

For vacuum $B = H$

It can be shown that

$$X_m = N\mu^2 / 3kT$$

where N is Avogadro's Number; k is the Boltzmann constant and T the absolute temperature, μ is magnetic moment, and X_m is magnetic susceptibility. Rewriting this gives the magnetic moment as

$$\mu = 2.828(X_m T)^{1/2}$$

A modern theory of magnetism is based on the electron spin principle. From the study of atomic structure it is known that all matter is composed of vast quantities of atoms, each atom containing one or more orbital electrons. The electrons are considered to orbit in various shells and subshells depending upon their distance from the nucleus. The structure of the atom has previously been compared to the solar system, wherein the electrons orbiting the nucleus correspond to the planets orbiting the sun. Along with its orbital motion about the sun, each planet also revolves on its axis. In an elementary idea of electron spin, the electron is similarly supposed to be spinning around its axis, as it also around the nucleus. The current associated with this spin, also generated magnetic field, in addition to that associated with the orbital motion. The effectiveness of the magnetic field of an atom is determined by the number of electrons spinning in each direction. If an atom has the number of electrons spinning in opposite directions, the magnetic fields surrounding the electrons cancel one another, and the atom is unmagnetized. However, if more electrons spin in one direction than another, the atom is magnetized. An atom with an atomic number of 26, i.e. iron, has 26 protons in the nucleus and 26 revolving electrons orbiting the nucleus. If 13 electrons are spinning in clockwise direction and 13 electrons are spinning counter-clockwise, the opposing magnetic fields will be neutralized. When more than 13 electrons spin in either direction, the atom is magnetized. It must be remarked here that comparing electrons as planets orbiting around nucleus is too simplistic picture. Quantum mechanics is required to explain magnetic properties of matter fully. But as an approximation we shall first assume the simple picture and that too also explains several important properties of matter. These are classification of materials as dia-, para-, ferro-, ferri- and antiferro- magnetic, Curie temperature at which ferromagnetism transforms to paramagnetism, etc. Here, every electron in an atom has two types of magnetic moments, one due to 'rotation' of electron around its own axis and other due to motion round the nucleus. The former is called spin dipole magnetic moment and the latter is known as orbital dipole magnetic moment. In certain cases a third type of magnetic moment called nuclear magnetic moment also plays important role. But in approximate theory it is usually neglected. The two dipole magnetic moments (μ_s and μ_0) combine vectorially for each electron. The resultant vectors from each electron then combine for the whole atom, often canceling each other out. For most materials the net dipole moment for each atom is about zero. For some materials each atom has a nonzero dipole moment, but because the atoms have all different orientations, the material as a whole remains non-magnetic. Ferromagnetic materials, like iron, are comprised of atoms each having net dipole moment. Furthermore, all the atoms have the same alignment, at least within very tiny regions called domains. The domains can have different orientations, though, leaving the iron non-magnetic except when placed in an external field. Permanent magnets are produced when the domains in a ferromagnetic material are aligned. Accordingly all materials can be classified as follows.

Diamagnetic : It has all its spins paired giving net magnetic spin zero. Such a material is slightly repelled when subjected to external magnetic field.

Paramagnetic: It will have some electrons with unpaired spins. Paramagnetic compounds are attracted by a magnet. Paramagnetism derives from the spin and orbital angular moments of electrons. This type of magnetism occurs only in materials having unpaired electrons, as the spin and orbital angular moments are cancelled out when the electrons exist in pairs.

Ferromagnetic: If the diamagnetic atoms are removed from the system then the paramagnetic centres interact with each other. This interaction leads to ferromagnetism (in the case where the neighbouring magnetic dipoles are aligned in the same direction) and antiferromagnetism (where the neighbouring magnetic dipoles are aligned in alternate directions). Figure 1 shows the variation of magnetic susceptibility X with temperature T, in different cases.

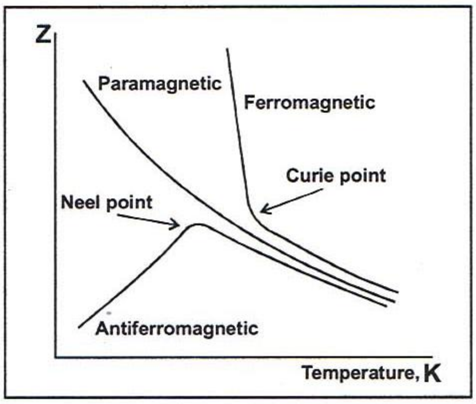

Figure - 1

The semi-classical theory could explain several features of magnetic properties of materials but certain features like domain wall motion, spin glass, magnetism in certain nano-sized materials such as gold, can only be explained using quantum theory. Electrons and all such elementary particles are not just particles. They are represented by associated wave functions.

Quantum-mechanical origin of magnetism

In principle all kinds of magnetism originate (similar to superconductivity) from specific quantum-mechanical phenomena e.g. wave functions due to spins and Pauli principle. In 1928 Heisenberg developed a successful model based on quantum mechanics to explain magnetism. He used Heitler-London idea of exchange interactions. In 1927 Heitler and London first derived how a hydrogen molecule is formed from two hydrogen atoms i.e. from the atomic hydrogen orbitals u_A and u_B centered at the nuclei *A* and *B*. According to the Heitler-London theory, the so-called two-body molecular orbitals are formed as follows.

$$\psi(r_1, r_2) = \frac{1}{\sqrt{2}}(u_A(r_1)u_B(r_2)+u_B(r_1)u_A(r_2))$$

Note the exchange involved in this expression. This "exchange" phenomenon is an expression for the quantum-mechanical property that fermions with identical properties cannot be distinguished. In this connection the term exchange interaction arises, and that is essential for the origin of magnetism, and is stronger, roughly by factors 100 and even by 1000, than the energies arising from the electrodynamic dipole-dipole interaction.

As for the spin function χ (S_1, S_2), which is responsible for the magnetism according to Pauli's principle, a symmetric orbital (i.e. with the + sign) must be multiplied with an antisymmetric spin function (i.e. with a – sign), and *vice versa*. Thus;

$$\chi(s_1, s_2) = \frac{1}{\sqrt{2}}(\alpha(s_1)\beta(s_2) - \beta(s_1)\alpha(s_2))$$

Thus, not only u_A and u_B must be substituted by α and β, respectively (the first entity means "spin up", the second one "spin down"), but also the sign + by the – sign, and finally r_i by the discrete values s_i (=±1/2), thereby we have $\alpha(+1/2) = \beta(-1/2) = 1$ and $\alpha(-1/2) = \beta(+1/2) = 0$. The "singlet state". i.e. the – sign, means that the spins are *antiparallel*, i.e. for the solid we have antiferromagnetism, and for two-atomic molecules one has diamagnetism. The tendency to form a (homopolar) chemical bond (i.e. the formation of a symmetric molecular orbital, or with the + sign) results through the Pauli principle automatically in an *antisymmetric* spin state (i.e. with the – sign). In contrast, the Coulomb repulsion of the electrons, i.e. the tendency that they try to avoid each other by this repulsion, would lead to an *antisymmetric* orbital function (i.e. with the – sign) of these two particles, and complementary to a symmetric spin function (i.e. with the + sign, one of the so-called "triplet function"). Thus, now the spins would be parallel (ferromagnetism in a solid, paramagnetism in two-atomic gases.) The last-mentioned tendency dominates in iron, cobalt and nickel, and in some rare earths, which are ferromagnetic. Most of the other metals, where the first-mentioned tendency dominates are non-magnetic (e.g. sodium, aluminium, and magnetism) or *antiferromagnetic* (e.g. manganese). Diatomic gases are also almost exclusively diamagnetic, and not paramagnetic. However, the oxygen molecule, because of the involvement of π - orbitals, is an exception and is important for the life-sciences.

Magnetism in nanoparticles:

Nanotechnology is a hot topic in Science and Technology of 21st Century. But before the word nanotechnology came into focus, nano-magnetic particles were synthesized and used in several fields of application. Use of nano-sized (10-50 nm) loh (iron) particles in *loh bhasma* were first used in India in ancient times and still such bhasma is used in Ayurvedic medicine to treat anaemic, jaundice, oedema etc. A nano-magnetic (NM) particle is a single domain particle and as you know the magnetization of such particles is saturated and it performs like a nanomagnet. Hence its position, motion etc can be controlled by applying a magnetic field. When used in large number to exhibit macroscopic effects each such tiny magnet should be kept well separated. This is usually done by either assigning electric charge or coating each particle with appropriated surfactant. This technique is used in preparing a magnetic fluid. Readers may refer to an article in Pragami Tarang 2014, Vol. VI. Apart from applications of NM particles in engineering devices, the presence of such particles is imprinted on several day-to-day applications such as credit and debit cards, bank cheques, currency note, magnetic key etc. In times to come applications of such NM particles in nanorobots, cancer treatment, drug delivery etc. will make a large impact in healthcare. Such particles are also helpful to design microspeakers, nanosensors etc. Space does not permit us to discuss all such devices at length. However some simple classical explanation of working principle behing drug delivery and cancer treatment is outlined here.

One of the most amazing findings for magnetism in nanoparticles is that in gold. The experimental observation of ferromagnetic moment formation at the nanosensors in Au nanoparticles is an interesting departure from the bulk behaviour of gold, which is diamagnetic. The measured magnetization is strongly size dependent, increasing with particle diameter at the smaller nanoparticle sizes, peaking at approximately 3 nm for Au-thiol nanoparticles, and subsequently decreasing with increasing nanoparticle size. This observation is consistent with the expected behaviour that as the nanoparticle size increases; the Au atomic configuration approaches that of the bulk gold lattice. This has been confirmed by using x-ray photoemission spectroscopy measurements of the nanoparticle size dependence of the Au cluster binding energies (relative to bulk). Several ideas are proposed to explain this property and all are mainly based on quantum mechanical treatment. Suffice is to say that only quantum mechanics can explain such results.

3. Novel and promising nanotechnological devices:

We shall now describe certain new nano-magnetic devices which will hold promise for future.

Spintronics:

The term Spintronics is coined from electronics in which apart from charge of electrons, spin also plays prominent role. Electron spin can be detected as a magnetic field having one of two orientations, known as *down* and *up*. This provides an additional two binary states to the conventional low and high logic values, which are represented by simple currents. With the addition of the spin state to the mix, a bit can have four possible states, which might be called *down-low, down-high, up-low, and up-high.* These four states represent quantum bits (qubits).

Spintronic technology has been tested in mass-storage components such as hard drives. The existence of four, rather than two, defined states for a logic bit translates into higher data transfer speed, greater processing power, increased memory density, and increased storage capacity, provided the properties of electron spin can be sufficiently controlled for practical applications. The prototype device that is already in use in industry as a read head and a memory-storage cell is the giant-magnetoresistive (GMR) sandwich structure which consists of alternating ferromagnetic and nonmagnetic metal layers, the device resistance changes from small (parallel magnetizations) to large (antiparallel magnetizations). This change in resistance (also called magneto-resistance) is used to sense changes in magnetic fields. Recent efforts in GMR technology have also involved magnetic tunnel junction devices where the tunnelling current depends on spin orientations of the electrons. At present efforts are being made to develop new materials with larger spin polarizations as well as improvement of existing devices. Another approach is to make semiconductor based spintronic devices that also can be used to amplify signals. It may be remembered that usual metal-based devices do not amplify signals. Still more challenging field is the application of electron and nuclear spins in quantum computers. It is known that quantum computations are much faster than the present day computers. Two bits for electrons and two bits for nuclear spins will provide basis for such computers.

Ferromagnetic versus Antiferromagnetic Storage Media

Recently also antiferromagnetic storage media have been studied, whereas hitherto always ferromagnetism has been used. The main advantages of using antiferromagnetic material are as follows.

1. Stray fields do not affect the sensitivity
2. Switching times are much faster.
3. Nearby particles do not affect the working of media.

Nanomagnetic particles in medicine and biotechnology:

Nanomagnetic particles behave as tiny magnets and when they are suspended in a liquid, under zero field all such magnets will be randomly oriented and hence net magnetization will be zero. Under the influence of field they will try to orient against randomizing thermal motion (Brownian motion). So they mimic paramagnetism. Since each particle has a giant magnetic moment such systems is called superparagnetic system. (Figure-2)

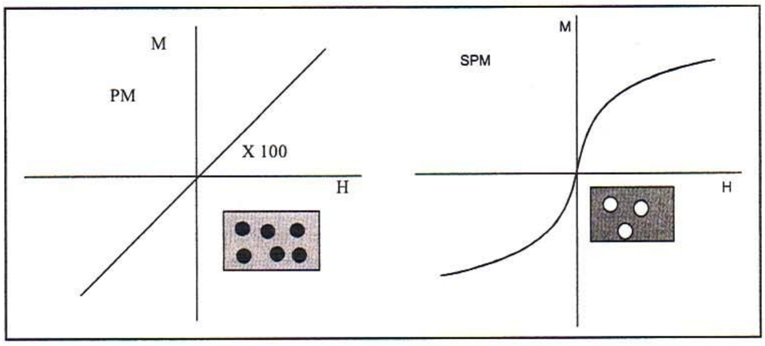

Figure - 2

With proper care, each of these particles can be coated with a drug (for example anti-cancer drug). Such a drug coated fluid can be injected in infected person and with help of external magnetic field the fluid along with drug can be brought to the desired portion of the body. Here, drug can be released. This looks like a simple technique, but there are several hurdles which must be removed before human trials.

For targeted drug delivery or magnetic separation of biomolecules, translatory motion of nanomagnets by application of magnetic field is required. Uniform field will yield torque on nanomagnet but not translatory motion, while gradient field will give rise such motion. For this purpose, we need to consider quite a few complicated aspects. Everything is not as simple as one would think! Briefly, we must take into account,

(1) Applied magnetic field H and its gradient, along with V_m - the particle volume – and M, the volumetric magnetization;

(2) Hyrdodynamic parameters like blood flow rate, ferrofluid concentration, infusion rate and circulation time;

(3) Physiological parameters like tissue depth, which decide distance of field source reversibility and strength of drug/cancer system tumour volume.

Thus, in this article we have briefly described certain important aspects of magnetism. We have not included several others theoretical as well as technological challenges being pursued presently.

Finally, let us not forget a huge but mild magnetic field ever present around us...! For some details, please see the box item, on the next page.

Earth as a magnet

The earth's central core (radius ∽ 1200 km) is mostly composed of Fe-Ni in solid form, but surrounding it is an outer region of ~ 2200 km thickness, which is composed of Fe-Ni liquid state (with some sulfur dissolved in it). As the heat from the center slowly escapes to the surface it sets up convection currents in this electricity conducting fluid. This, couples with the currents generated by earth's rotation, and generates its magnetic field by a mechanism known as the "magneto-hydrodynamic dynamo".

The magnetic field generated by this effect is "dipolar" to a very close approximation. It is however, interesting to note that for the Sun, the magnetic field generated by the magneto-hydrodynamic effect is "bipolar", because convection currents on the sun are close to the surface. Bipolar field is like distribution of a number of discrete "dipoles" on the surface. We see these "Poles" as the Sunspots.

At the current time or epoch, earth's magnetic south pole is close to its geographic north pole, and it wanders around it along an erratic path, but over time scales of around million years, earth's magnetic polarity undergoes "reversals". Thus, some 700,000 years ago the magnetic north was also the geographic north. Several such reversals have occured in the past. The magneto-hydrodynamic theory of the origin of earth's magnetic field successfully explains such reversals.

Substantial atmosphere of the earth, together with its magnetic field, creates a region around the earth, called its magnetosphere which prevents energetic cosmic rays and solar wind particles from directly reaching the earth's surface; thus giving a protection to life.

Think of how earth's magnetic field has been helpful in travels across the continents, and thereby in trade, commerce, exchange of knowledge and cultures...!!

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