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Teaching about Magnetic Materials—A Pedagogical Dilemma

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Although magnetic materials had been studied for over 2000 years, it was not until the development of quantum mechanics in the early years of the 20th century that any satisfactory explanation of their properties could be provided. This paper outlines some of the difficulties that this fact presents for teachers attempting to explain permanent magnetism to learners at different levels who do not have a background in quantum physics. The authors suggest how a consistent and physically correct approach may be achieved.

The dilemma

It is known that magnetic phenomena have been studied for at least two millennia in Greece,[1] China,[2] Mesoamerica,[3,4] India,[5] and, one can assume, in other parts of the world where mineral magnetite (lodestone) occurs naturally. Today, permanent magnets of various shapes and sizes together with magnetic compasses are widely used for discovery learning and experiments in primary school classrooms.[6,7] The study of magnetic materials forms part of almost all school science curricula and of modules in classical electromagnetism at upper secondary school and at college and university levels.

Nevertheless, no satisfactory explanation of magnetic materials can be given without some reference to quantum mechanical concepts. Even James Clerk Maxwell, who developed the complete classical theory of electromagnetism that we know today,[8] was aware that his formalism was unable to provide a satisfactory explanation of magnetic materials. We now understand that the reason for this is that Maxwell's theory does not allow for stable electronic orbits or intrinsic dipole moments. In classical electromagnetism, all accelerating charges, including those moving in closed orbits, emit radiation and thus lose their energy; indeed, in classical theory, permanent magnets cannot exist.[9]

Simple macroscopic explanations

Teachers, therefore, are faced with a challenge when discussing magnetic materials with pupils who have no knowledge of quantum mechanical principles. How, for example, are permanent magnets to be understood at a very elementary level? The usual solution adopted is to introduce the concept of magnetic poles. In the case of a long, straight magnet or a horseshoe-shaped one, for example, the idea of magnetic poles is a convenient model.[6] Phenomena such as the forces between magnets, forces on magnets in a magnetic field, Earth's magnetic field, and the orientation of a magnetic compass can all be explained to a greater or lesser extent in terms of a (point) pole model.

Some teachers and authors, however, choose to play down the use of this model on the grounds that in reality, free magnetic poles do not exist. Single poles cannot be isolated. Nor are they located at geometric points, except possibly in the case of a very long, thin magnet (magnetic needle dipole). Nevertheless, it is extremely difficult to give any coherent macroscopic explanation of the phenomena mentioned above without involving magnetic poles.

The magnetic pole model also presents an opportunity for teachers to introduce learners to the idea and use of models in physics. Modeling, of course, plays a central role in all scientific disciplines; such models are "horses for courses" in that every model has a limited range of applicability and, like magnetic poles, must be abandoned and ultimately replaced by a higher-level model.

Classical microscopic models

Historically, microscopic models of permanent magnets have been considered as comprising either (i) infinitesimal current loops ("Amperian" model) or (ii) short magnetic needles ("Gilbertian" model).[10] The Gilbertian model[11] presents the same difficulties as the macroscopic dipole model mentioned above. The Amperian current loop is even more problematic, in that classical electromagnetism requires a source of emf to maintain an enduring current in a closed loop.[12]

The idea of a "spinning electron" as an explanation of ferromagnetism was first suggested by Compton[13] in 1921. It was soon realized, however, that this model of an electron as a rotating spherical cloud of charge was nonviable, since its surface speed would be greater than the speed of light. Whereas today it is understood that the electron is a point particle, i.e., it has no size and its radius is zero, in the 1920s the size of the electron was estimated from the need for its mass to be completely due to its electrostatic potential energy. For example, by equating the electrostatic self-energy of a uniformly charged sphere,

$$\frac{1}{4\pi\varepsilon_0}\frac{3}{5}\frac{e^2}{r_e},$$

to mc^2, the following value can be estimated[14] for the so-called "classical electron radius":

$$r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2} \approx 2.8\times10^{-15}\,\text{m}.$$

The original argument treated an electron as a spinning rigid sphere of mass m_e for which the angular momentum would be

$$I\omega = \left(\frac{2}{5}m_e r_e^2\right)\frac{v}{r_e}.$$

Equating this to $1/2\,\hbar$, one finds that the speed at the surface of the sphere is given by

$$v = \frac{5}{4}\frac{\hbar}{m_e r_e} > 10^{10}\,\text{m/s},$$

more than an order of magnitude greater than c.

Despite this, even a century later, the "spinning electron" still features in a number of well-respected textbooks in both physics and chemistry and on numerous pedagogically oriented websites. In particular, this model shows up in some very popular and widely used textbooks in colleges and universities, including, for example, Griffiths,[15] Feynman et al.,[16] and Chabay and Sherwood.[17] Like the last of these, many other authors present a model of an electron as a spinning sphere but with the caveat (often as an aside or in parentheses) that such a "classical" picture isn't really adequate. Such an approach risks generating misconceptions in the learner. If a teacher considers some mental picture to be essential, however, that of an infinitesimally small "charged bar magnet" would seem preferable.

Following the development of quantum mechanics later in the 1920s, the term "spin" continued to be used but in a distinctly different context (see below). This can present a further challenge for teachers since the term can conjure incorrect images in a learner's mind associated with rotating rigid bodies. Unless teachers are very careful, this can lead to serious contradictions and misconceptions.

Addenda to classical theories of magnetic materials

In fact, no satisfactory explanation of the magnetic properties of matter can be provided without at least some minimal reference to quantum mechanical ideas. Even the simplest accounts of diamagnetism require the acceptance of stable electron orbits. Microscopic models of paramagnetism and ferromagnetism require, in addition, the existence of permanent magnetic dipoles. While some teachers and textbooks are willing to accept the role of atomic electron orbits in explanations of these phenomena, there is often a reluctance to acknowledge, even in an *ad hoc* way, the *intrinsic* nature of electron magnetic moments.

While the concept of intrinsic angular momentum has its root in relativistic quantum mechanics,[18] it can be treated in a semiclassical manner, similar to the way in which stable atomic orbits are appended to classical treatments to explain various macroscopic phenomena in physics and chemistry. It is an unavoidable fact that the intrinsic magnetic moments of unpaired electrons are almost exclusively responsible for permanent magnetism.[19]

Pedagogical strategies

As a teaching strategy, one can hardly do better than follow the approach taken by those great teachers of university physics, Halliday and Resnick. In their seminal textbook *Physics for Students of Science and Engineering*,[20] originally published in the 1960s, they point out that "whether an electron is trapped in an atom or is free, it has an intrinsic spin angular momentum S, often called spin. (Recall that intrinsic means that S is a basic characteristic of an electron, like its mass and electric charge.)," and they go on to say that "It is tempting to account for electron spin by thinking of the electron as a tiny sphere spinning about an axis. However, that classical model, like the classical model of orbits, does not hold up. In quantum physics, spin angular momentum is best thought of as a measurable intrinsic property of the electron; you simply can't visualize it with a classical model."

Unfortunately, this point was not as clearly articulated in later editions of that text and has been avoided or fudged in many high school and freshman textbooks published in the intervening years, particularly in the treatment of ferromagnetism.

Adopting a strategy along the lines suggested here should enrich the learners' understanding of both modern particle physics and magnetic materials. In particle physics, it introduces the idea that elementary particles have a number of intrinsic properties such as mass, charge, and angular momentum(/magnetic moment). In explaining the magnetic behavior of materials, it is essential to understand that each electron carries with it, not just a charge, but also a magnetic moment. Both the charge and the magnetic moment of the electron are intrinsic and always present, carried with the electron wherever it goes.

In quantum mechanics, the Heisenberg uncertainty principle dictates that we must think of the location of an electron in an atom, molecule, or solid as being "smeared out"—that is, one cannot define exactly where it is, only where it is likely to be. This smearing out of the location of the electron gives the familiar charge distribution that is often pictured in illustrations of atoms and molecules, but it also gives a *smeared-out magnetic distribution* or magnetization.

In many cases, the electrons are paired, so that the magnetic dipole of one of the electrons of the pair is pointing in the direction opposite the other, canceling each other and giving no net magnetization. However, in some atoms, molecules, or solids, not all the electrons are paired in this way, and it is the smeared-out distribution of the magnetic moment of these electrons that is responsible for magnetization.[21]

When a magnetic field is applied to an atom, molecule, or solid, magnetic moments pointing along the magnetic field direction will be favored (just like a compass needle aligning along the direction of Earth's magnetic field), giving rise to paramagnetism.

The magnetization of iron and other magnetic materials is a little more complicated. In these materials, the unpaired electrons cooperate to spontaneously align their magnetic dipoles, giving rise to strongly magnetized microscopic regions—so-called magnetic domains—each domain acting like a microscopic bar magnet. The size of a typical magnetic domain can be about 10^{-6}–10^{-4} m, depending on the specific material and its temperature. Nearby domains may be magnetized in opposite directions, giving rise to very small average magnetic moment per unit volume. When an external magnetic field is applied, however, the magnetized domains align, resulting in the strong magnetization characteristic of permanent magnets.

Summary

To minimize the likelihood of misconceptions on the part of learners, teachers and lecturers (of senior physics in schools, freshman physics, and intermediate modules in atomic physics and electromagnetism in colleges and universities, etc.) need to present this material in a consistent and physically correct way. Individual instructors, of course, must judge for themselves how much information to reveal in the classroom depending on the age, experience, and background of the learners involved; provisional models, such as those mentioned in the "Classical microscopic models" section, may well play some role in in that context. It is important, however, that instructors themselves be fully aware of the issues discussed above. In particular, to avoid embedding misconceptions when discussing magnetic materials, even within classical electromagnetism, the electron must be understood as **an elementary particle that has two *independent* fundamental electromagnetic properties—its charge *and* its magnetic moment.**

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