All magnetic phenomena are NOT due to electric charges in motion

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LETTERS TO THE EDITOR

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All magnetic phenomena are NOT due to electric charges in motion

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There is a considerable body of the physics education literature purporting to show that all magnetic dipoles are uniquely "Amperian"; that is, at a fundamental level all magnetic dipoles effectively arise from electric current loops. This long-held view has had an unfortunate effect, particularly on the teaching of magnetic properties of materials, in that it has generated an unwarranted over-emphasis on a current loop analogy. Statements such as

> all magnetic phenomena are due to electric charges in motion, and in fact, if you could examine a piece of magnetic material on an atomic scale you would find tiny currents: electrons orbiting around nuclei and *spinning about their axes*[1]

or

> Sometimes, it is easier to think in terms of the "Gilbert" model of a magnetic dipole (separated monopoles), instead of the physically correct "Ampère" model (current loop)[1]

or

> The electron also has a spin rotation about its own axis (something like the earth rotating on its axis), and as a result of that spin it has both angular momentum and a magnetic moment[2]

are misleading, to say the least.[3]

The suggestion that classical spin of electrons could explain bulk magnetic properties was first proposed by Compton as early as 1920,[4] but the idea was not embraced by the physics community at the time. In 1925, the concept was reintroduced by Kronig[5] and, famously, by Uhlenbeck and Goudsmith.[6] It was realized almost immediately, however, that a model of an electron as a rotating charged sphere was not viable since its surface speed would be superluminal; this remains the accepted position almost a hundred years later.

In any event, the development of quantum mechanics from 1926 cast a very different light on these issues. Pauli's inclusion of spin matrices[7] in non-relativistic quantum mechanics was followed in 1928 by Dirac's relativistic quantum mechanical equation for the electron[8] from which electron spin emerges naturally. It is now recognized that Lorentz invariance requires that intrinsic angular momentum arises as a particle property inherent to the symmetries of Minkowski space-time and has an associated intrinsic magnetic dipole moment.

In the intervening years, however, attempts were made to model intrinsic magnetic dipole moments of particles as either (i) "Amperian" (infinitesimal current loops) or (ii) "Gilbertian" (infinitesimally short magnetic needles); for more details, see Ref. 9 and numerous references therein. The thinking behind this was reviewed by Mezei[10] in 1986. It was asserted that the force experienced when a magnetic dipole passed through an inhomogeneous magnetic field, like that in a Stern-Gerlach experiment or scattering in a solid, would be different for each model. Certain experiments[9] have been interpreted to favor the "Amperian" model, but these experiments involved particles such as neutrons that are known to have non-zero radius.

A recent paper by Rafelski *et al.*,[11] using a rigorous Lorentz invariant treatment, confirms that any point particle has an intrinsic angular momentum and associated intrinsic magnetic dipole moment without the need for either of the above analogies. These authors proceed to show that the Stern-Gerlach force on a point magnetic dipole *is the same for both models*, and thus, it is not possible to distinguish dynamically between them. Accordingly, neither the "Amperian current loop" nor the "Gilbertian dipole" analogs can be applied meaningfully to electrons.

While permanent and/or induced current loops at an atomic level do indeed contribute to various magnetic phenomena, this is not the case for the magnetic dipole moments that stem from intrinsic angular momentum, such as that of the unpaired electrons involved in paramagnetism and ferromagnetism. This is a point of conceptual and practical importance, because, for example, the magnetic properties of all ferromagnetic materials arise almost entirely from the intrinsic magnetic moments of their electrons and their contribution should be understood as separate from (small) orbital electric current contributions.[12]

In the context of teaching classical electromagnetism, however, it *may* sometimes be pedagogically helpful to recognize that the magnetic moment of fundamental point particles can be visualized heuristically in either model, but neither heuristic visualization should be presented as fundamental. Forcing a "current loop" or "spinning charged sphere" interpretation on the origin of the magnetic dipole moment of the electron inevitably leads to pedagogical difficulties, contradictions, and misconceptions. Indeed, in the limit that the area of the loop becomes infinitesimally small, a relativistic treatment is clearly required.

It is important that instructors emphasize that dominant magnetic effects in real materials arise from the intrinsic magnetic moment of the electrons and acknowledge that the physical origin of intrinsic magnetic moments lies outside the remit of classical electromagnetism. Failure to recognize this impedes a proper understanding of magnetic effects in materials.[12]

We are not suggesting that intrinsic magnetic moments fit seamlessly into the classical theory of electromagnetism. Even Ampere and Maxwell[13] appreciated that something beyond their electromagnetism was needed to understand magnetic materials. The something beyond, of course, turned out to be quantum mechanics and its intrinsic magnetic moment of the electron.

Spin arises from fundamental symmetry requirements of relativistic quantum mechanics—it is as intrinsic to a particle as its charge. Thus, when discussing magnetic materials even within classical electromagnetism, the electron should be recognized as a point particle that has two independent fundamental electromagnetic properties: its charge *and* its magnetic moment. A clear statement of this fact is essential, even in the context of elementary pedagogical treatments. Quite simply, it is not physically correct to state that all magnetic phenomena are due to electric charges in motion.

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[1]D. J. Griffiths, *Introduction to Electrodynamics*, 4th ed. (Cambridge U. P., Cambridge, 2017), Sec. 6.1, pp. 266, 269. Underlining added.

[2]*The Feynman Lectures on Physics* (Addison-Wesley, Boston, 1964), Sec. 36-1, p. 36-2. However, in an earlier section (34-1, p. 34-2), Feynman had already pointed out that "it is not possible to understand the magnetic effects of materials in an honest way from the point of view of classical physics. Such magnetic effects are a completely quantum-mechanical phenomenon."

[3]We do not wish to imply that such misconceptions are unique to Griffiths's or Feynman's otherwise excellent texts. They appear in some form in many other undergraduate electromagnetism textbooks in English, but Griffiths and Feynman are probably among the most widely used. Similar misunderstandings can be found in numerous pedagogically oriented internet websites.

[4]A. H. Compton, "The magnetic electron," J. Franklin Inst. **192**, 145–155 (1921).

[5]See, for example, E. D. Commins, "Electron spin and its history," Annu. Rev. Nucl. Part. Sci. **62**, 133–157 (2012).

[6]G. E. Uhlenbeck and S. Goudsmit, "Spinning electrons and the structure of spectra," Nature **117**, 264–265 (1926).

[7]W. Pauli, "Zur quantenmechanik des magnetischen elektrons," Z. Phys. **43**, 601–623 (1927).

[8]P. A. M. Dirac, "The quantum theory of the electron," Proc. R. Soc. London A **117**, 610–624 (1928); "The quantum theory of the electron. Part 2," *ibid*. **118**, 351–361 (1928).

[9]K. T. McDonald, *Forces on Magnetic Dipoles* (Joseph Henry Laboratories, Princeton University, Princeton, 2018), http://kirkmcd.princeton.edu/examples/neutron.pdf

[10]F. Mezei, "La nouvelle vague in polarized neutron scattering," Physica **137B**, 295–308 (1986).

[11]J. Rafelski, M. Formanek, and A. Steinmetz, "Relativistic dynamics of point magnetic moment," Eur. Phys. J. C **78**, 6 (2018).

[12]D. Vanderbilt, *Berry Phases in Electronic Structure Theory* (Cambridge U. P., Cambridge, 2018).

[13]J. C. Maxwell, *Electricity and Magnetism*, 3rd ed. (Clarendon Press, Oxford, 1892), Chap. XXII.