Foundations of Magnetic Conduction

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Abstract

It is shown that a spinning magnetic dipole (magnet) effectively behaves as a magnetic charge, creating magnetic current. The question of a 'magnetic conductor' then immediately arises, for without their practical existence pursuing 'magnetonics' would seem futile. Applying a rotational version of the Drude model to materials with magnetic dipoles I then conclude that the existence of magnetic conductors is indeed possible.

I then sketch the idea of preparing a 'magnetolyte' which is the foundation of operation of any 'magnetic battery', without which magnetonics is impossible.

It has been almost a century since we had a coherent theory of *magnetic charges* and yet they remain merely a theoretical curiosity, to the extent that the basic concepts required for studying magnetic currents are obscure and mostly undeveloped.

Conclusive evidence of existence of 'true' magnetic monopoles is not still at hand. *Spin ice* is the only place so far where we have observed deconfined magneic monopoles and these materials offer little chance of developing *magnetonics* in an economically-viable manner. If we are to have affordable magnetonics in our era, we must do it with materials that are available relatively easy. With 'magnetic wires' and 'magnetic batteries' being the bread and butter of any hypothetical field of magnetonics, we cannot hope for much if we cannot find affordable examples of them.

Studying a phenomenon that does not genuinely exist can only be justified if at least it can be created 'artificially' and observed as an effective phenomenon. This is the main premise and promise of this paper.

We currently have two pictures of magnetism[1]:

- *Orthodox picture*, according to which there are no 'magnetic charges', only magnetic dipoles. The quantitative description is given by

$$\nabla \cdot \mathbf{B} = 0,$$

[1]In this paper I use the so-called microscopic version of Maxwell equations as they are more transparent but using the macroscopic version does not alter the arguments.

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J}_e + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right). \tag{1}$$

- *Dirac's picture*, according to which magnetic charges and currents do exist. The main difference is that magnetism now can have sources

  $$\nabla \cdot \mathbf{B} = \mu_0 \rho_m, \tag{2}$$

  and electricity finds magnetic currents as a new source

  $$-\nabla \times \mathbf{E} = \mu_0 \mathbf{J}_m + \frac{\partial \mathbf{B}}{\partial t}. \tag{3}$$

We expect the two pictures to be compatible.

According to the first picture, a magnetic *dipole* in a magnetic field experiences torque, given by

$$\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B}.$$

Since

$$P = \boldsymbol{\tau} \cdot \boldsymbol{\omega},$$

we have

$$P = -(\boldsymbol{\mu} \times \boldsymbol{\omega}) \cdot \mathbf{B}. \tag{4}$$

According to the second picture, for a magnetic charge without electric charge, the modified Lorentz force is

$$\mathbf{F} = q_m (\mathbf{B} - \frac{\mathbf{v}}{c} \times \mathbf{E}). \tag{5}$$

Since

$$P = \mathbf{F} \cdot \mathbf{v},$$

we have

$$P = q_m \mathbf{v} \cdot \mathbf{B} \tag{6}$$

Comparing (6) and (4) we arrive at

$$\boxed{q_m \mathbf{v} \equiv -\boldsymbol{\mu} \times \boldsymbol{\omega}} \tag{7}$$

This means that *a spinning magnet is a source of magnetic current.*
Nowhere in the Maxwell equations do we see this! According to Maxwell equations *magnetism cannot have a magnetic source.*
(7) shows that two magnets spinning in the opposite direction would effectively behave as opposite magnetic charges, hence attract one another. Similarly, two magnets spinning in the same direction effectively behave as like charges, hence repel each other. This is the **first prediction** of this paper.
Quantitatively, the force between two magnetic charges q_m and q'_m is

$$\mathbf{F} = \frac{\mu_0}{4\pi} \frac{q_m q'_m}{r^2} \hat{\mathbf{r}}. \tag{8}$$

We can go further to state

$$|q_m| \geq \frac{\mu\omega}{c}, \tag{9}$$

meaning that **a spinning magnet (magnetic dipole) is effectively a magnetic charge**. This fact suggests the possibility of using spinning magnets to test the consistency and utility of the theory of magnetic charges.

It is illuminating to reverse the analogy and investigate whether a *macroscopic permanent electric dipole* can exist.

Luckily we do not need to do the investigation ourselves: it is known that such material exists; it is called an *electret.*

When a magnet and an electret are near one another, a rather unusual phenomenon occurs: while stationary, neither has any effect on one another. However, when an electret is moved with respect to a magnetic pole, a force is felt which acts perpendicular to the magnetic field, pushing the electret along a path 90 degrees to the expected direction of ”push” as would be felt with another magnet.

This suggests we ask the question: what happens when the electret is stationary and we move the magnet instead?

According to the existing theories, nothing happens! Neither the magnet nor the electret will experience any force.

According to my proposal, however, it is easy to see that the magnet should experience the following force

$$\mathbf{F} = \frac{1}{c}\mathbf{m} \times \boldsymbol{\omega} \times \mathbf{E}. \tag{10}$$

This is the **second prediction** of this paper and paves the way for *using electrets to build a device that measures magnetic current.*

There are three key elements required for setting up a *magnetic circuit*:

- Magnetic Wire,
- Magnetic Battery,
- Magnetic Lamp.

The ability to access/build these elements using fairly-available material and technology provides a critical test for viability and utility of magnetonics. Without them, there is not much for us in this new field.

In the following I shall prove that all such elements are possible!

According to Ampère’s law (in presence of magnetic currents) (1) electric field and currents interfere with magnetism. So the first step towards *magnetonics* is (modified) magnetostatics, that is, to shield the configuration from any electric currents. This means **a magnetowire should be an electric insulator**.

We assume a material consisting of magnetic dipoles, placed in an external uniform magnetic field. We assume that these dipoles are free to spin (experience net torque) under the application of magnetic field, but otherwise experience no net force.

In the Drude model, free electrons move in a conductor (metal) and sometimes collide with crystal ions. Collision occurs when the location of the free electron coincides with an ion.

The analogue here would be *collisions in angle space*, meaning that collisions occur when the *phase* (rotational analogue of location) of a dipole coincides with that of an 'ion-analogue', whose meaning shall soon be found.

This picture implies that a magnetic conductor should consist of two kinds of magnetic dipoles: rotationally-mobiles and rotationally-immobiles. Mobile dipoles are free to spin under the application of an external magnetic field, whereas immobile dipoles are 'rotationally locked' and have a constant phase. This can be translated to saying that a magnetic conductor should consist of weak and strong dipoles. Given that a magnetic conductor should be an electrical insulator, we can thus readily conclude that *magnetic conductors are probably ferrimagnets*.

We are now ready to provide a simple mathematical model.
Our assumptions are

- Dipoles have a scattering time τ. The probability of scatting within a time interval dt is dt/τ.
- Once a scattering event occurs, we assume the dipole returns to angular momentum $\mathbf{L} = 0$.
- In between scattering events, the dipoles respond to externally applied magnetic field $\mathbf{B}$.

We consider a dipole with angular momentum $\mathbf{L}$ at time t and ask what angular momentum it will have at time $t + dt$. There are two terms in the answer. There is a probability dt/τ that it will scatter to angular momentum zero. If it does not scatter to angular momentum zero (with probability $1 - dt/\tau$) it will simply gain torque as dictated by its usual equation of motion $d\mathbf{L}/dt = \boldsymbol{\tau}$. Putting the two terms together we have

$$\langle \mathbf{L}(t + dt) \rangle = \left(1 - \frac{dt}{\tau}\right)(\mathbf{L}(t) + \boldsymbol{\tau} dt) + \mathbf{0}dt/\tau.$$

Keeping terms only to linear order in dt then rearranging,

$$\frac{d\mathbf{L}}{dt} = \boldsymbol{\tau} - \frac{\mathbf{L}}{\tau}, \tag{11}$$

where here the torque $\boldsymbol{\tau}$ on the dipole is just

$$\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B}.$$

Therefore in the steady state $d\mathbf{L}/dt = 0$

$$\mathbf{L} = \boldsymbol{\mu} \times \mathbf{B}\tau.$$

On the other hand

$$\mathbf{L} = I\boldsymbol{\omega},$$

therefore

$$\mathbf{J}_m = -n\boldsymbol{\mu} \times \boldsymbol{\omega} = -n\boldsymbol{\mu} \times \frac{\mathbf{L}}{I} = -\frac{n\tau}{I}\boldsymbol{\mu} \times (\boldsymbol{\mu} \times \mathbf{B}) = \frac{n\tau}{I}\left(\mu^2\mathbf{B} - \boldsymbol{\mu}(\boldsymbol{\mu} \cdot \mathbf{B})\right), \tag{12}$$

which can be called *Ohm's law for magnetic conduction.*

One might assume that magnetic currents need free magnetic monopoles (which are not readily available to us) as carriers and neglect the possibiltiy of magnetic conduction in material with magnetic dipoles. We see here that might not be the case. This seems promising and justifies our further study of the field.

For a 'magnetic lamp' we need a device that turns magnetic energy into light. **Induction lamps** are promising for this part.

And finally, the main practical contribution of this paper: magnetic battery.
For the production of a magnetic battery we need to produce the magnetic analogue of an electrolyte; a *magnetolyte.* A magnetolyte should form by **dissolving a (para)magnetic salt (e.g. manganous ammonium sulphate, iron alum) in a magnetic ionic liquid (e.g. 1-Butyl-3-methylimidazolium tetrachloroferrate).**