Nature Material: Discovery of magnetic monopole? Really?

Yiqun Luo

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On 12/05, an article from Cambridge University was published in Nature Material. [1] "**Monopoles had been predicted theoretically, but this is the first time we've actually seen a two-dimensional monopole in a naturally occurring magnet**," said co-author Professor Paolo Radaelli, from the University of Oxford, written on the Cambridge news website.

The work invokes hot discussion widely. If you know the basics of electromagnetism, you must know there are no magnetic monopoles. So the question remains: Is the work reliable? Or how do we understand the work?

The short answer is the definitions of magnetic monopoles vary.

1. In the original definition, a magnetic monopole should be a single particle. However, this work, as well as related work, is about the collective behavior of particles, or the so-called quasiparticle, not a single elementary particle.

2. The non-existence of magnetic monopoles indicates the divergence of the magnetic field $\nabla \cdot \mathbf{B}$ is always 0. In works similar to this, it is not the divergence of the magnetic field that is 0, but the divergence of a related field is 0.

I am not an expert in magnetism. I am a PhD in physics, so I am welcome to talk if there is anything wrong.

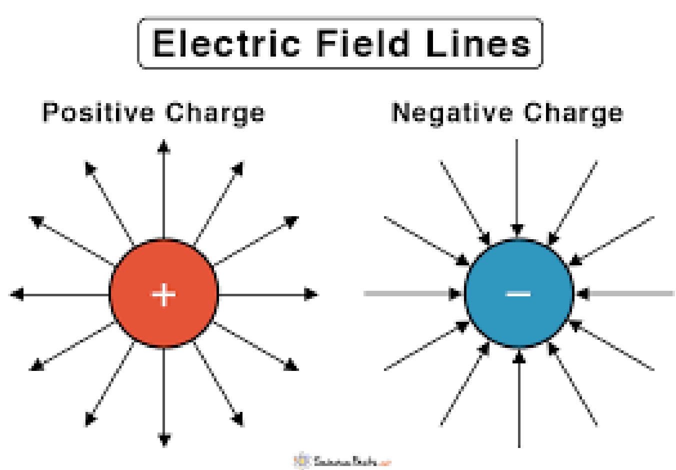
Without further ado, let's start.

1 Introduction

This part is about background knowledge. If you already know this, please skip to the Sec. 2.

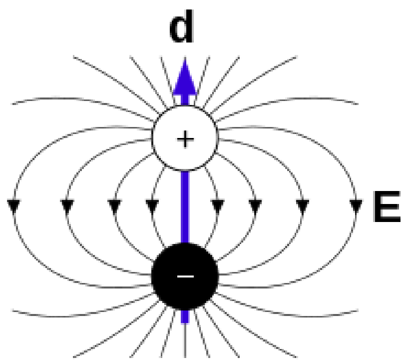
If you know anything about electromagnetism, you must know that there are electric charges, which can be either positive or negative.

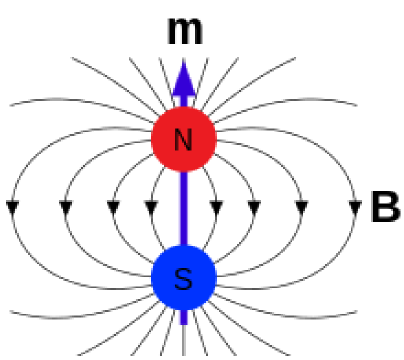
The electric field invoked by a positive or negative electric charge looks like this:

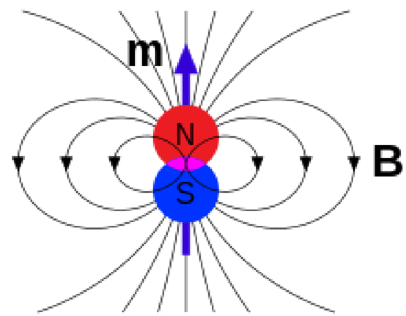


[1] Tan A K C, Jani H, Högen M, et al. Revealing emergent magnetic charge in an antiferromagnet with diamond quantum magnetometry[J]. Nature Materials, 2023: 1-7.

And if a pair of positive and negative electric charges gather together, it will look like this figure:







And one can imagine a similar picture for the "magnetic charge", shown in the two figures above.

However, experiments indicate the magnetic field always looks like the right figure, which can only be invoked by a pair of "magnetic charges" binding together, which is called magnetic dipole.

In terms of magnetic field lines, they cannot start or end at any place. Any magnetic field line either forms a loop or starts from infinitely far away to infinitely far away.

Using another approach, if we want to describe it more precisely, we may use the mathematical formula in the Maxwell's equation:

$$\nabla \cdot \mathbf{B} = 0. \tag{1}$$

However, it is only the experiments that indicate the non-existence of magnetic monopoles. They emerge in many theories.

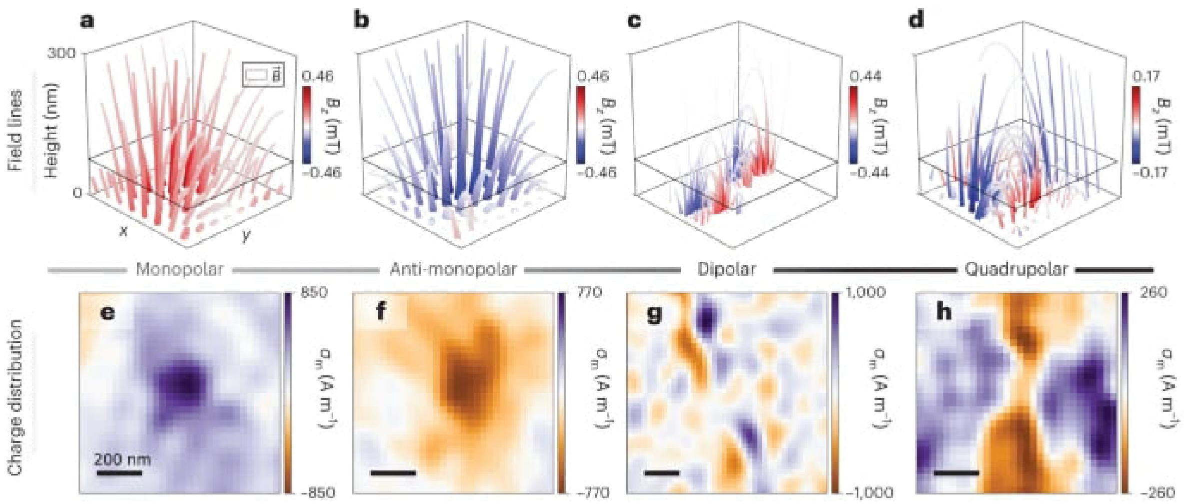
Dirac pointed out in 1931 that if magnetic monopoles exist, they would explain why electric charge is quantized. Many Grand Unified Theories (GUT) also say that conditions in the early universe would have allowed for the creation of magnetic monopoles. These monopoles are predicted to be very massive and thus difficult to produce and detect with current technology.

People have tried long to detect magnetic monopoles. A magnetic monopole may actually be discovered in 1982 on the famous Valentine's day experiment/incident, but no reproduction.

2 Content of the Paper

The paper applies the diamond quantum magnetometry, which meets the demand of highly sensitive vectorial magnetic field sensing with negligible backaction, and reads out 2-dimensional topological antiferromagnetic spin vorticity textures in haematite, namely, $\alpha - \mathrm{Fe_2O_3}$. Similar materials have many interesting topological spin textures, namely, the magnetic moments inside do not align like simple ferromagnetism or antiferromagnetic.

Sounds too complex? Here is a simplified version of what the paper does. The work measures a bunch of the magnetic field and infers the charge distributions very precisely.



In some textures, it shows the existence of magnetic monopoles, like in fig. a above.

Or, if you want to see the formula, for this specific case,

$$B_z = \alpha * \nabla \cdot \mathbf{m}_{xy} \tag{2}$$

$$m_z = 0, \tag{3}$$

where $\mathbf{B}$ is the magnetic field, $\mathbf{m}$ is the magnetization, $*$ indicates convolution, α is some function indicating the ratio between B and m. So, the magnetic field along the z direction B_z is directly related to the divergence of $\mathbf{m}$. The experiment detects non-zero B_z, which means the divergence of magnetization $\nabla \cdot \mathbf{m}_{xy} \neq 0$.

3 Discussion

So, actually, the meaning of monopoles here is different from its original meaning.

The monopole here is an emergent quasi-particle, which is a collective behavior of many spins. It is not a fundamental particle.

Also, it does not violate $\nabla \mathbf{B} = 0$. It is the related $\mathbf{m}$ whose divergence is non-zero. Actually, $\nabla \mathbf{B}$ is still 0 in this work.

And apparently, it does not offer theoretical insights.

So, maybe the most innovative point is applying the highly sensitive diamond quantum magnetometry into the system.

Actually, there are other works about emergent magnetic monopoles previously, maybe the most famous of which is the spin ice, and in a spinor Bose–Einstein condensate.

By the way, fancy concepts in condensed matter are frequently borrowed from one place to another, which causes puzzles like this, maybe intentionally.