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Magnetic monopole field exposed by electrons

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The experimental search for magnetic monopole particles[1–3] has, so far, been in vain. Nevertheless, these elusive particles of magnetic charge have provided a rich field of theoretical study[4–10]. Here, we created an approximation of a magnetic monopole in free space at the end of a long, nanoscopically thin magnetic needle[11]. We experimentally demonstrate that the interaction of this approximate magnetic monopole field with a beam of electrons produces an electron vortex state, as theoretically predicted for a true magnetic monopole[3,11–18]. This fundamental quantum mechanical scattering experiment is independent on the speed of the electrons and has consequences for all situations where electrons meet such monopole magnetic fields as e.g in solid state physics. The setup not only shows an attractive way to produce electron vortex states but also provides a unique insight into monopole fields and shows that electron vortices might well occur in unexplored solid state physics situations.

Magnetic monopoles have provided a rich field of study, leading to a wide area of research in particle physics[4–6], solid state physics[7], ultra-cold gases[8], superconductors[9], cosmology[4], and gauge theory[10]. As electric charges can be seen as monopole sources and sinks of electric field lines, the strong symmetry with magnetic and electrical fields e.g. in the free space Maxwell equations[19–21] hints to the possible existence of magnetic monopoles as well. So far, the search for such magnetic monopoles has been unsuccessful. However, an effective monopole field can be produced at the tip of a nanoscopic magnetized ferromagnetic needle[11,17]. The Aharanov-Bohm effect[12] can be used to understand the effects of such a monopole field on its surroundings which is crucial to its observation and provides a better grasp of fundamental physical theory. Previous studies have been limited to theoretical semi-classical optical calculations of the motion of electrons in such a monopole field[13]. Solid state systems like the recently studied 'spin ice' provide a constrained system to study similar fields, but make it impossible to separate the monopole from the material[7]. Here, we realize the diffraction of fast electrons on the magnetic monopole field generated by the extremity of a long magnetic needle. Free space propagation of the electrons helps to understand the dynamics of the electron-monopole system without the complexity of a solid state system and will allow various areas of physics to use the effects of monopole fields. Various predictions about angular momentum, paths of travel and general field effects can readily be studied using the available equipment. The experiment performed here shows that even without a true magnetic monopole particle, the theoretical background on monopoles serves as a basis for experiments.

Indeed it has been predicted that when a plane electron wave interacts with a hypothetical magnetic monopole, a vortex electron state would arise[3,11–18]:

$$\Psi_{out} = \Psi_{in} exp(im\phi), \qquad (1)$$

with m depending on the charge of the magnetic monopole and ϕ the azimuthal angle in the plane perpendicular to the electron wave propagation.

Approximating the magnetic monopole now by the end of a magnetic needle leads to similar effects. Indeed, such a semi-infinite cylinder of magnetic flux has been considered in earlier work on magnetic monopoles but has remained a Gedanken experiment so far[22]. From the description of the monopole field by a vector potential, a flux line, or 'Dirac string' arises as a mathematical pathology which should be undetectable if a magnetic monopole was to be a true monopole, leading to the famous magnetic charge quantization[1].

The magnetic vector potential is a mathematical tool used in quantum physics which has real, measurable effects[12] which were experimentally demonstrated by electron diffraction[18,23]. The Aharonov-Bohm (AB) phase is acquired by an electron when its path encloses magnetic flux:

$$\Delta\phi_{AB} = \frac{e}{\hbar c} \oint \mathbf{A}.d\mathbf{s}. \qquad (2)$$

This phase is a purely quantum mechanical effect as it is present even if the electron does not cross a region containing magnetic flux, a case where classical forces have no influence on the passing electrons. The Aharonov-Bohm effect is most often discussed with infinite cylinders of magnetic flux, avoiding the interesting end points where the magnetic field $\mathbf{B} = rot\mathbf{A}$, takes the form of a monopole:

$$\mathbf{B} = \frac{\mathbf{r}}{r^3} \qquad (3)$$

If one calculates the Aharonov-Bohm phase for electrons passing perpendicular by a semi-infinite cylinder of flux, one obtains a linear azimuthal dependency around the ending point of the cylinder[24]:

$$\Delta\phi_{AB} = \frac{2e}{\hbar c} g\phi. \qquad (4)$$

This means that a passing electron will indeed be transformed into a vortex state:

$$\Psi_{out} = \Psi_{in} exp(im\phi). \qquad (5)$$

For a true monopole field, where the charge g is quantized, this leads to an integer m ($g = m\hbar c/(2e)$), resulting in a perfect phase vortex of topological charge m. There are several different derivations of this phase factor, all extensively discussed in literature, and all predicting the same vortex phase factor[3,22,24]. A sketch and discussion on the subtle differences between the effect of a semi-infinite cylinder of flux and a true monopole is given in Supp. Fig.8.

Carefully tuning a magnetic needle leads to the same phase structure which is indistinguishable from a true monopole as long as the needle is thin and the flux converges towards a quantized flux. In this letter we successfully produced an approximation to a Dirac string with a nanoscopic magnetized ferromagnetic needle. The interaction of a plane electron wave with only one end of the needle allows the typical azimuthal AB phase shift to occur and vortex electron states to be created, as sketched in Fig. 1a.

From an experimental point of view, the needle is extracted from bulk Ni making use of a focused ion beam (FIB) instrument, resulting in a cone approximating an elongated cylinder with a cone angle of about 2 degrees shown in Fig. 1b. The strong shape anisotropy between the needle length (21.4 μm) and the tip diameter of only 200 nm leads to a situation where only a single on-axis magnetic domain occurs. After shaping the needle, it is positioned over a 20 μm circular aperture drilled in a nonmagnetic Au coated thin SiN film, in order to make sure electrons can only interact with one end of the needle and its magnetic monopole field.

We can verify the magnetic state at the tip of the nickel needle (red square in Fig. 2a) by inserting it in a transmission electron microscope (TEM) and performing electron holography in field free conditions[11,18], sketched in Supp. Fig. 1. This method measures the Aharanov-Bohm phase shift of the electrons caused by the magnetic vector potential around the needle. The resulting experimental phase map is shown in Fig. 2b and reveals the typical spiraling character in qualitative agreement with a finite element simulation for the same shape given in Fig. 2(c) and Supp. Fig. 2. The phase image resembles that of optical spiral phase plates, as used to create optical vortices[25]. Exposing the needle to an external on-axis magnetic field flips the axis of magnetization without going through multi domain states (Supp. Fig. 3). When the magnetization direction is reversed, the handedness of the phase reverses as expected (Supp. Fig. 3). In this sense, the needle tip behaves as a magnetic monopole with a polarity that can be chosen depending on the magnetization direction.

Illuminating the needle with a plane electron wave (300 keV, λ =1.97 pm) inside a TEM allows to experimentally verify whether a magnetic monopole field creates a vortex electron state. A series of images is recorded in the far field at different defocus of an imaging lens showing, in Fig. 3a, the presence of a central dark region. This persistent area of destructive interference is a clear sign of a phase discontinuity in the center, as expected for vortex waves. The ring is not exactly closed which occurs when a

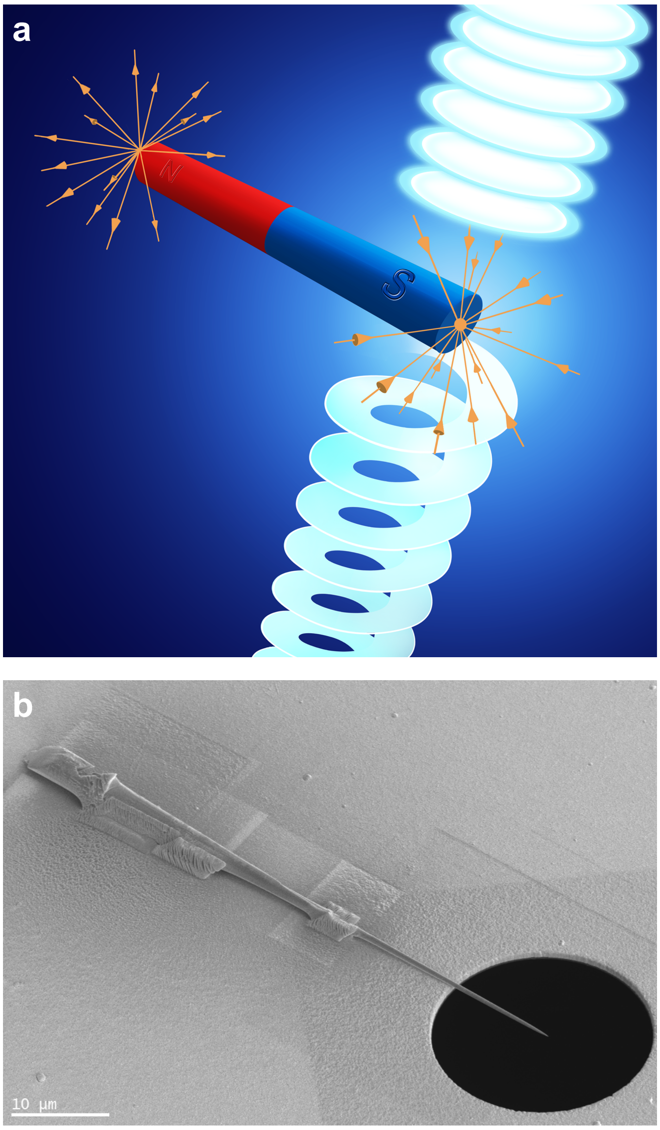

FIG. 1: *Concept and design of the monopole field: (a) An incoming electron plane wave is transformed into a vortex beam with a helical wavefront, through interaction with the magnetic monopole field. (b) SEM view of the experimental design. The nickel needle and its copper base are soldered to a gold plated SiN aperture using FIB assisted Pt deposition. Half the Ni needle is positioned over a 20 μm circular aperture, forming a local monopole field.*

non-integer orbital angular momentum is present[26]. Decomposing the phase map over the full aperture for the simulated magnetized needle into OAM eigenmodes indeed indicates that the deviation from a pure cylindrical shape leads to a distribution of OAM eigenmodes with an average of -5.8$\hbar$ per electron (Supp. Fig. 5). These experimental observations agree remarkably well with wave optical simulations presented in Fig. 3b ruling out the possibility that the dark region is caused by a shadowing effect (see Supp. Fig. 6 for further simulations).

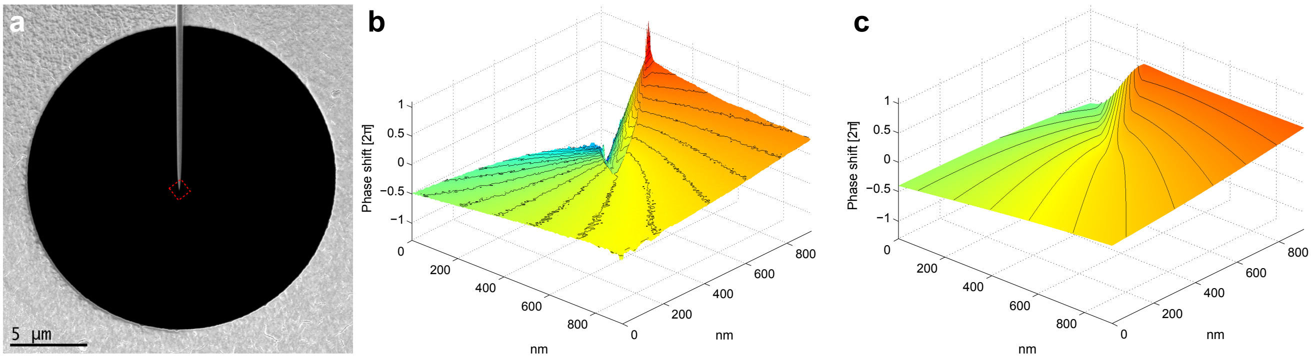

FIG. 2: *Effect of the needle on the phase of the electrons: (a) Magnified SEM image of the needle positioned onto the circular aperture. The red dashed square region indicates the position of images b and c. (b) Experimental phase map caused by the magnetic field around the Ni needle obtained by electron holography in field free conditions. The phase map is drawn in 3D to emphasize its helicity. (c) Finite element simulation of the phase map around a model for the needle. Detailed phase profiles are supplied in Supp. Fig. 4.*

We can also prove experimentally that this electron wave now possesses net orbital angular momentum, induced by the interaction with the monopole field, making use of the Gouy phase method[27,28], sketched in Supp. Fig. 1. For waves with net OAM we expect a π rotation of the image when going through focus with a direction of rotation depending on the sign of the OAM. This exact behavior is observed in Fig. 3c, which shows a clear clockwise rotation when going from under to over-focus.

These experiments show that our approximation to a Dirac string indeed provides a magnetic monopole field. The difference between a true monopole and this approximation lies in the effects of the flux returning to the needle making the field divergence free again as can be seen from the defocused images showing Fresnel fringes from the edge and a reconnection of the phase over the needle (Fig. 3a). This effect is the reason why no forked fringes are observed in the experimental holograms (Supp. Fig. 3a,b). Detailed holographic simulations showing this subtle reconnection difference between a true monopole and a Dirac string are shown in Supp. Fig. 7 together with a sketch explaining the creation of the phase singularities in both cases (Supp. Fig. 8).

The further we go into the far field, the more this effect of the needle disappears and the more the resulting wave becomes a true electron vortex as if the interaction took place with a real monopole. It is expected that a needle presenting an integer charge will allow a vortex with sufficient purity to heal itself, removing this distortion[29].

The above experiment shows how quantum experiments with magnetic monopoles are feasible and provides a very promising way to make electron vortices for applications in electron microscopy with an almost eight fold gain in beam intensity while avoiding other unwanted beams as compared to currently used holographic reconstruction methods[13,30]. The current device is static and its magnetic polarization depends entirely on the shape and material of the needle. However, there are no fundamental obstacles to create a nanoscale solenoid in order to provide any flux in the Dirac string depending on applied current. This extension would provide a dynamically switchable source of vortex electrons which would be highly desirable to improve the speed, flexibility and signal to noise ratio in vortex electron experiments.

Even though an electron microscope was used to conveniently demonstrate the effect, the consequences of this experiment reach much further as the AB effect is independent on the speed of the electrons and vortex states can be generated in e.g. solid state systems where conduction electrons encounter similar monopole fields. Indeed if a sufficiently coherent electron wave packet in a material would encounter a similar approximate monopole field (e.g. generated by a ferromagnetic inclusion), it would gain a topologically protected azimuthal phase, possibly changing its propagation dynamics.

I. METHODS

The needle was prepared from bulk nickel by a focused ion beam instrument (FIB) using a FEI Helios Nanolab with Ga ions accelerated to 30 kV. After extraction from the bulk sample, a large nickel chunk ($\sim$ 10x3x30 μm^3) was welded onto an already prepared conical shaped copper base and thinned concentrically. The resulting needle is 21.4 μm long, 700 nm wide at the bottom and 200 nm at the top. The nickel needle and part of its copper base were then extracted and sealed over a gold plated SiN film. The needle was precisely placed in order for half of its length to hang over a 20 μm circular aperture previously drilled in the Au/SiN film. Electron holography was performed in Lorentz (field free) mode at 300 kV on the QuAntEM microscope (a double corrected Titan^3 80-300) and is sketched in Supp. Fig. 1. The Möllensted biprism voltage was set to +180 V in order to have a

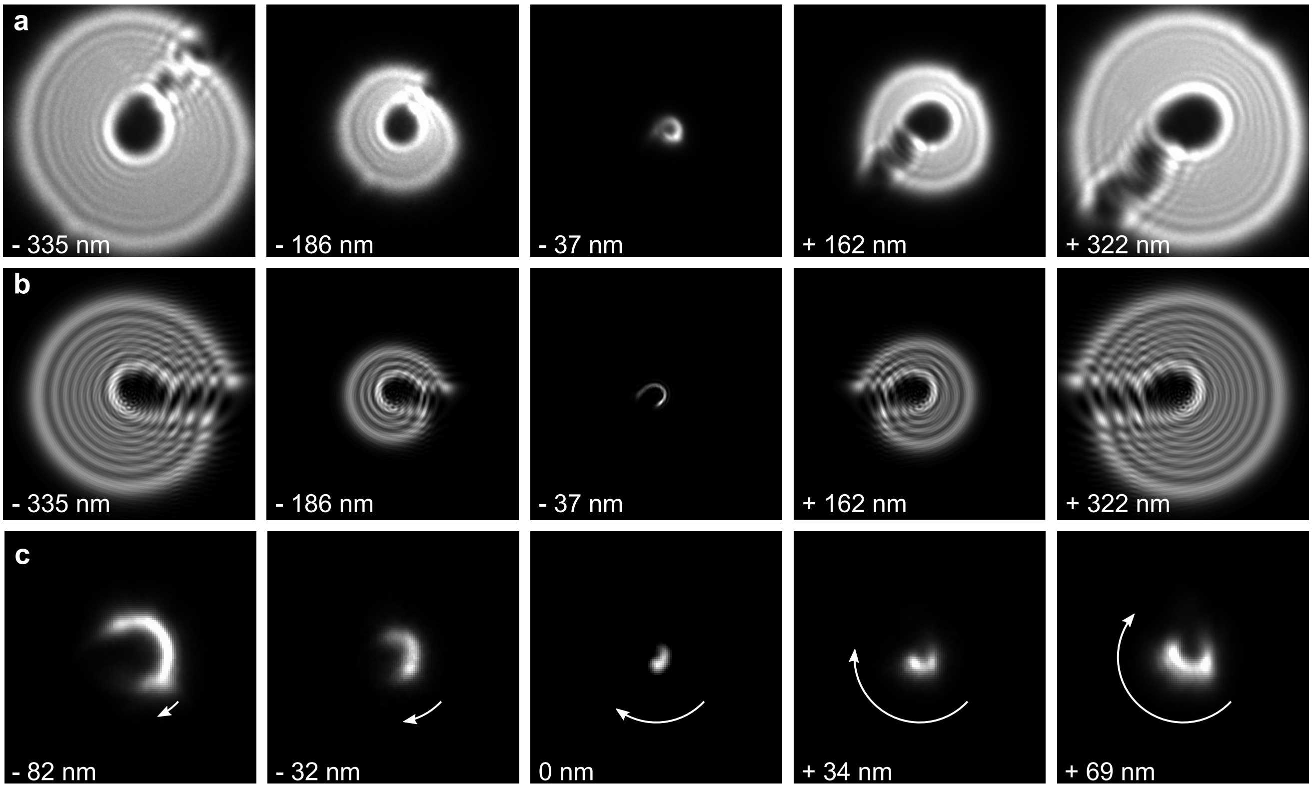

FIG. 3: *Electron vortex states observed after interaction with the monopole field: (a) Through focus series of the needle aperture in the diffraction plane. Note the persistent dark region in the centre caused by destructive interference typical for vortex waves. The near-focus central image shows a doughnut like intensity profile, typical of a vortex beam which opens on one side and indicating a non-integer total orbital angular momentum. (b) Wave optical simulation obtained by Fourier transforming the complex wave from Fig.2c with a Fresnel defocus applied. Note the detailed agreement with the experimental figures in (a). A similar simulation assuming no azimuthal phase is given in Supp. info showing a very different behavior ruling out the possibility that the black region is caused by shadowing effects from the needle. Intensity profiles are also given in Supp. info. (c) Through focus series of the beam half cut by a sharp edge. The rotation of the image along the series proves the presence of a net negative orbital angular momentum.*

large field of view and good sampling of the interference fringes. The phase maps were reconstructed from holograms using the standard Fourier filtering method with a final unwrap step. Such phase maps suffer from the presence of the electrostatic potential which is corrected by flipping the magnetisation of the needle and subtracting the phase maps obtained from two opposite magnetisations. The magnetisation state of the needle is changed by tilting the needle 30 degrees and applying a small magnetic field (∼0.15 T) by raising the current in the objective lens to 5% of its full strength. Through focus series were recorded in the diffraction plane of the Lorentz lens using the highest camera length available (18 m) and recorded on a CCD mounted at the end of a Gatan Quantum Image Filter. The Gouy phase experiment was realized in the exact same conditions, cutting the beam with the sharp edge of an objective aperture to clearly see the rotation effects (Supp. Fig. 1).

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II. CONTRIBUTIONS

A.B. and J.V. conceived the experiment; A.B. designed the sample and carried out the TEM measurements. All authors contributed to theory, data analysis and writing the paper.

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