Observation of Dirac monopole-like particles in a Spinor Bose-Einstein Condensate (BEC)

Observation of Dirac Monopoles in a Synthetic Magnetic Field,
M.W. Ray et al., Nature 505, January 2014

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What are Dirac monopoles?

• A new particle!

• Magnetic monopole solutions to Maxwell’s equations, i.e.,
  \[ \nabla \cdot \vec{B} \neq 0 \]

• A possible explanation for (electric) charge quantization!
  \[ \frac{q_e q_m}{2 \pi \hbar} \in \mathbb{Z} \]
How are Dirac monopoles produced?

\( \vec{A} \rightarrow \) monopole field for all space, but is singular along a single semi-infinite line, the “Dirac string.”

A charge circulating the string will acquire a phase change (think: Aharanov-Bohm effect)
How are Dirac monopoles produced?

Dirac string visualization

cds.cern.ch/record/1360999
Dirac monopole-like particles in condensed matter systems

😊 Dirac monopole-like quasiparticles in condensed matter systems

• *Not* a new particle

• Emergent phenomenon involving known particles

• Does not violate $\vec{\nabla} \cdot \vec{B} = 0$

😢 Search for actual Dirac monopoles – unsuccessful so far (Ex: MoDEAL experiment)
Why do we care about monopoles in condensed matter systems?

• A way for us to understand “magnetic excitations” in the same way as electronic excitations

• Could a collection of monopoles lead to emergent phenomena?

• Could shed light on properties of actual monopoles
Monopoles in Spin Ice Systems

• Degenerate ground state because of geometrical frustration
• Thermal fluctuations near 0 K → Spin flips

The spins obey the two in- two out ice rule

http://www.ctc.cam.ac.uk/
Monopoles in spin ice systems

Spins at a particular site can flip due to thermal fluctuations, resulting in a net magnetic moment.

Analogs of the “Dirac string”

Monopole-like quasiparticles

Can move the “poles” of the magnet apart by continuously deforming the spins.
Monopoles in spinor BECs

• BEC – Wavefunctions of many particles collapse into a single quantum state

• Spinor BEC – Single condensate, but atoms are in a superposition of internal quantum states

Ex: Spin-1 BEC $\rightarrow$ Atoms in a superposition of 3 spin projections:
$m = -1, 0, 1$
# Real vs. Emergent Monopoles

<table>
<thead>
<tr>
<th>Conventional Monopoles</th>
<th>Monopole-like particles in spinor BECs</th>
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<tbody>
<tr>
<td>Sources of the B-field</td>
<td>Sources of vorticity</td>
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<tr>
<td>$\nabla \cdot \vec{B} \neq 0$</td>
<td>$\nabla \cdot \vec{\Omega} \neq 0$</td>
</tr>
<tr>
<td>$\nabla \times \vec{A} = \vec{B}$</td>
<td>$\nabla \times \nu_s = \vec{\Omega}$</td>
</tr>
<tr>
<td>“Dirac string” – unobservable, mathematical entity</td>
<td>“Dirac string” analog – Special vortex line that is observable</td>
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</table>
Methods for probing monopole-like particles

• Neutron scattering has been used in spin ice systems since the spin chains interact only through spin and magnetism

• Changes in heat capacity of the system by modeling the system as a gas of monopoles

• Magnetic currents – “magnetricity” → measured in (doi:10.1038/nature08500)
METHODS
Overview of the Experiment

- Produce condensate
- Create monopole by changing B-field
- Image results

- Move zero of the quadrupole field into the BEC
- Zero of the B-field corresponds to the vortex (interpreted as monopole)
Step 1: Produce condensate

- Produce BEC in spin = 1 state using:
  - Magnetic traps
  - Optical traps

http://cold-atoms.physics.lsa.umich.edu/projects/bec/evaporation.html
Step 2: Control the B-field

- There are two fields: a quadrupole field and bias fields
  - Spins around the quadrupole zero point orient like they are around a monopole
  - The bias field ($B_Z$) is used to move the zero point into the BEC
Step 2: Control the B-field

• There are two fields: a quadrupole field, bias fields
  – Spins around the quadrupole zero point orient like they are around a monopole
  – The bias field (BZ) is used to move the zero point into the BEC
Step 3: Imaging

Only a single spin state can be imaged at a time

- To avoid imaging the irrelevant spins, force them into another spin state with the bias field ($B_z$)
- Turn off the $B_z$ and quadrupole fields, and let the BEC expand freely
- Use the $B_z$ field to select a single spin state and image its distribution
RESULTS AND IMPLICATIONS
Monopole signature #1: Double Vortex Decay

After moving the B-field zero into the condensate, the vortex decays into two, indicating double quantization.

The doubly quantized vortex is a signature of the spin structure from the monopole.
Monopole signature #2: Spin State Distribution

As the zero field region is lowered, the spin distribution changes *precisely* as they would from the movement of a Dirac Monopole
As the zero field region is lowered, the spin distribution changes *precisely* as they would from the movement of a Dirac Monopole.
What’s in the Future?

• Study the interactions, lifetimes, and transport of these monopoles

• How do these monopoles behave in other BEC phases (e.g., antiferromagnets)? What properties are universal, and what are system specific?

• Can you make other spin textures with the same monopole field? Do they have the same properties?

• New experimental setup for multiple nodal lines and better imaging
<table>
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<th>Citation</th>
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<th>Authors</th>
<th>Journal</th>
<th>Year</th>
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<tr>
<td>U(3) artificial gauge fields for cold atoms</td>
<td>Hu, Y.-X., Miniatura, C., Wilkowski, D., Grémaud, B.</td>
<td>2014</td>
<td>Physical Review A - Atomic, Molecular, and Optical Physics</td>
<td>0</td>
<td>Experimental</td>
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<td>A Raman waveplate for spinor Bose-Einstein condensates</td>
<td>Schultz, J.T., Hansen, A., Bigelow, N.P.</td>
<td>2014</td>
<td>Optics Letters</td>
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<td>Experimental</td>
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<td>Synthetic Lorentz force in classical atomic gases via Doppler effect and radiation pressure</td>
<td>Dubček, T., Šantić, N., Jukić, D., (…), Ban, T., Buljan, H.</td>
<td>2014</td>
<td>Physical Review A - Atomic, Molecular, and Optical Physics</td>
<td>0</td>
<td>Theoretical</td>
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<td>Creation and dynamics of two-dimensional skyrmions in antiferromagnetic spin-1 Bose-Einstein condensates</td>
<td>Ollikainen, T., Ruokokoski, E., Mottonen, M.</td>
<td>2014</td>
<td>Physical Review A - Atomic, Molecular, and Optical Physics</td>
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<td>Same authors</td>
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<tr>
<td>Atomic physics: Polar exploration</td>
<td>Leblanc, L.J.</td>
<td>2014</td>
<td>Nature</td>
<td>0</td>
<td>Review article</td>
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What the paper excelled at

• Provided important details on their methods of measurement

• Very useful diagrams

• Gave an alternate explanation with monopoles of how velocity and vorticity come about

• Referenced everything necessary to understand the context of the paper
Critiques

• The term monopole is being used to describe many excitations, the paper does not distinguish between them.

• What are the implications of observing this excitation in a “quantum field” as opposed to a material such as a spin ice?
Summary

• Studying quasi-monopoles in condensed matter allows us to see materials physics through the lens of magnetic excitations

• The authors observed monopole excitations in BECs for the very first time

• This paper has developed the experimental techniques to study monopoles in a highly controlled environment
Thank you!