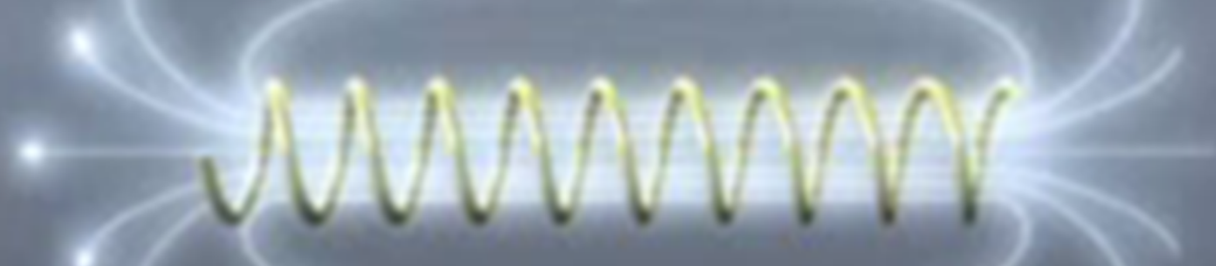
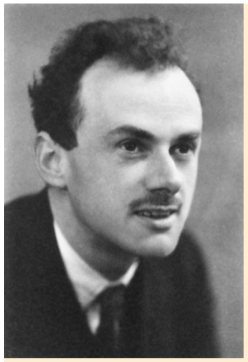
Observation of Dirac monopole-like particles in a Spinor Bose-Einstein Condensate (BEC)



***Observation of Dirac Monopoles in a Synthetic Magnetic Field**,*

M.W. Ray et al., Nature 505, January 2014

Ji Young Kim
Ashwathi Iyer
Ali Husain



What are Dirac monopoles?

- A new particle!
- Magnetic monopole solutions to Maxwell's equations, i.e.,

$$\vec{\nabla} \cdot \vec{B} \neq 0$$

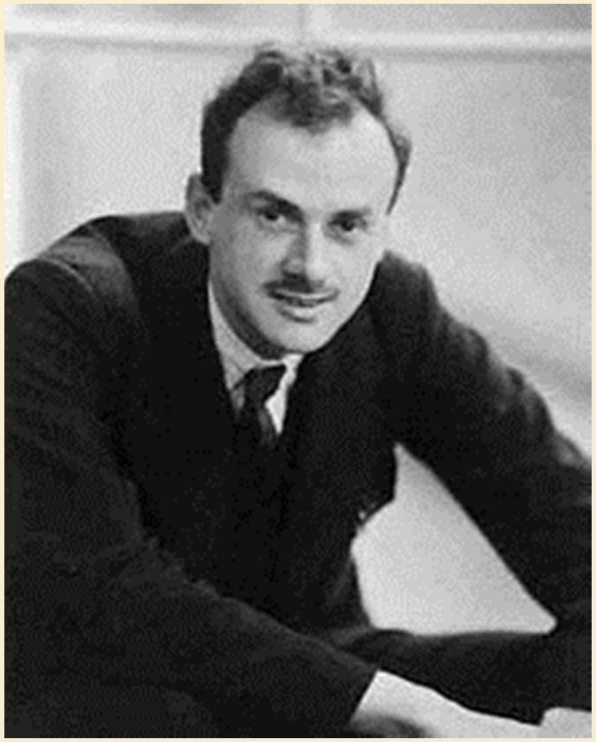
- A possible explanation for (electric) charge quantization!

$$\frac{q_e q_m}{2\pi\hbar} \in Z$$

How are Dirac monopoles produced?

$\vec{A}$ → 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)



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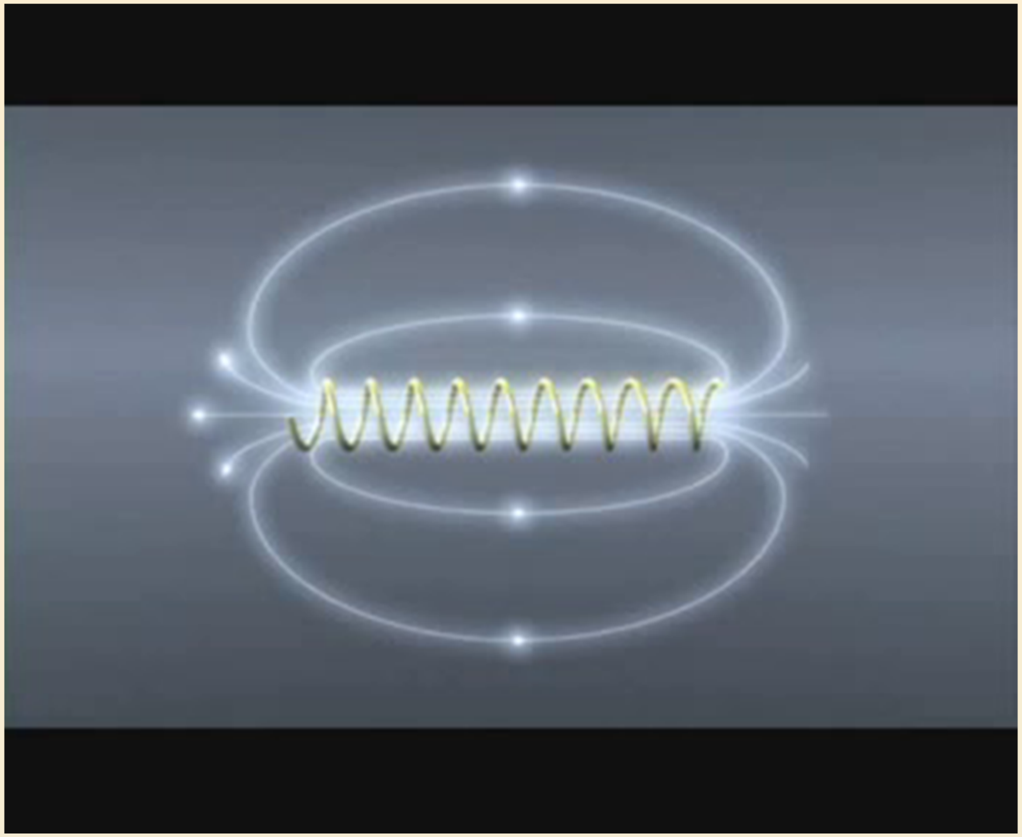
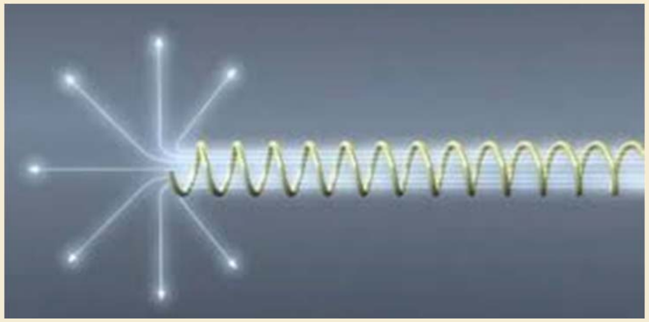




Dirac string visualization

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?

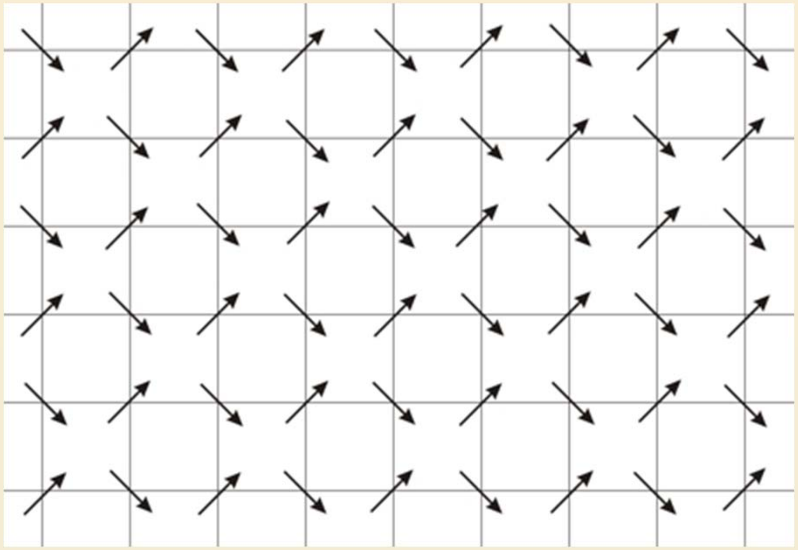
- A way for us to understand “magnetic excitations” in the same way as electronic excitations

- Could a collection of monopoles lead to emergent phenomena?

- Could shed light on properties of actual monopoles

Monopoles in Spin Ice Systems

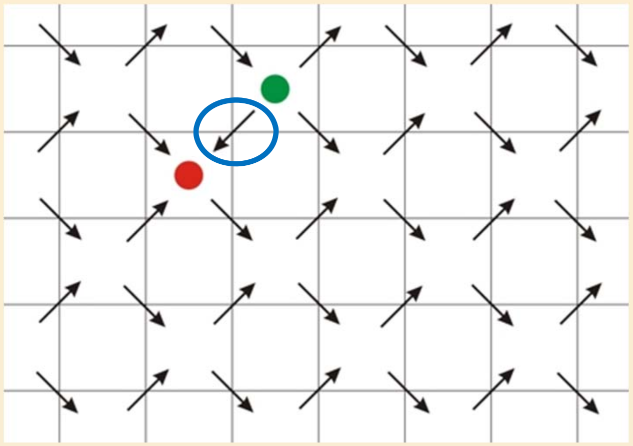
- Degenerate ground state because of geometrical frustration
- Thermal fluctuations near 0 K → Spin flips



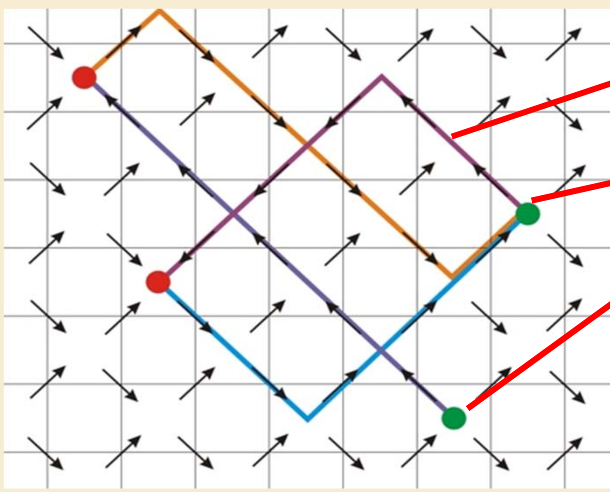
http://www.ctc.cam.ac.uk/

The spins obey the two in- two out ice rule

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

http://www.ctc.cam.ac.uk/

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 → Atoms in a superposition of 3 spin projections:

  m = -1, 0, 1

Real .vs. Emergent Monopoles

Conventional Monopoles	Monopole-like particles in spinor BECs
Sources of the B-field $\vec{\nabla}.\vec{B} \neq 0$	Sources of vorticity $\vec{\nabla} \cdot \vec{\Omega} \neq 0$
$\vec{\nabla} \times \vec{A} = \vec{B}$	$\vec{\nabla} \times v_s = \vec{\Omega}$
“Dirac string” – unobservable, mathematical entity	“Dirac string” analog – Special vortex line that is observable

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

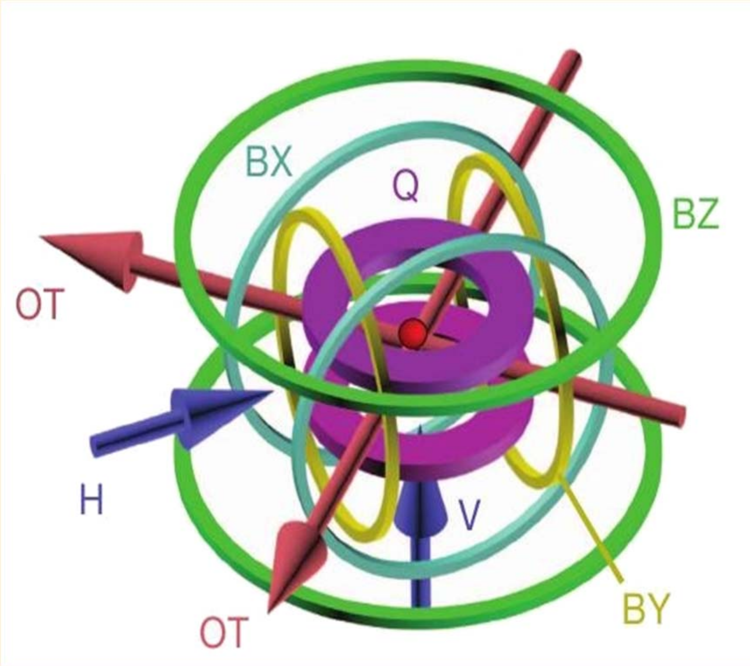
Overview of the Experiment

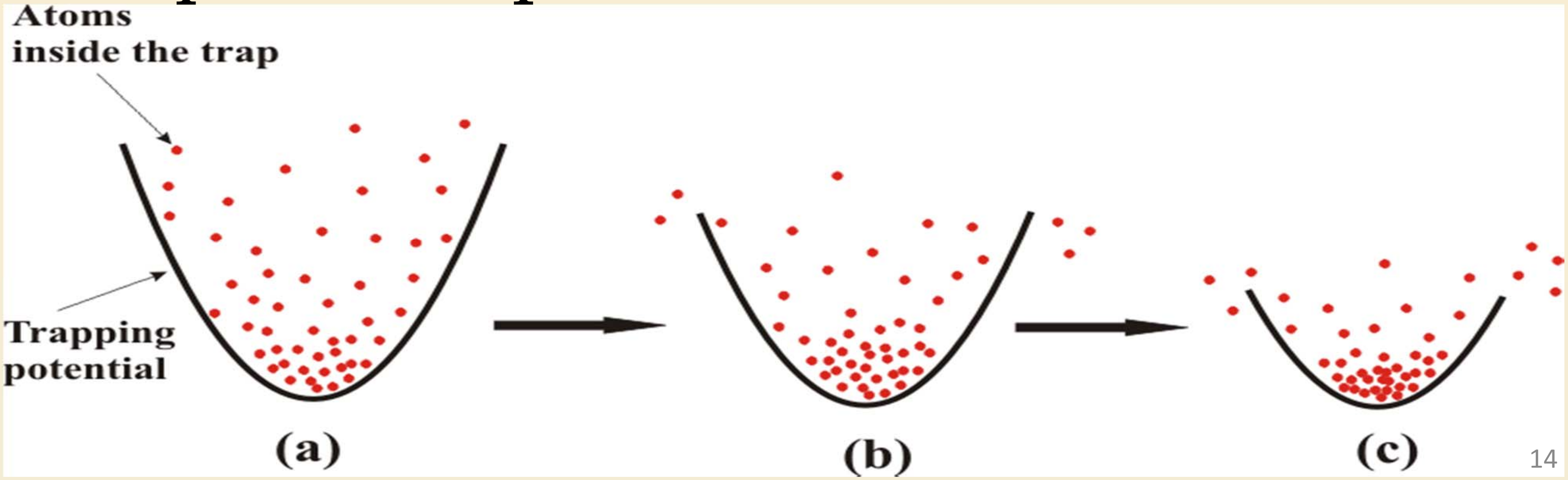
Produce condensate → Create monopole by changing B- field → Image results

- 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

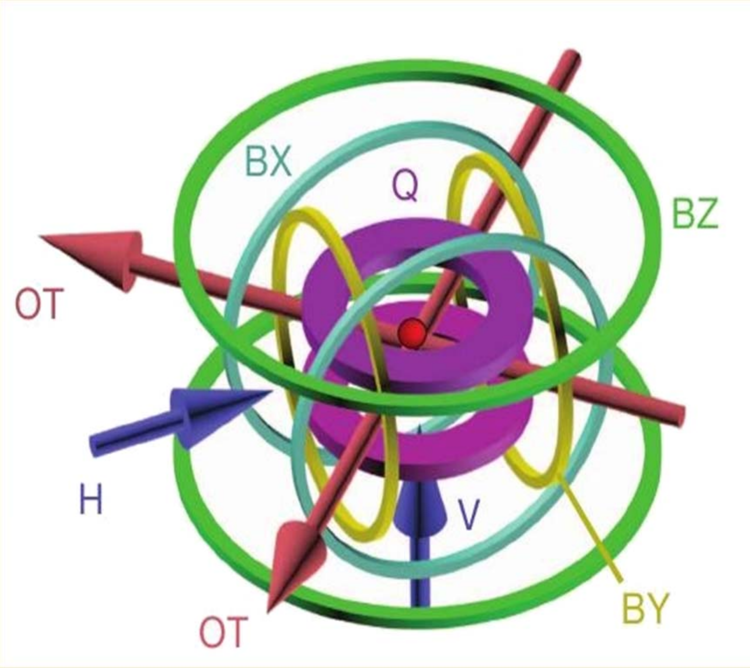




http://cold-atoms.physics.lsa.umich.edu/projects/bec/evaporation.html

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



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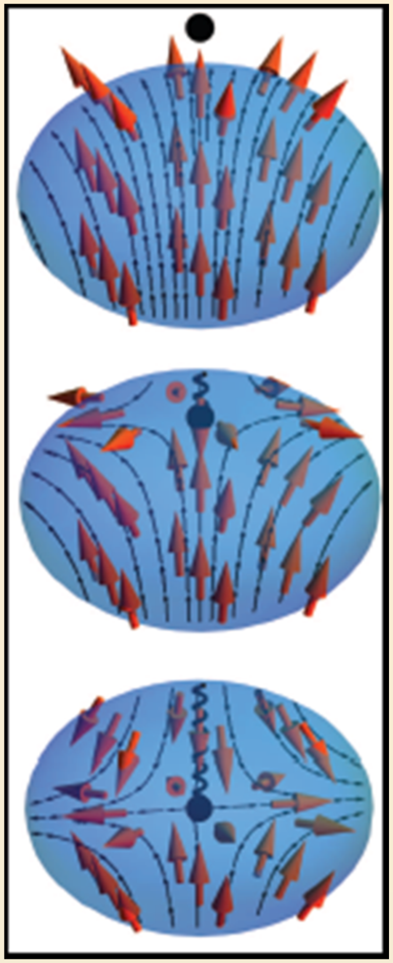
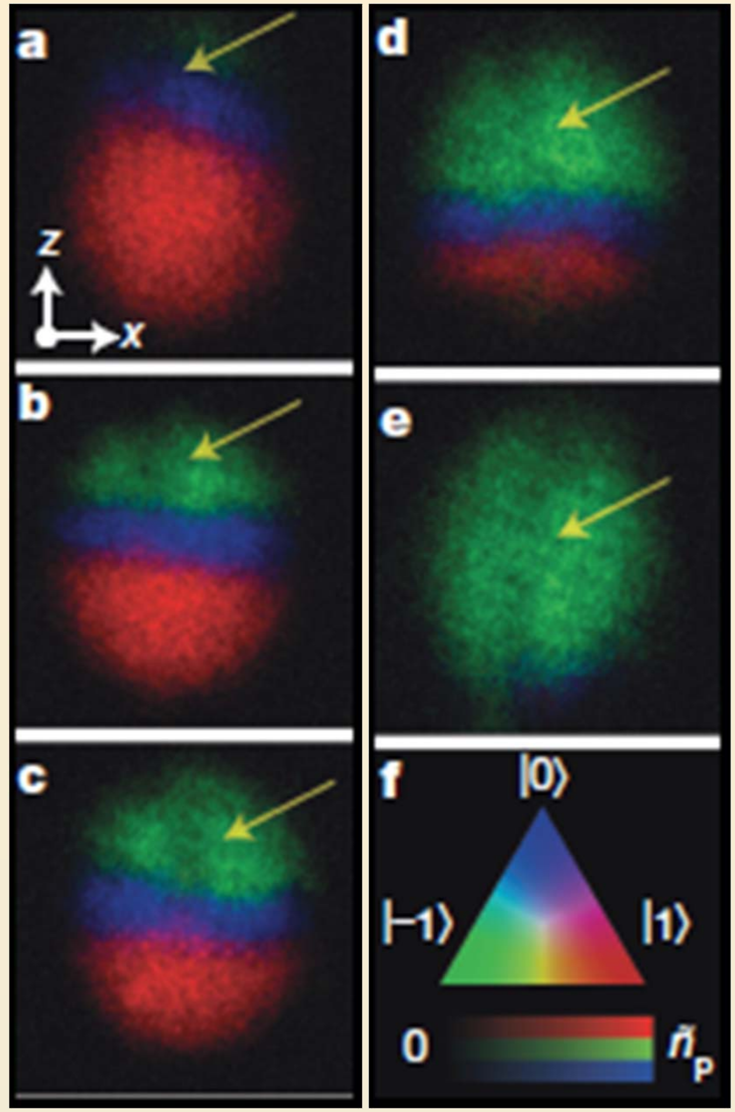


Step 3: Imaging

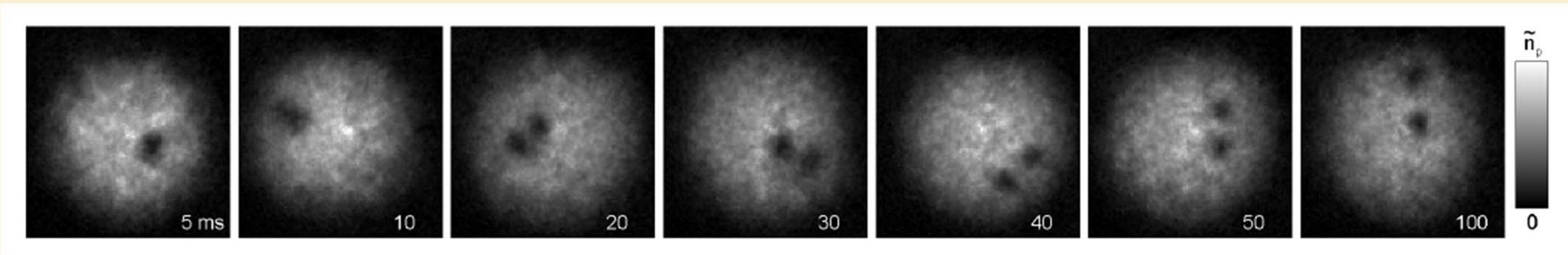
Only a single spin state can be imaged at a time

- 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 Bz field to select a single spin state and image its distribution



RESULTS AND IMPLICATIONS

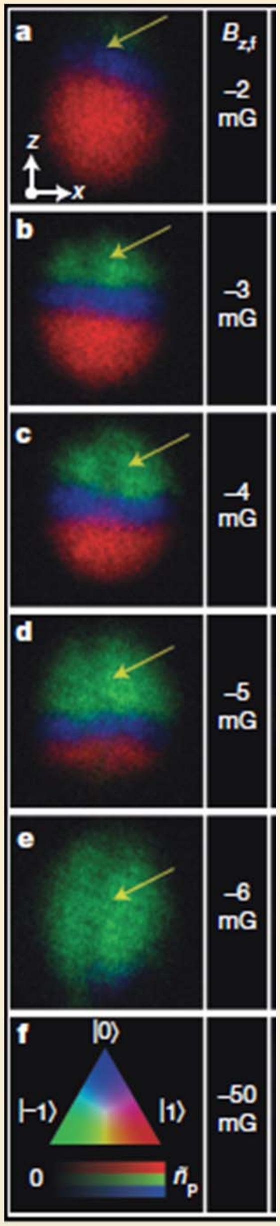
Monopole signature #1: Double Vortex Decay

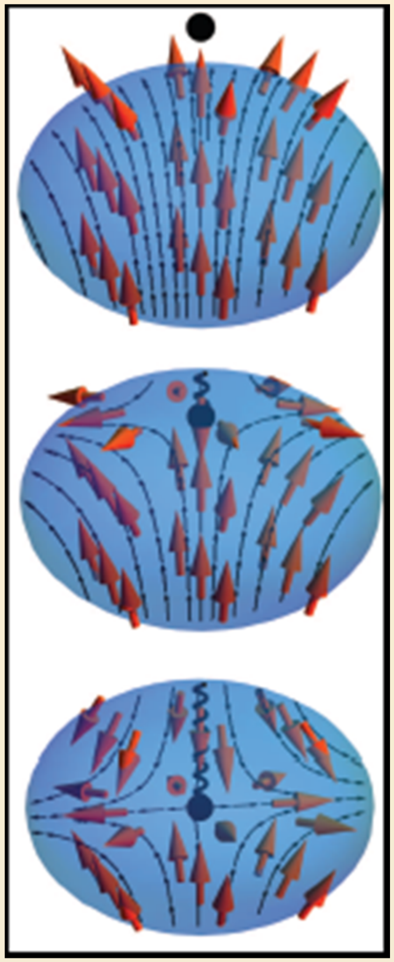


After moving the B-field zero into the condensate, the vortex decays into two, indicating double quantization

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

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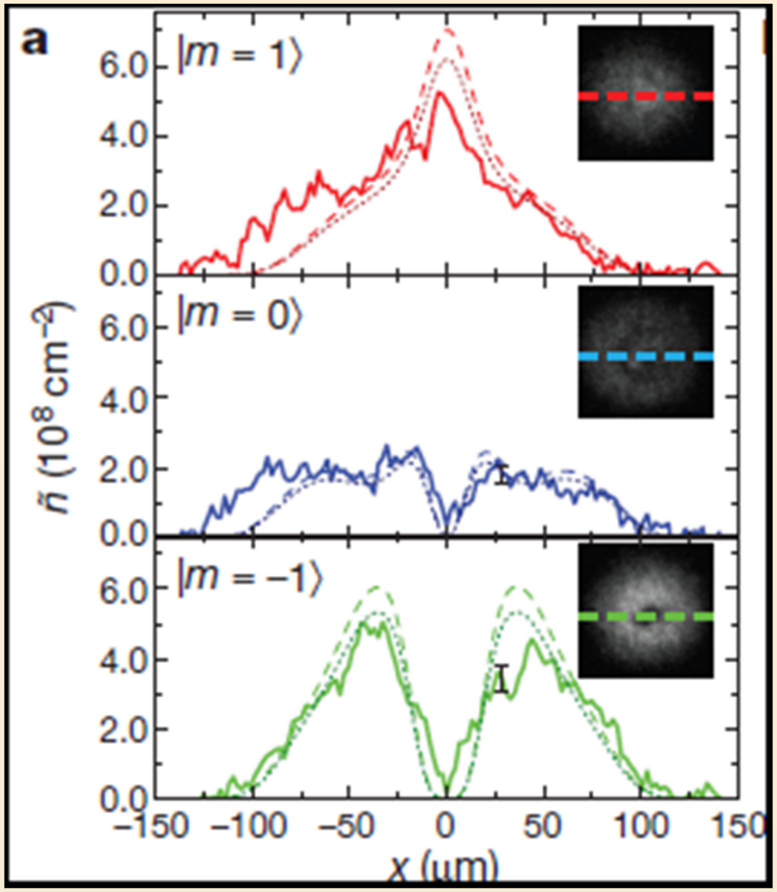


As the zero field region is lowered, the spin distribution changes *precisely* as they would from the movement of a Dirac Monopole

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

Citations

1	U(3) artificial gauge fields for cold atoms Discover full text View at Publisher	Experimental	Hu, Y.-X., Miniatura, C., Wilkowski, D., Grémaud, B.	2014	Physical Review A - Atomic, Molecular, and Optical Physics	0
2	A Raman waveplate for spinor Bose-Einstein condensates Discover full text View at Publisher	Experimental	Schultz, J.T., Hansen, A., Bigelow, N.P.	2014	Optics Letters	0
3	Synthetic Lorentz force in classical atomic gases via Doppler effect and radiation pressure Discover full text View at Publisher	Theoretical	Dubček, T., Šantić, N., Jukić, D., (...), Ban, T., Buljan, H.	2014	Physical Review A - Atomic, Molecular, and Optical Physics	0
4	Momentum-space dynamics of Dirac quasiparticles in correlated random potentials: Interplay between dynamical and Berry phases Discover full text View at Publisher	Theoretical	Lee, K.L., Grémaud, B., Miniatura, C.	2014	Physical Review A - Atomic, Molecular, and Optical Physics	1
5	Creation and dynamics of two-dimensional skyrmions in antiferromagnetic spin-1 Bose-Einstein condensates Discover full text View at Publisher	Same authors	Ollikainen, T., Ruokokoski, E., Möttönen, M.	2014	Physical Review A - Atomic, Molecular, and Optical Physics	0
6	Atomic physics: Polar exploration Discover full text View at Publisher	Review article	Leblanc, L.J.	2014	Nature	0

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

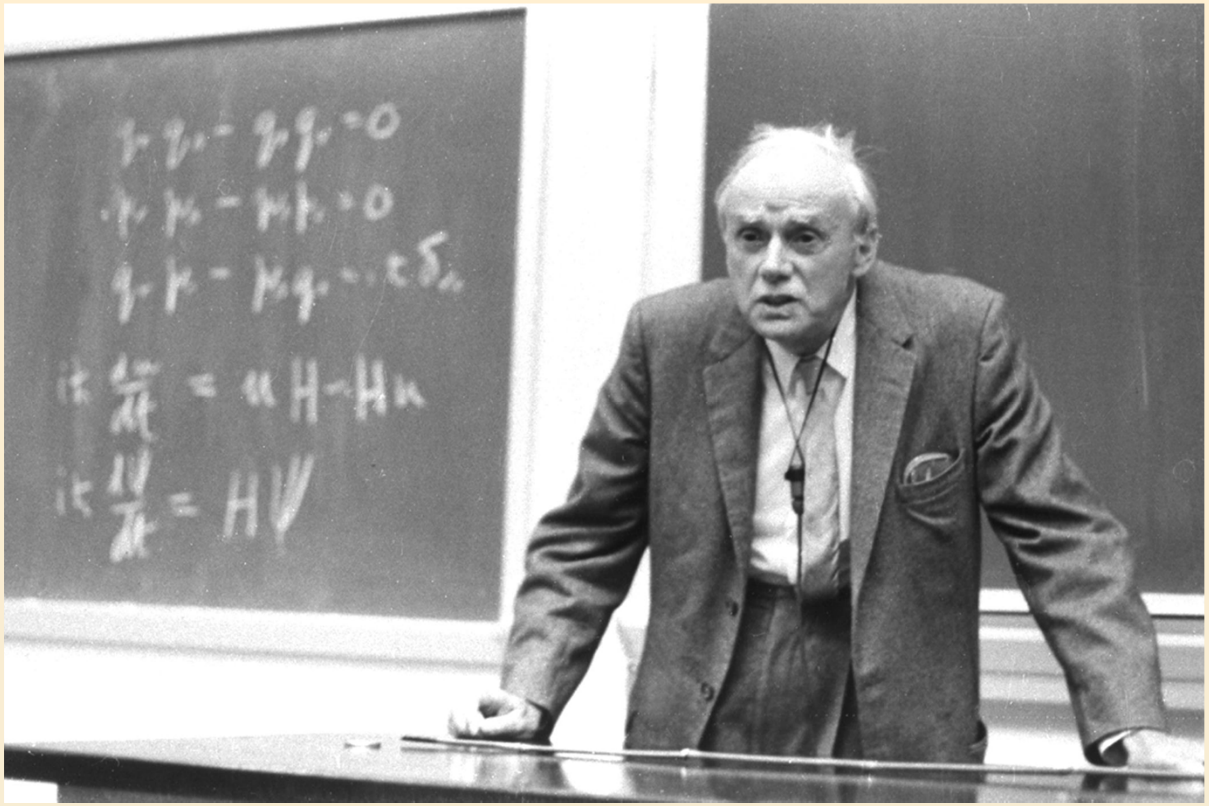
Critiques

- 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!