Spontaneous magnetization in a superfluid vortex

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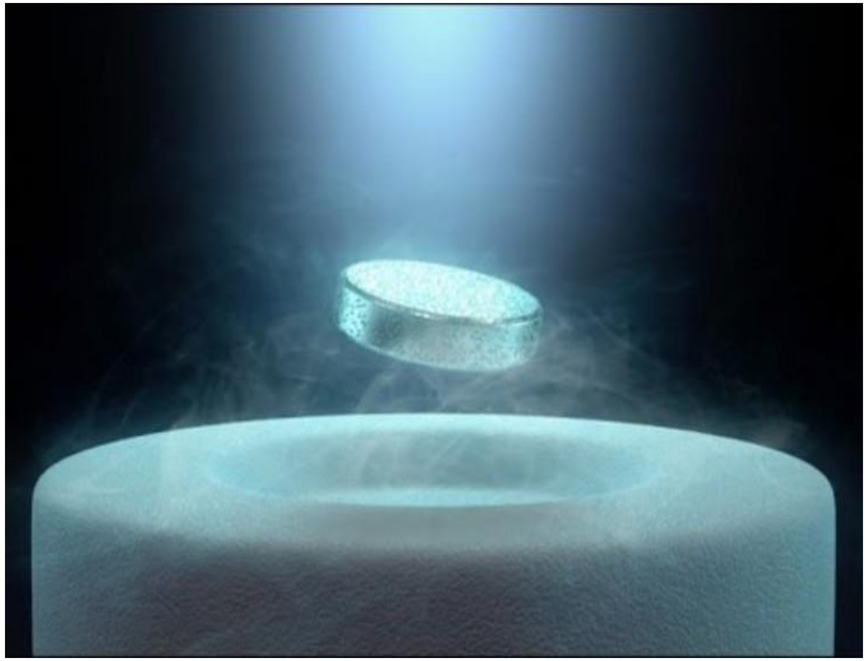
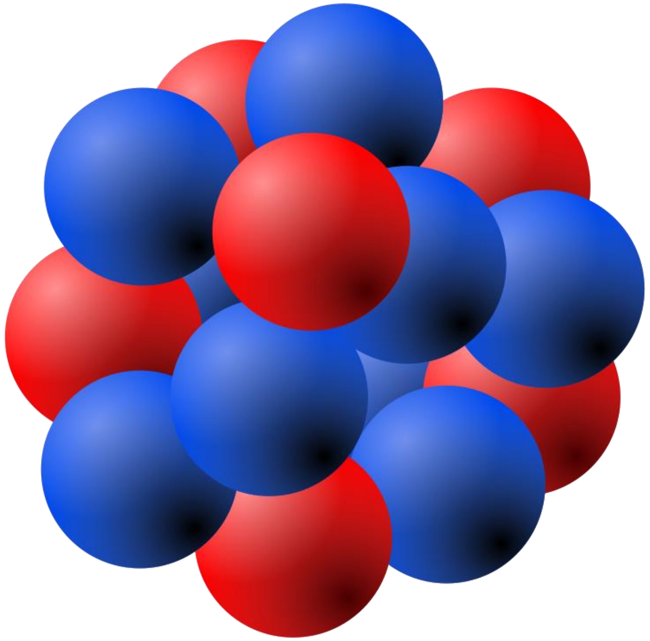
Two of the most important phenomena in many body physics : superfluidity and superconductivity.

They are everywhere..



Metallic superconductor



Heavy nuclei

Neutron star

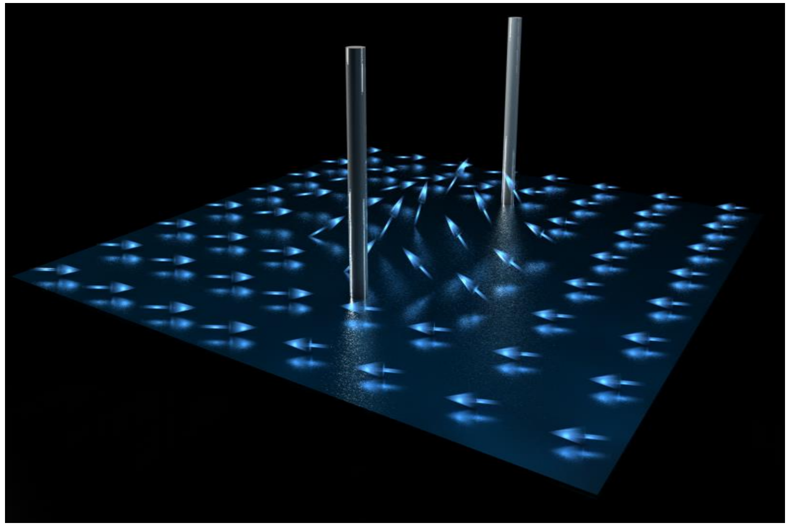
Credit: newatlas.com, U pf Amsterdam, wikipedia

What is superfluidity / superconductivity ?

Condensation of neutral or charged bosons or Cooper pairs.

BEC **BCS**

Macroscopic wave function describing order. → Winding in phase of the wave function →



Credit: phys.org

Vortices

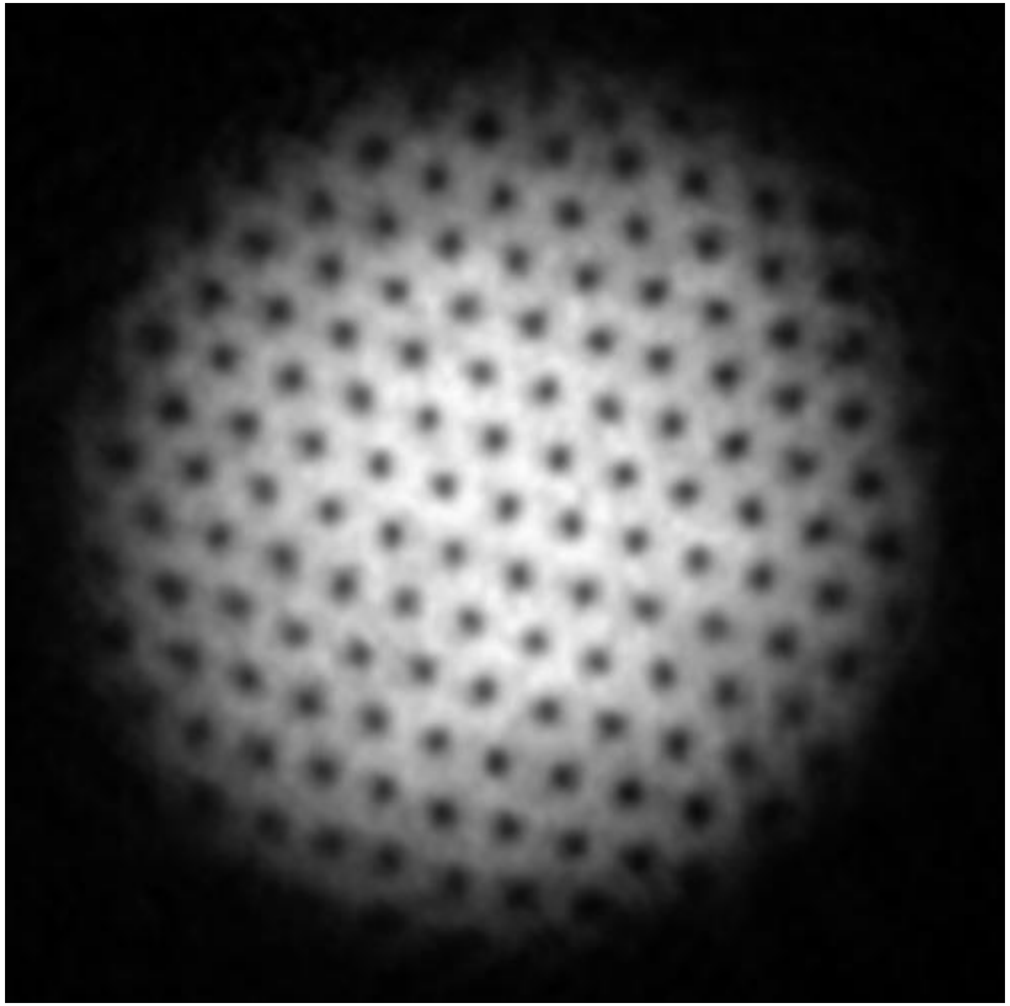
Signature: quantized vortices, flux tubes

Why quantization ?

1. Wave functions are single-valued.

2. Hence winding numbers have to be integers.

3. As a result superconductors contain quantized flux tubes and superfluids have quantized circulation.



Credit: UMD

Remember why metallic superconductors have magnetic flux tubes.

The system is neutral : ionic lattice + electrons.

Ions heavy.. Do not move.

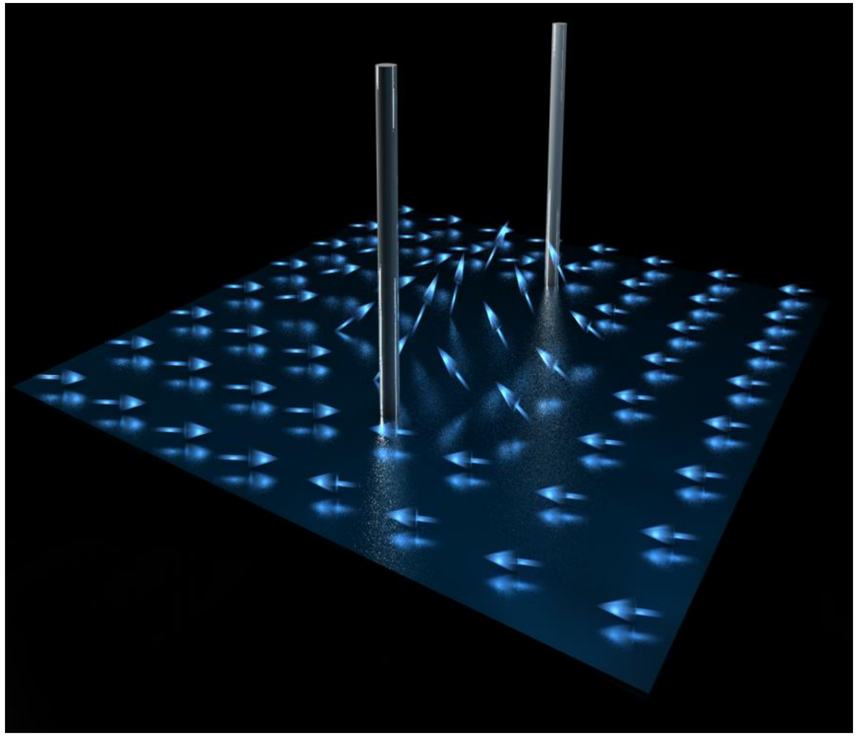
The "almost-free" electrons pair up and form supercurrents around a vortex.

$\longrightarrow$ Magnetic field in the core of the vortex.

What’s the deal with superfluids (BEC)?

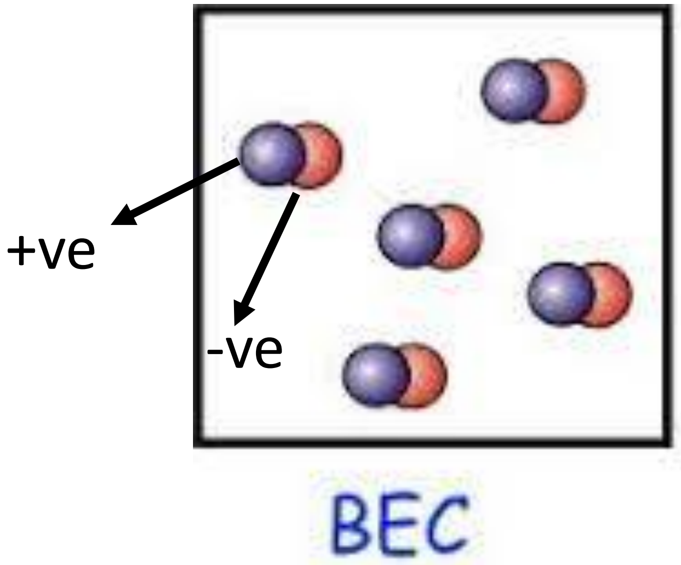
Conventional wisdom : condensing particle is neutral.

no currents… no magnetic field.

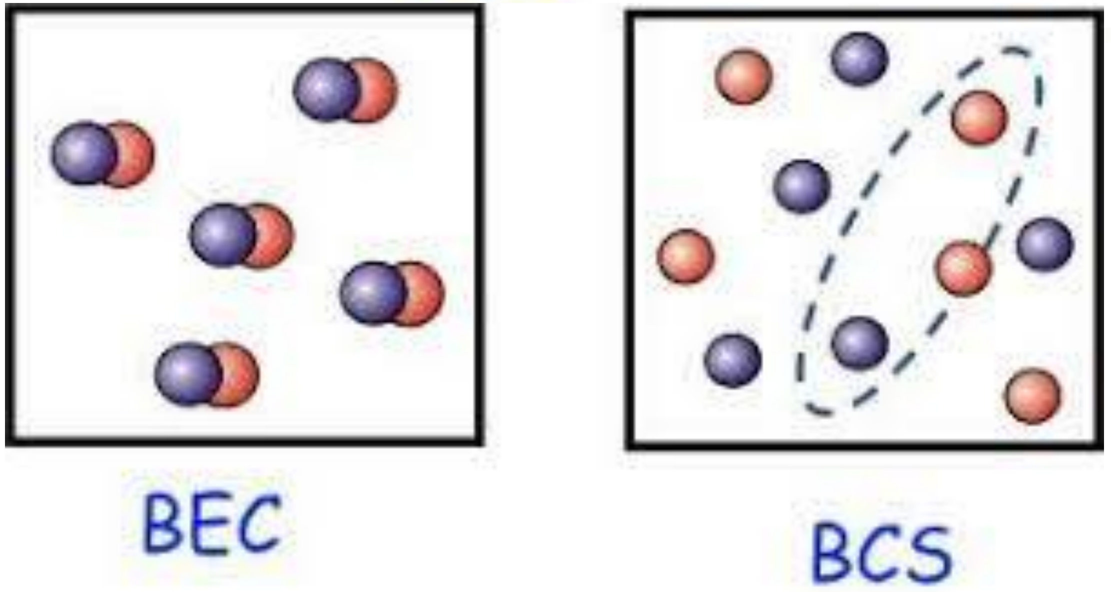


Is this intuition correct ?

Thinking carefully about BEC superfluids.



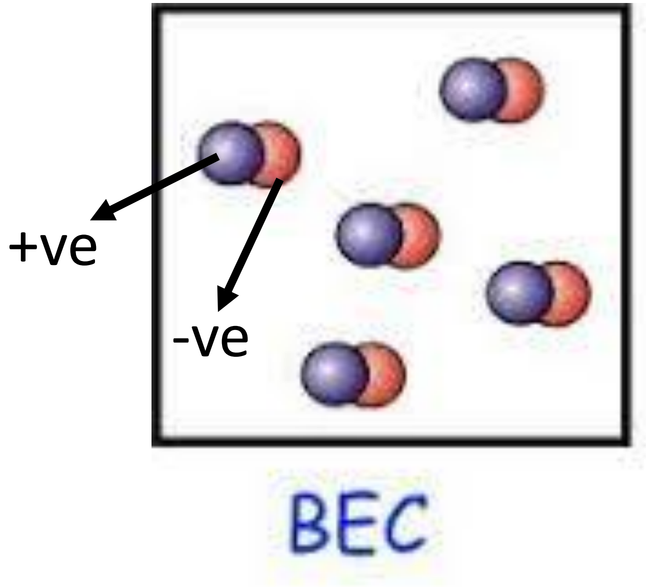
Neutral bosons made of charged excitations.



Difference between BEC and BCS

Credit: physics.stackexchange

Thinking carefully about BEC superfluids.



Then coupling to gauge field possible though $F^{\mu\nu}$.

e.g. superfluid vortices have vorticity near the core : couple to magnetic field ?

In the language of Effective field theory

Neutral atom field

Gauge field strength

$$L = \psi^* \left(\partial_t - \frac{\nabla^2}{2M} \right) \psi + \frac{F^2}{4} + ..$$

Can write operators involving F and the neutral field ψ.

In the language of Effective field theory

Neutral atom field

Gauge field strength

$$L = \psi^* \left(\partial_t - \frac{\nabla^2}{2M} \right) \psi - \mu |\psi|^2 + \lambda |\psi|^4 + \frac{F^2}{4} + ..$$

ψ gets a vacuum expectation value → superfluidity.

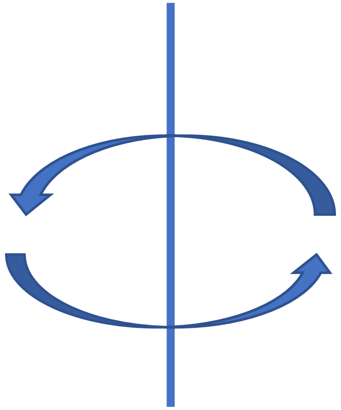
Around a vortex $\psi \sim f(r) e^{i\theta}$.

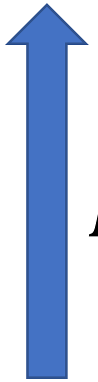
Can I write a (<u>vorticity</u>). B coupling ?

What is a vorticity – B coupling ?

Looks like

$$\underbrace{\left(\partial_i\psi^*\partial_j\psi - \partial_j\psi^*\partial_i\psi\right)}_{\text{vorticity}}F^{ij}$$





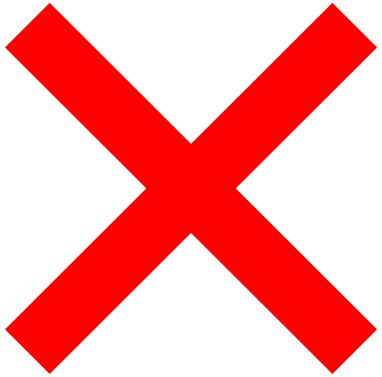
B field

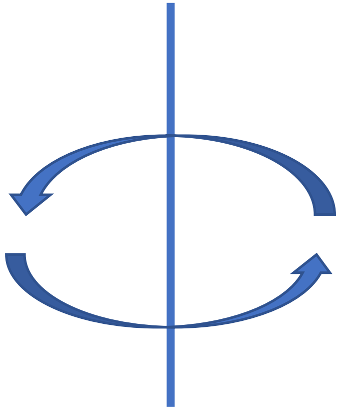
When is a vorticity – B coupling allowed?

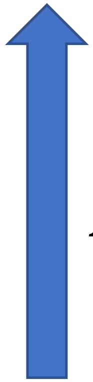
Looks like

$$\underbrace{\left(\partial_i\psi^*\partial_j\psi - \partial_j\psi^*\partial_i\psi\right)}_{\text{vorticity}}F^{\mu\nu}$$

If $A \to -A$ is a symmetry

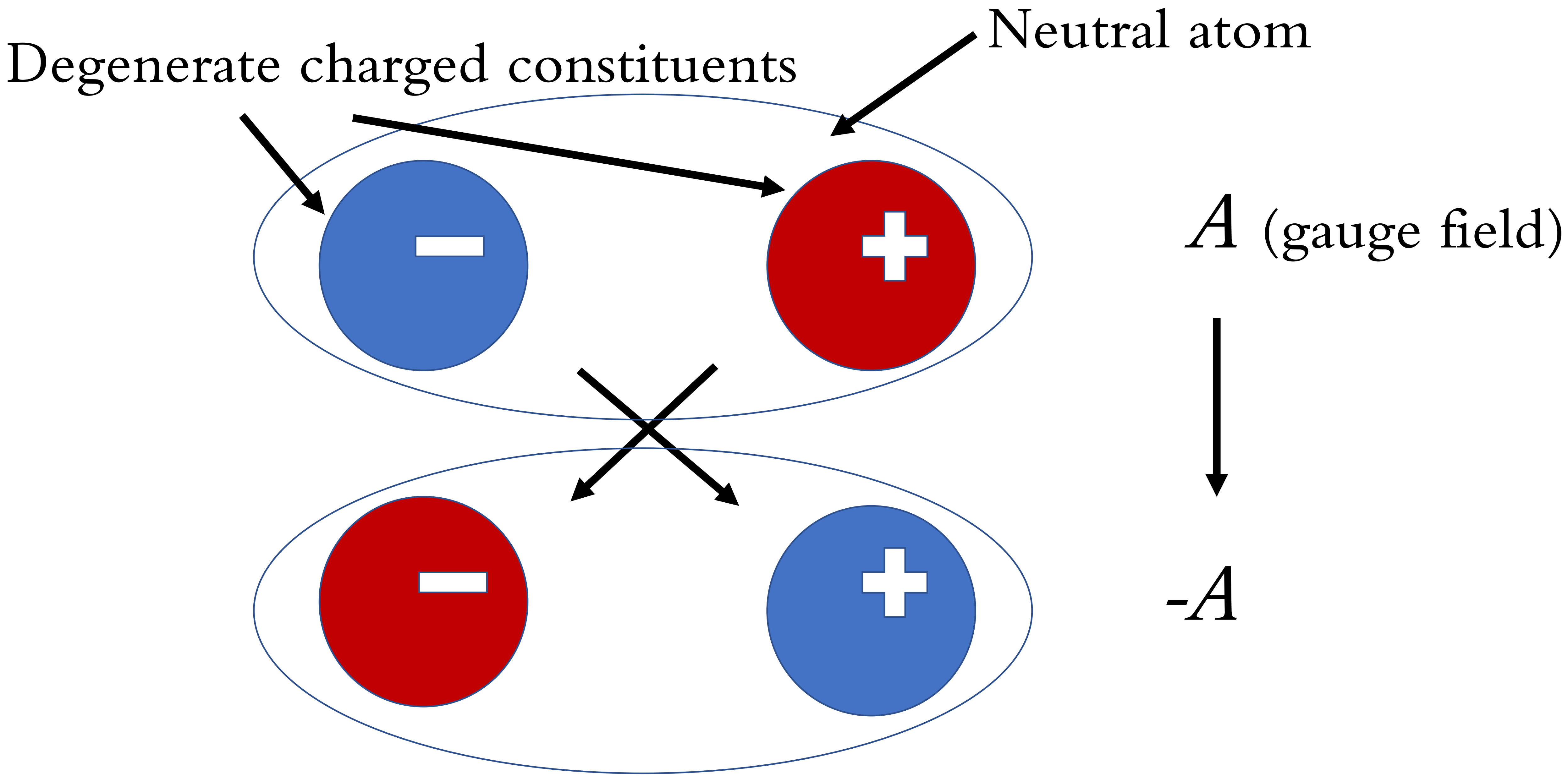




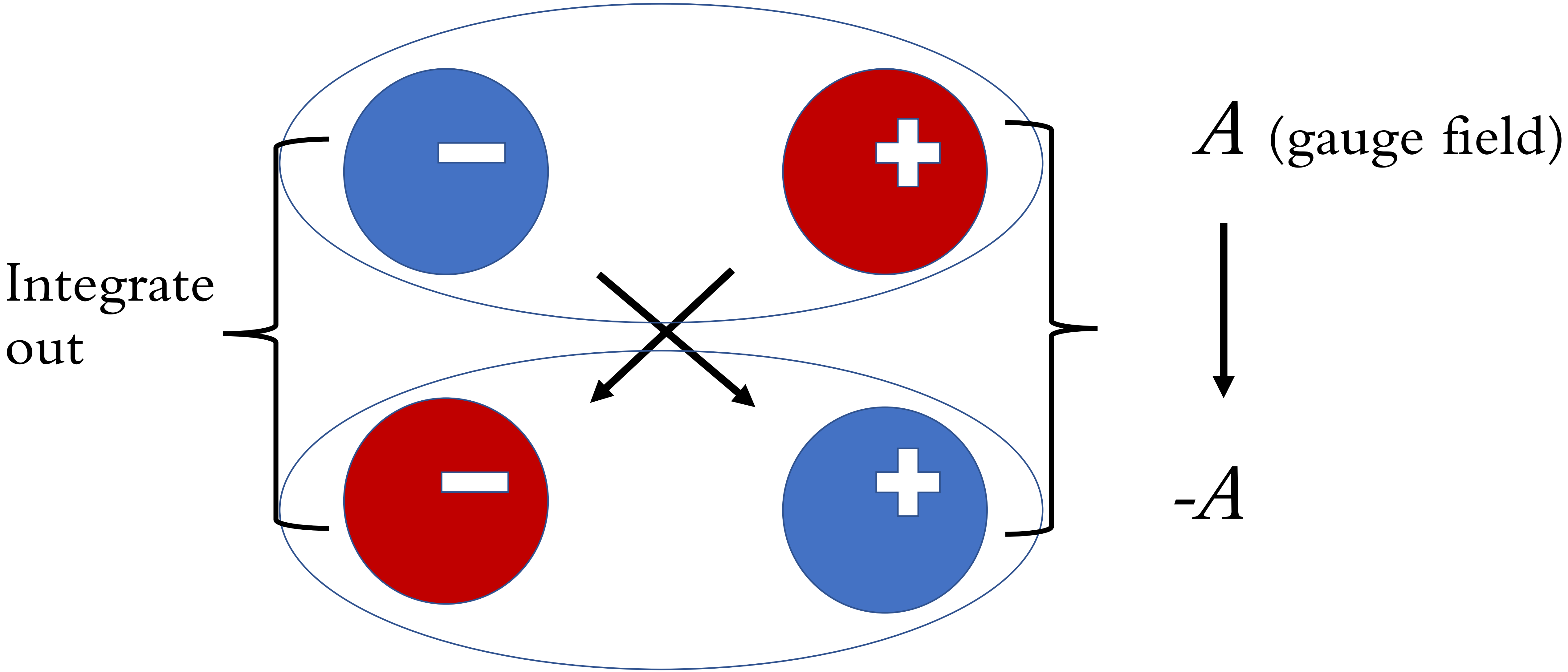


B field

Effective field theory : Flavor flip symmetry



Effective field theory :



Effective field theory :

A (gauge field)

$\downarrow$

$-A$

Effective field theory :

A (gauge field)

$$A \longrightarrow -A$$

No operator with linear power of the gauge field : no vorticity magnetic field coupling.

Effective field theory

In the absence of degeneracy, vorticity-magnetic field coupling is allowed. Assume far from degeneracy.

Neutral atom field

$$L = \psi^* \left(\partial_t - \frac{\nabla^2}{2M} \right) \psi - \mu |\psi|^2 + \lambda |\psi|^4 + \frac{F^2}{4}$$

Low energy constant

$$+$$

$$\frac{b}{\lambda^\alpha} \left(\partial_i \psi^* \partial_j \psi - \partial_j \psi^* \partial_i \psi \right) F^{ij}$$

Dimensionful scale

$b \sim O(1)$: to be obtained by a matching calculation.

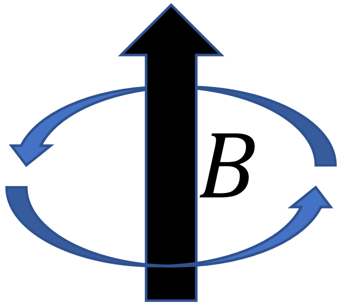
What is λ ? It is set by the inverse Bohr radius of the atom.

What is α ? Using the relevant power counting $\alpha = 2$.

$$\Rightarrow \quad e\,\frac{a_0^2}{M}\left(\partial_i\psi^*\partial_j\psi - \partial_j\psi^*\partial_i\psi\right)F^{ij}$$

$$\underbrace{e\,\frac{a_0^2}{M}\left(\partial_i\psi^*\partial_j\psi - \partial_j\psi^*\partial_i\psi\right)}_{S_{ij}\,=\,\text{vorticity}}F^{ij}$$

Integrate by parts to write as $\longrightarrow$ $$A^i\underbrace{\partial_j S^{ij}}_{\text{Current around vortex core}}$$



Another way to estimate the flux

The energy density in the magnetic field and vortex

$$\epsilon = B^2 + S.B$$

The magnetic field profile can be determined by equating

$$B^2 \sim B.S$$

$$\psi(r,\theta) = f(r)e^{i\theta} \longrightarrow \text{vorticity} = \frac{f(r)f'(r)}{r}\frac{e\,a_0^2}{M}$$

Compute the flux

$$\Phi \sim e\,\frac{a_0^2}{M} f_0^2 \,:\, f_0 = f(r \to \infty)$$

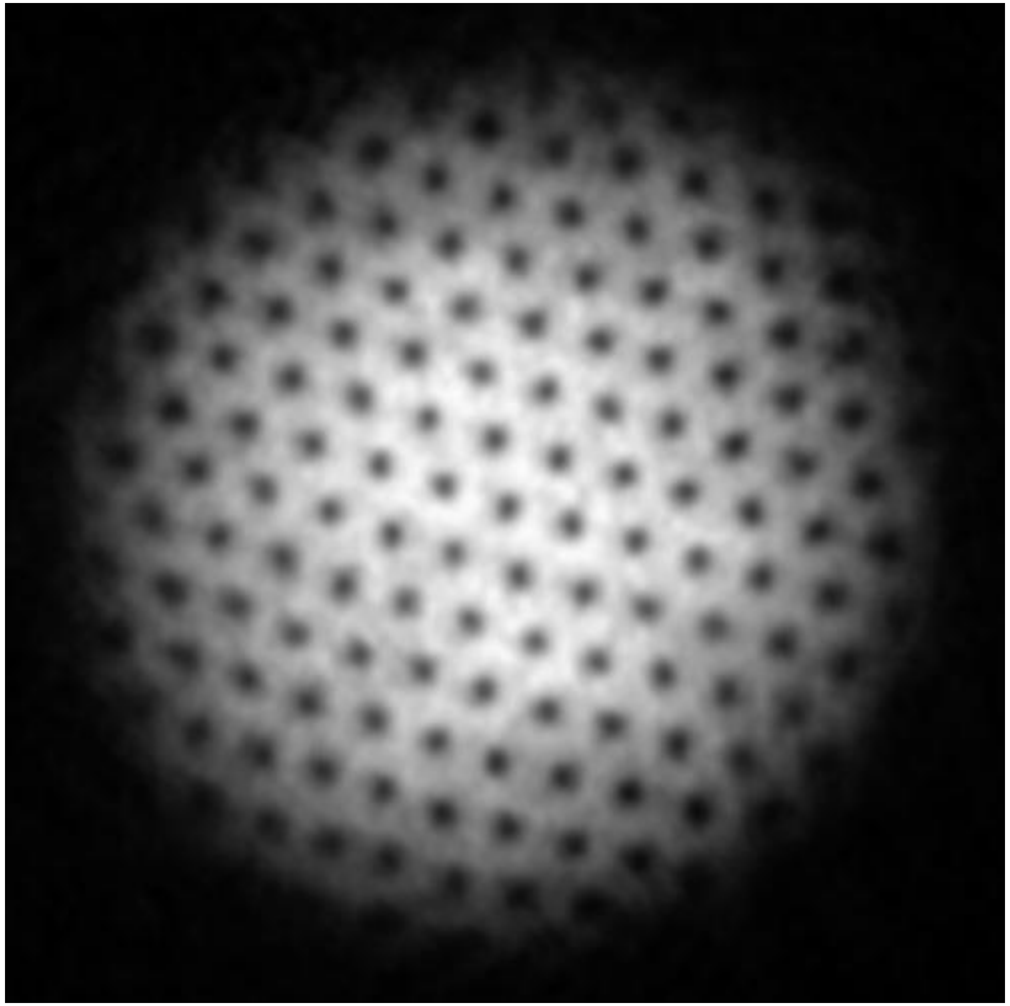
f_0 is related to density or interparticle spacing

$$\Rightarrow \quad \frac{\Phi}{\Phi_0} \sim \frac{e}{M\,a_0}\left(\frac{a_0}{l}\right)^3 \sim 10^{-10} \text{ for Helium}$$

l is interparticle spacing.

Final message

Spin-0 superfluid vortices can carry magnetic fields in their core.



We believe this magnetic field is experimentally observable.

See our forthcoming paper..