MAGNET is being levitated by an unseen superconductor in which countless trillions of electrons form a vast interconnected quantum state. Astoundingly, the quantum state of many modern materials is subtly related to the mathematics of black holes.

Quantum Entanglement and Superconductivity

Subir Sachdev, Perimeter Institute and Harvard University
In a landmark study, scientists at Delft University of Technology in the Netherlands reported that they had conducted an experiment that they say proved one of the most fundamental claims of quantum theory — that objects separated by great distance can instantaneously affect each other’s behavior.

Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.
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High temperature superconductors

$\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$
Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University
Efficient Rotating Machines

Power Efficiency/Capacity/Stability

Power Bottlenecks

Accommodate Renewable Power

Information Technology

Next Generation HEP

Ultra-High Magnetic Fields

Medical

Transport

Slide by J. C. Seamus Davis
Quantum superposition and entanglement
The double slit experiment

Interference of water waves
Principles of Quantum Mechanics: 1. Quantum Superposition

The double slit experiment

Interference of water waves
Principles of Quantum Mechanics: 1. Quantum Superposition

The double slit experiment

Send electrons through the slits
Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

Interference of electrons
The double slit experiment

Is the electron a wave?

Interference of electrons
The double slit experiment

Unlike water waves, electrons arrive one-by-one (so is it like a particle?)

Interference of electrons
The double slit experiment

Unlike water waves, electrons arrive one-by-one (so is it like a particle?)

Interference of electrons
The double slit experiment

But if it is like a particle, which slit does each electron pass through?

Interference of electrons
Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

But if it is like a particle, which slit does each electron pass through?

No interference when you watch the electrons

Interference of electrons
The double slit experiment

But if it is like a particle, which slit does each electron pass through?

Each electron passes through both slits!

Interference of electrons
Let $|L\rangle$ represent the state with the electron in the left slit.
The double slit experiment

Let $|L\rangle$ represent the state with the electron in the left slit.

And $|R\rangle$ represents the state with the electron in the right slit.

**Principles of Quantum Mechanics: 1. Quantum Superposition**
The double slit experiment

Let $|L\rangle$ represent the state with the electron in the left slit.

And $|R\rangle$ represents the state with the electron in the right slit.

Actual state of each electron is $|L\rangle + |R\rangle$. 

Principles of Quantum Mechanics: 1. Quantum Superposition
Quantum Entanglement: quantum superposition with more than one particle
Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:
Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

Hydrogen molecule:

\[
\begin{align*}
\text{Hydrogen atom:} & \quad \bullet \quad | \uparrow \rangle \\
\text{Hydrogen molecule:} & \quad \bullet \quad \bullet \quad + \quad \bullet \quad \bullet \\
& \quad = \quad \bullet \quad \bullet \quad | \uparrow \rangle \quad + \quad | \downarrow \rangle \\
& \quad = \quad \frac{1}{\sqrt{2}} \left( | \uparrow \downarrow \rangle - | \downarrow \uparrow \rangle \right)
\end{align*}
\]
Quantum Entanglement: quantum superposition with more than one particle
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Quantum Entanglement: quantum superposition with more than one particle

Einstein-Podolsky-Rosen “paradox”: Measurement of one particle instantaneously determines the state of the other particle arbitrarily far away
Quantum superposition and entanglement
Quantum phase transitions
Quantum superposition and entanglement
Quantum theory of black holes

Long-range quantum entanglement of electrons in matter:
(A) superconductors
(B) graphene
Quantum superposition and entanglement

Long-range quantum entanglement of electrons in matter:
(A) superconductors
(B) graphene

Quantum theory of black holes
High temperature superconductors

\[ YBa_2Cu_3O_{6+x} \]
Strange metal
Antiferromagnet
Superconductor

Figure: K. Fujita and J. C. Seamus Davis
Antiferromagnet

Spins of electrons on Cu sites

Figure: K. Fujita and J. C. Seamus Davis
Square lattice of Cu sites
Square lattice of Cu sites

Remove density $p$ electrons
Square lattice of Cu sites

Electrons entangle in ("Cooper") pairs into chemical bonds
Square lattice of Cu sites

Cooper pairs form quantum superpositions at different locations: "Bose-Einstein condensation" in which all pairs are "everywhere at the same time"
Square lattice of Cu sites

Cooper pairs form quantum superpositions at different locations: “Bose-Einstein condensation” in which all pairs are “everywhere at the same time”

\[ | \uparrow \downarrow \rangle - | \downarrow \uparrow \rangle \]
Square lattice of Cu sites

Superconductivity!

Cooper pairs form quantum superpositions at different locations: “Bose-Einstein condensation” in which all pairs are “everywhere at the same time”

\[
\left| \uparrow \downarrow \right\rangle - \left| \downarrow \uparrow \right\rangle = 0
\]
Cooper pairs form quantum superpositions at different locations: “Bose-Einstein condensation” in which all pairs are “everywhere at the same time”
Electrons entangle by exchanging partners, and there is long-range quantum entanglement near the strange metal.
Square lattice of Cu sites

High temperature superconductivity?

Electrons entangle by exchanging partners, and there is long-range quantum entanglement near the strange metal.

\[ = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \]
Square lattice of Cu sites

High temperature superconductivity?

Electrons entangle by exchanging partners, and there is long-range quantum entanglement near the strange metal.
Square lattice of Cu sites

High temperature superconductivity?

Electrons entangle by exchanging partners, and there is long-range quantum entanglement near the strange metal.

\[ \begin{pmatrix} \uparrow \downarrow \downarrow \uparrow \end{pmatrix} - \begin{pmatrix} \downarrow \downarrow \uparrow \uparrow \end{pmatrix} \]
Square lattice of Cu sites

High temperature superconductivity?

Electrons entangle by exchanging partners, and there is long-range quantum entanglement near the strange metal.
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\[ = | \uparrow \downarrow \rangle - | \downarrow \uparrow \rangle \]
Square lattice of Cu sites

High temperature superconductivity?

Electrons entangle by exchanging partners, and there is long-range quantum entanglement near the strange metal.

\[ = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \]
Antiferromagnet

Strange metal

Superconductor

Figure: K. Fujita and J. C. Seamus Davis
Quantum superposition and entanglement

Long-range quantum entanglement of electrons in matter:
(A) superconductors
(B) graphene

Quantum theory of black holes
Graphene

A single layer of carbon atoms in a honeycomb lattice
Graphene

\[
\sim 1 \sqrt{n} (1 + \lambda \ln \Lambda \sqrt{n})
\]

\[n = \frac{10^{12}}{m^2}\]

Electron Fermi liquid

Hole Fermi liquid

Dirac liquid

M. Müller, L. Fritz, and S. Sachdev, PRB 78, 115406 (2008)
M. Müller and S. Sachdev, PRB 78, 115419 (2008)
The strange metal is a much better conductor of heat than electricity, when compared to ordinary metals.

M. Müller, L. Fritz, and S. Sachdev, PRB 78, 115406 (2008)
M. Müller and S. Sachdev, PRB 78, 115419 (2008)

Quantum superposition and entanglement

Long-range quantum entanglement of electrons in matter:
(A) superconductors
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Quantum theory of black holes
Quantum superposition and entanglement

Long-range quantum entanglement of electrons in matter:
(A) superconductors
(B) graphene

Quantum theory of black holes
Horizon radius $R = \frac{2GM}{c^2}$

Objects so massive that light is gravitationally bound to them.

In Einstein’s theory, the region inside the black hole horizon is disconnected from the rest of the universe.
Around 1974, Bekenstein and Hawking showed that the application of the quantum theory across a black hole horizon led to many astonishing conclusions.
Quantum Entanglement across a black hole horizon
Quantum Entanglement across a black hole horizon

Black hole horizon
Quantum Entanglement across a black hole horizon
Quantum Entanglement across a black hole horizon

There is long-range quantum entanglement between the inside and outside of a black hole.
Quantum Entanglement across a black hole horizon

Hawking used this to show that black hole horizons have an entropy and a temperature.
Quantum Entanglement across a black hole horizon

The Hawking entropy matches the entropy of some simple strange metal states of electrons

(S. Sachdev, 2015)
Quantum Entanglement across a black hole horizon

The Hawking entropy matches the entropy of some simple strange metal states of electrons

(S. Sachdev, 2015)

The dynamics of black hole horizons has many similarities to strange metals, and this has led us to a better understanding of the observable properties of strange metals in superconductors and other quantum materials.
Quantum superposition and entanglement
Quantum superposition and entanglement

Quantum theory of black holes

Long-range quantum entanglement of electrons in matter:
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Superconductor, levitated by an unseen magnet, in which countless trillions of electrons form a vast interconnected quantum state. Scientific American, January 2013

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