Quantum entanglement: “Spooky action at distance” in the lab, and in black holes

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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.
Quantum entanglement
The double slit experiment

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

The double slit experiment

Bullets
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
Principles of Quantum Mechanics: I. Quantum Superposition

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

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

Interference of electrons
The double slit experiment

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

Interference of electrons

No interference when you watch the 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

Principles of Quantum Mechanics: 1. Quantum Superposition
Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

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

$$|L\rangle + |R\rangle$$
Quantum Entanglement: quantum superposition with more than one particle
Quantum Entanglement: quantum superposition with more than one particle

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

Hydrogen atom:

\[
\begin{align*}
\text{Hydrogen molecule:} & = \begin{pmatrix} |\uparrow\rangle \end{pmatrix} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)
\end{align*}
\]
Quantum Entanglement: quantum superposition with more than one particle
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Einstein-Podolsky-Rosen “paradox” (1935): Measurement of one particle instantaneously determines the state of the other particle arbitrarily far away.
Quantum entanglement
Quantum entanglement

Black holes
Black Holes

Objects so dense 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.

Horizon radius \( R = \frac{2GM}{c^2} \)
On September 14, 2015, LIGO detected the merger of two black holes, each weighing about 30 solar masses, with radii of about 100 km, 1.3 billion light years away.
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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
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.
Hawking used this to show that black hole horizons have an entropy and a temperature (because to an outside observer, the state of the electron inside the black hole is an unknown)
Quantum entanglement

Black holes
Quantum entanglement

Black holes

Superconductors
High temperature superconductors

YBa$_2$Cu$_3$O$_{6+x}$
Nd-Fe-B magnets, YBaCuO superconductor
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
Square lattice of Cu sites
Square lattice of Cu sites

Remove some electrons
Square lattice of Cu sites

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

Electrons entangle “en masse” by exchanging partners, and there is long-range quantum entanglement

\[ | \uparrow \downarrow \rangle - | \downarrow \uparrow \rangle \]
Electrons entangle “en masse” by exchanging partners, and there is long-range quantum entanglement.
Square lattice of Cu sites

Electrons entangle “en masse” by exchanging partners, and there is long-range quantum entanglement.

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

Electrons entangle “en masse” by exchanging partners, and there is long-range quantum entanglement.
Square lattice of Cu sites

Electrons entangle “en masse” by exchanging partners, and there is long-range quantum entanglement.
Quantum entanglement

A “toy model” which describes both a superconductor and a black hole!
The Sachdev-Ye-Kitaev (SYK) model

Pick a set of random positions
The SYK model

Place electrons randomly on some sites
The SYK model

Place electrons randomly on some sites
Entangle electrons pairwise randomly
Entangle electrons pairwise randomly
The SYK model

Entangle electrons pairwise randomly
Entangle electrons pairwise randomly
The SYK model

Entangle electrons pairwise randomly
Entangle electrons pairwise randomly
The SYK model

Entangle electrons pairwise randomly
The SYK model

Entangle electrons pairwise randomly
Entangle electrons pairwise randomly
The SYK model

Entangle electrons pairwise randomly
Entangle electrons pairwise randomly
The SYK model

This describes both a superconductor and a black hole!
Maxwell’s electromagnetism and Einstein’s general relativity allow black hole solutions with a net charge.
Maxwell’s electromagnetism and Einstein’s general relativity allow black hole solutions with a net charge. Zooming into the near-horizon region of a charged black hole at low temperature, yields a quantum theory in one space ($\xi$) and one time dimension.
Maxwell’s electromagnetism and Einstein’s general relativity allow black hole solutions with a net charge.

The quantum versions of Maxwell’s and Einstein’s equations in this two-dimensional spacetime are also the equations describing electron entanglement in the SYK model.
Maxwell’s electromagnetism and Einstein’s general relativity allow black hole solutions with a net charge. This has led to a deeper understanding of entanglement in superconductors and of Hawking’s black hole information “paradox”.
Quantum entanglement

Black holes

Superconductors

A “toy model” which describes both a superconductor and a black hole!