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.
Ultra-spooky action at a distance: from quantum materials in the lab to black holes

Helen and Morton Sternheim Lecture
University of Massachusetts, Amherst
March 10, 2020

Subir Sachdev
Talk online: sachdev.physics.harvard.edu
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
Principles of Quantum Mechanics: 1. Quantum Superposition

The double slit experiment

Interference of water waves
The double slit experiment

Electron source

TWO SLITS

Interference of electrons
The double slit experiment

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

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 $|L\rangle + |R\rangle$.
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:

\[ = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \]

Hydrogen molecule:
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
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 \( R = \frac{2GM}{c^2} \)

\( G \) Newton’s constant, \( c \) velocity of light, \( M \) mass of black hole
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 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 (because to an outside observer, the state of the electron inside the black hole is an unknown)
Quantum Black holes

- Black holes have an entropy and a temperature, $T_H$
- The entropy is proportional to their surface area.

J. D. Bekenstein, PRD 7, 2333 (1973)
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 0.1 seconds later!
The ring-down time \( \frac{8\pi GM}{c^3} \) \( \sim \) 8 milliseconds. Curiously, for essentially all types of black holes, the ring-down time equals \( \frac{\hbar}{k_B T_H} \), \( \hbar \) Planck’s constant, \( k_B \) Boltzmann’s constant.
Black holes have an entropy and a temperature, $T_H$.

The entropy is proportional to their surface area.

They relax to thermal equilibrium in a Planckian time $\sim \hbar/(k_B T_H)$. 

Quantum Black holes
Quantum entanglement

Black holes
Quantum phase transitions
Metals (ordinary and strange) and superconductors
Black holes
Quantum entanglement
Ordinary metals are shiny, and they conduct heat and electricity efficiently. Each atom donates electrons which are delocalized throughout the entire crystal.
Almost all many-electron systems are described by the quasiparticle concept: a quasiparticle is an “excited lump” in the many-electron state which responds just like an ordinary particle.
The resistivity, $\rho$, of a metal from the flow of quasiparticles is

$$\rho = \frac{m^*}{ne^2} \frac{1}{\tau}$$

where $m^*$ is the effective mass of a quasiparticle, $n$ is the density of electrons, $e$ is the charge of an electron, and $\tau$ is a quasiparticle scattering time.

The theory of ordinary metals implies that as the temperature $T \to 0$

$$\tau \sim \frac{1}{T^2} \gg \frac{\hbar}{k_B T}$$
High temperature superconductors

$\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$
High temperature superconductors

Ultra-quantum matter!

$\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$
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
Strange Metal

- AF insulator
- Superconductor
- $T_N$
- $T^*$
- $T_c$
Insulating antiferromagnet
Antiferromagnet doped with hole density $p$
Antiferromagnet doped with hole density $p$

$p$ mobile holes in a background of fluctuating spins
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$p$ mobile holes in a background of fluctuating spins
Strange Metal

Temperature (K)

AF insulator

Hole doping, \( \rho \)

Superconductor
Remarkable recent observation of ‘Planckian’ strange metal transport in cuprates, pnictides, magic-angle graphene, and ultracold atoms: the resistivity, $\rho$, is

$$\rho = \frac{m^*}{ne^2} \frac{1}{\tau}$$

with a universal scattering rate

$$\frac{1}{\tau} \approx \frac{k_B T}{\hbar},$$

independent of the strength of interactions!
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Current flow without quasiparticles

<table>
<thead>
<tr>
<th>Material</th>
<th>$n$ (10$^{27}$ m$^{-3}$)</th>
<th>$m^*$ (m$_0$)</th>
<th>$A_1 / d$ (Ω / K)</th>
<th>$h / (2e^2 T_F)$ (Ω / K)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi2212</td>
<td>$p = 0.23$</td>
<td>6.8</td>
<td>8.4 ± 1.6</td>
<td>8.0 ± 0.9</td>
<td>7.4 ± 1.4</td>
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<tr>
<td>Bi2201</td>
<td>$p \sim 0.4$</td>
<td>3.5</td>
<td>7 ± 1.5</td>
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<td>$p = 0.26$</td>
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<td>8.2 ± 1.0</td>
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<tr>
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<td>$p = 0.24$</td>
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<td>TMTSF</td>
<td>$P = 11$ kbar</td>
<td>1.4</td>
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**Slope of $T$-linear resistivity vs Planckian limit in seven materials.**

$$\frac{1}{\tau} = \alpha \frac{k_B T}{\hbar}$$

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Slope of $T$-linear resistivity vs Planckian limit in seven materials.

$$ \frac{1}{\tau} = \alpha \frac{k_B T}{\hbar} $$

Remarkably similar universality in strange metals and black holes!
The long-range entanglement in the “quantum critical” state near $p = p_c$ leads to the non-quasiparticle current flow with relaxation time $\sim \frac{\hbar}{k_B T}$ in the strange metal.
Square lattice of Cu sites at $p=p_c$

Remove fraction $p$ electrons

\[ \begin{array}{c}
\text{=} | \uparrow \downarrow \rangle - | \downarrow \uparrow \rangle
\end{array} \]
Square lattice of Cu sites at $p=p_c$

Electrons entangle in (“Cooper”) pairs into chemical bonds

$$\begin{align*} &|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \end{align*}$$
Electrons entangle “en masse” by exchanging partners, and there is long-range quantum entanglement.
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\text{“en masse”} \\
\text{by} \\
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Quantum entanglement

Black holes

Metals (ordinary and strange) and superconductors
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Holography:
Quantum black holes “look like” quantum-critical many-particle systems without quasiparticle excitations, residing “on” the surface of the black hole.

Quantum entanglement

Black holes

Metals (ordinary and strange) and superconductors
Quantum entanglement

Black holes

Metals (ordinary and strange) and superconductors

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


Variation described in
Allow electron motion and bond exchange between ANY pair of sites, all with a random amplitude

\[ |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \]
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This describes both a strange metal and a black hole!

Allow electron motion and bond exchange between ANY pair of sites, all with a random amplitude
Maxwell’s electromagnetism and Einstein’s general relativity allow black hole solutions with a net charge.
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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”.
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**Holography:**

**Charged** quantum black holes “look like” **SYK models** without quasiparticle excitations, residing “on” the surface of the black hole

Quantum entanglement

Metals (ordinary and strange) and superconductors

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