Title: The Fascinating, Weird World of Quantum Matter

Speakers:

Collection: Perimeter Public Lectures

Date: December 02, 2020 - 7:00 PM

URL: http://pirsa.org/20120032

Abstract: In her December 2 Perimeter Public Lecture webcast, Hallberg will explore examples of emergent phenomena and demonstrate how we can tackle these problems using quantum information to filter the most relevant data. By advancing research in this field, we hope to seed advances with applications from medical equipment and new materials to efficient energy generation, transportation, and storage.
The fascinating and weird world of quantum matter

Karen Hallberg
Centro Atómico Bariloche and Instituto Balseiro, Bariloche, Argentina
CONICET, CNEA, UNCuyo
Bariloche, Argentina
1900 black-body radiation

Light as a particle?
Photons!

1905 photoelectric effect

Max-Planck

E=hv=hc/\lambda

Planck's constant \( h = 6.626 \, 069 \, 934 \, 10^{-34} \, \text{kg m}^2/\text{s} \)

\[ \tilde{h} = \frac{h}{2\pi} \]
1900 black-body radiation

Max-Planck

Planck's constant \( h = 6.626 \, 069 \, 934 \times 10^{-34} \text{ kg m}^2/\text{s} \)

1905 photoelectric effect

Light as a particle? Photons!

\[ E = h \nu = hc/\lambda \]

\[ \bar{h} = \frac{h}{2\pi} \]

Albert Einstein
Particles as waves?
Young's double slit experiment!

\[ \lambda = \frac{h}{mV} \]

electron \( \lambda \approx 0.1\text{nm} \)

A. Tonomura 2007
Entanglement!
Uncertainty!

1927 Werner Heisenberg
Uncertainty!

\[ \Delta x \Delta p \geq \frac{\hbar}{2} \]

1927 Werner Heisenberg
Tunneling!

- E: particle energy
- U₀: forbidden region
- incoming particle wavefunction
- particle wavefunction past the barrier
- Reduced probability, but **not** reduced energy!
STM and electronic surface waves

Quantum corrals, Manoharan et al, IBM
In spite of its weirdness quantum behavior is ubiquitous!
Google's Sycamore processor
Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...], John M. Martinis

*Nature* 574, 505–510 (2019) *Cite this article*

- generated random number in 200s (vs 10000yrs classical computer?)

**Applications:**
- drug design
- new materials design
- climate science
- finances
- optimization problems
- cryptography
- communications
The concept of emergence

Emergent phenomena in condensed-matter and materials physics are those that cannot be understood with models that treat the motions of the individual particles within the material independently. Instead, the essence of emergent phenomena lies in the complex interactions between many particles that result in the diverse behavior and often unpredictable collective motion of many particles. (US National Academies)
The concept of emergence

Emergent phenomena in condensed-matter and materials physics are those that cannot be understood with models that treat the motions of the individual particles within the material independently. Instead, the essence of emergent phenomena lies in the complex interactions between many particles that result in the diverse behavior and often unpredictable collective motion of many particles. (US National Academies)

The reductionist hypothesis does not by any means imply a “constructionist” one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.
The concept of emergence

Emergent phenomena in condensed-matter and materials physics are those that cannot be understood with models that treat the motions of the individual particles within the material independently. Instead, the essence of emergent phenomena lies in the complex interactions between many particles that result in the diverse behavior and often unpredictable collective motion of many particles. (US National Academies)

The reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.

Everything that matters in science now is organisational. The reductionist (fundamental) approach has stopped from being useful. Bob Laughlin*
<table>
<thead>
<tr>
<th>Topic or Phenomenon</th>
<th>Individual piece</th>
<th>Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ant colony</td>
<td>Ants</td>
<td>Pheromone trails</td>
</tr>
<tr>
<td>Consciousness</td>
<td>Neurons</td>
<td>Neural connections and firing</td>
</tr>
<tr>
<td>Crystals</td>
<td>Molecules</td>
<td>Intermolecular forces</td>
</tr>
<tr>
<td>Traffic patterns</td>
<td>Cars</td>
<td>People’s reactions to car distance or brake lights</td>
</tr>
<tr>
<td>Schooling or Flocking</td>
<td>Fish or Birds</td>
<td>Fish/bird reactions to neighbor’s distance and movement</td>
</tr>
<tr>
<td>City neighborhoods</td>
<td>People</td>
<td>People’s and businesses’ reactions to a neighborhood’s reputation and flavor.</td>
</tr>
<tr>
<td>Superconductivity</td>
<td>Electrons</td>
<td>Lattice vibrations called phonons</td>
</tr>
<tr>
<td>Slime mold slug</td>
<td>Slime mold spores</td>
<td>Chemical signals</td>
</tr>
<tr>
<td>Superfluid</td>
<td>Atoms</td>
<td>Bose-Einstein statistics/quantum attraction</td>
</tr>
<tr>
<td>Crowd behavior</td>
<td>People</td>
<td>Rules for social interaction/neighbor distances</td>
</tr>
<tr>
<td>Magnetism</td>
<td>Magnetic domains</td>
<td>Magnetic coupling</td>
</tr>
<tr>
<td>Heartbeat (synchronicity of pacemaker cells)</td>
<td>Pacemaker cells in heart</td>
<td>Coupled action potentials of pacemaker cells</td>
</tr>
<tr>
<td>Synchronicity</td>
<td>Fireflies</td>
<td>Mimicry plus internal pacemaker cells</td>
</tr>
<tr>
<td>Liquid crystals</td>
<td>Molecules</td>
<td>Intermolecular interactions</td>
</tr>
<tr>
<td>Bose-Einstein Condensation</td>
<td>Atoms or molecules</td>
<td>Quantum mechanical uncertainty resulting in single wave function for all atoms</td>
</tr>
<tr>
<td>Color</td>
<td>Atoms</td>
<td>Light and atomic structure</td>
</tr>
<tr>
<td>Stock market</td>
<td>Investors</td>
<td>Transactions</td>
</tr>
</tbody>
</table>
Examples of emergent phenomena in quantum condensed matter

Is there a critical number above which crystal order emerges?
Pradzynski et al, Science 2012

And what if we combine quantum weirdness and complexity?
quantum condensed matter!
Emergent phenomena in low-dimensional systems: Charge-spin fractionalisation of the electron

Haldane, Schulz, Anderson Lieb&Wu
Emergent phenomena in low-dimensional systems: Charge-spin fractionalisation of the electron

Haldane, Schulz, Anderson Lieb&Wu
Numerical study of charge and spin separation in low-dimensional systems

E. A. Jagla, K. Hallberg, and C. A. Balseiro

Centro Atómico Bariloche and Instituto Balseiro, 8400 S. C. de Bariloche, Argentina
(Received 16 June 1992)

\[ \rho_j^{\pm} = \langle n_{j,\uparrow} \rangle \pm \langle n_{j,\downarrow} \rangle \]

U=0

\[ \rho_j^{\pm} = \langle n_{j,\uparrow} \rangle \pm \langle n_{j,\downarrow} \rangle \]

U=10t

charge

spin
Observation of separated dynamics of charge and spin in the Fermi-Hubbard model

Google AI Quantum and collaborators*  
(Dated: October 19, 2020)

Simulation of correlated models using quantum computers!  
QC Sycamore (google), using superconducting resonators
Sycamore

1. \( J \) odd
2. \( U \) odd
3. \( \text{SWAP} \)
4. \( U \) even
5. \( J \) even \& \( \text{SWAP} \)

\[
\begin{align*}
K &= \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \theta & -i \sin \theta & 0 \\
0 & -i \sin \theta & \cos \theta & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}, \\
G &= \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \theta & -\sin \theta & 0 \\
0 & \sin \theta & \cos \theta & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\end{align*}
\]
Ultracold atomic gases
(quantum simulators)

Bose-Einstein condensation (BEC) (5th state of matter, macroscopic)
1995: Weimann* and Cornell* in $^{87}\text{Rb}$ @170nK
Ketterle* et al with $^{23}\text{Na}$ (Nobel Prize 2001)

In June 2020, the Cold Atom Laboratory experiment on board the International Space Station successfully created a BEC
High temperature superconductors (High Tc)
discovered by Bednorz and Müller at IBM, Zürich in 1986
Nobel prize 1987
High temperature superconductors (High Tc)
(discovered by Bednorz and Müller at IBM, Zürich in 1986)
Nobel prize 1987

[Diagram showing temperature vs. year for various superconductors, with symbols for O, Cu, Ba, and Y, and annotations for CuO2 planes and CuO chains.]
Example: Heisenberg model

\[ H = J \sum_i S_i S_{i+1} \]  

\( N \) sites (qubits), \( 2^N \) states

Exponential amount of configurations!
Using quantum information to optimise calculations:
An interesting new perspective on Quantum Mechanics

“The most challenging and interesting problems in quantum
dynamics involve understanding the behaviour of strongly-coupled
many-body systems... Better ways of characterizing the features of
many particle entanglement may lead to new and more effective
methods for understanding the dynamical behaviour of complex
We use the Density Matrix Renormalisation Group (S. White 1992):
- it uses quantum information to keep the most relevant quantum states

combine DMRG+DMFT!

- Garcia, Hallberg, Rozenberg, PRL. 2004 and PRB(RC) 2005
- Hallberg, García, Cornaglia, Facio, Núñez Fernández, EPL Perspectives 2015
Núñez-Fernández, Kotliar, Hallberg, PRB(R) 2018
Main collaborators:
Gabriel Kotliar (Rutgers)
Cristian Batista (Tennessee)
Elbio Dagotto (Tennessee)
Marcelo Rozenberg (Orsay)
Michel Avignon (Grenoble)
Diego Frustaglia (Spain)
Peter Horsch (Stuttgart)
Arno Kampf (Augsburg); T. Pruschke (Göttingen)
Bruce Normand (Switzerland)
Masatoshi Imada (Tokyo)
Hiroyuki Shiba (Tokyo)
S. Ramasesha (Bangalore)
Jose d’Albuquerque e Castro (Rio)
Yuriel Núñez-Fernández (Bariloche)
Julián Rincón (Colombia)
Marco Nizama (Bariloche)
Daniel García (Bariloche)
Blas Alascio (Bariloche)
Pablo Cornaglia (Bariloche)
Carlos Balseiro (Bariloche)
Armando Aligia (Bariloche)
César Proetto (Bariloche)

Liliana Arrachea (Buenos Aires)
María E. Torio (Rosario)
Adriana Moreo (Tennessee)

Students: Nair Aucar Boidi
Hernén Fernández García
Correlated quantum matter is one of the most interesting, complex and challenging areas in science!

We are just beginning to unveil its mysteries
There's a long but fascinating way ahead!

Fitz Roy, Patagonia, Argentina