

24th Solvay Conference on Physics  
on the  
Quantum Theory of Condensed Matter

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What is it all about?

What are we trying to do?

# What is “Condensed Matter”?

Materials or structures with **large numbers of particles**, (electrons or atoms) that are **close together**, so that the **interactions** between them are important.

Includes almost all the states of matter that we find on earth and that are important to technology:

liquids

crystalline solids

glasses

liquid-crystals

metals

insulators

semiconductors

magnets.

## What is “Condensed Matter”? (2)

Condensed matter science includes the study of **surfaces, thin films** and **interfaces** between different materials.

It includes the study of **electrical, mechanical, magnetic,** and **thermal properties of devices** made from these materials.

# Why Quantum Theory ?

As discovered in the early 20th century, the **classical laws** of physics **break down** when discussing the behavior of electrons on the **length scale of individual atoms or molecules**; must be **replaced** by the laws of **quantum mechanics**.

Quantum mechanics is essential for understanding the **forces between atoms** -- responsible for microscopic structure of materials, and for all of chemistry.

**Quantum mechanics can also be manifest** in electronic behavior on **larger macroscopic length scales**, particularly at low temperatures.

**This conference is focused on such situations.**

# The Solvay Tradition

Previous Solvay Physics Conferences with subjects related to the Quantum Theory of Condensed Matter include:

1. 1911 Theory of radiation and quanta
2. 1913 Structure of matter
4. 1924 Electrical conductivity of metals
6. 1930 Magnetism
9. 1951 The solid state
10. 1954 Electrons in metals
17. 1978 Order and fluctuations ... in statistical mechanics
20. 1991 Quantum Optics

# Why is this a subject for a Solvay Conference?

The quantum theory of condensed matter is important both for the fundamental questions it raises and for practical applications.

Improved understanding of condensed matter systems in the quantum realm may be a key to solving a number of technological problems of vital importance to society.

Although there has been enormous progress since the 1920s, many questions are still poorly understood.

New experimental methods have given us tools to examine these systems-but have also uncovered many surprising results

The Solvay Conference on the Quantum  
Theory of Condensed Matter  
is an occasion for a small number  
of leaders in the area  
to exchange ideas about the  
outstanding problems of the field.

# Conference Focus: Collective Effects

Condensed matter systems are made up of simple point particles: electrons and atomic nuclei. The microscopic equations, which govern their motion, have been known since the 1920s.

But the **consequences of these equations**, when you have large numbers of interacting particles, can be very subtle, and are still **only partially understood**.

**Interactions can give rise to collective effects**, where the **behavior** of a material is **very different** from what one would find if the individual particles moved in an independent way.

# Some subjects discussed at the Solvay Conference on Quantum Theory of Condensed Matter

- Superconducting materials
- Nano-scale devices
- Ultra-cold atoms
- Phases and phase transitions

# Example: Superconductivity

Superconductivity was discovered by Kamerlingh-Onnes in 1911, in mercury, tin and lead. Below a critical temperature ( $T_c$ ) the superconductor can carry an electric current without energy loss, in contrast to a normal metal.

Superconductivity was finally understood in 1957 as a collective effect: electrons in a superconductor bind into pairs, and these pairs condense into a state described by a single collective quantum-mechanical “wavefunction”.

# Low Tc Superconductivity

From 1911 through 1985, many new superconductors were discovered, but the highest Tc was below 30K.

Temperatures can only be reached, using liquid helium and elaborate thermal insulation, which is too expensive for most applications.

# High Tc Superconductivity

In 1986, a new class of superconductors was discovered, the **high Tc “cuprates”**.

Superconductivity is generated in crystal planes containing copper and oxygen atoms.

Their **critical temperatures** are commonly in the range of **95K**, almost four times as high as any previously known Tc. Can be **reached using liquid nitrogen**, which is much cheaper than liquid helium.

Can imagine many new applications.

# Applications of superconductivity

Conventional, low  $T_c$  superconductors are already being used, despite the expense of helium cooling, for certain essential applications. These include high-field magnets for scientific research, and for medical applications, in magnetic resonance imaging (MRI) machines.

High  $T_c$  superconductors are just beginning to enter the commercial market, for electric power applications and in specialized electronic applications.

We can expect much more to come.

## Other peculiar materials.

Cuprates belong to a wider class of materials where the **repulsion between electrons is particularly strong**. An electron can move from one atom to another only by pushing another electron out of its way.

**Even the non-superconducting states** of these materials (e.g., for cuprates at temperatures above  $T_c$ ) **are very peculiar**, and not well understood.

Several sessions in this Solvay conference are devoted to the theory of **high  $T_c$  cuprates** and **related materials**

# Is Superconductivity Possible at Room Temperature? Nobody knows!!

Highest known  $T_c$ , (for a cuprate under pressure) is 150K, about 1/2 of room temperature.

If room temperature superconductivity can be found, the technological implications could be staggering.

We do not know what really limits the maximum achievable  $T_c$ , and in fact we still do not understand very well the microscopic mechanism for superconductivity in the cuprates.

# Topic: Nano-scale Devices

Today's economy is based on technology made possible by the dramatic reduction in size of the basic electronic devices, such as transistors and magnetic memory elements. Reduction in size has been the key to higher speeds, improved performance, and reduction in cost. If current trends continue, devices will soon become so small that current engineering principles can no longer work.

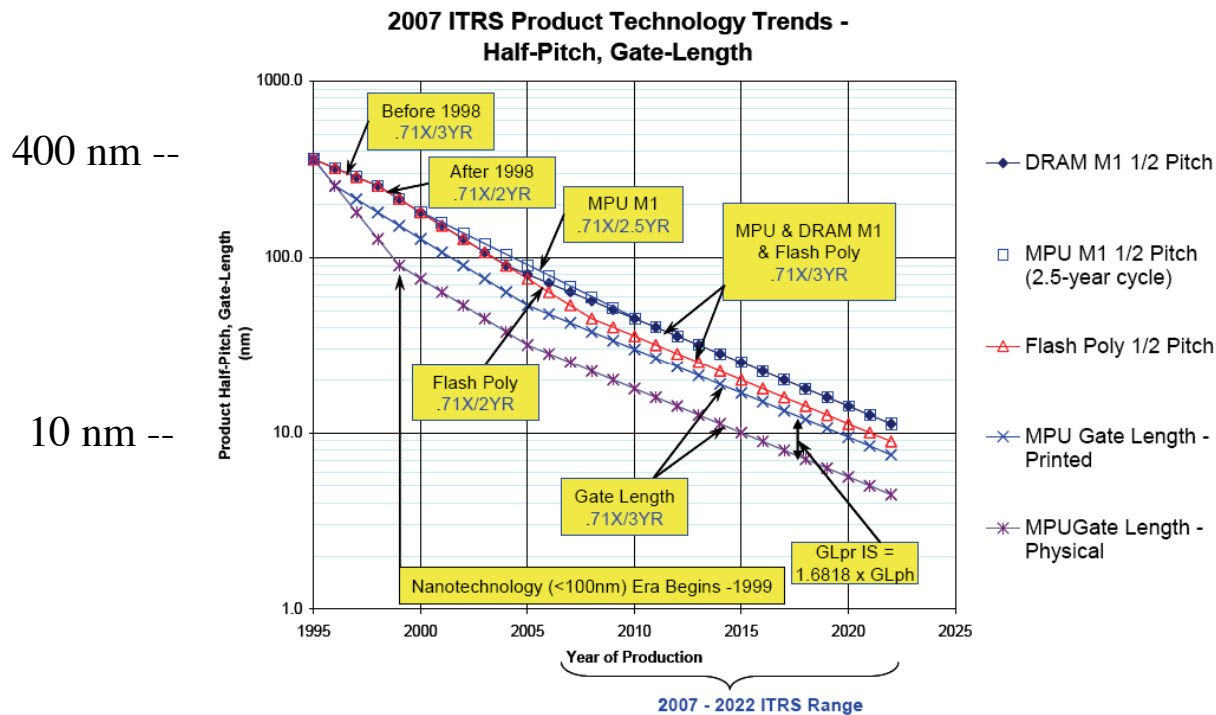
It is crucial that we understand the limitations of current devices and discover principles for new devices at the smallest possible scales.

## Nano-scale devices (2)

In very small devices, quantum mechanics may become important in subtle new ways. A very small device may behave very differently than a larger version of the same device.

Several sessions of this conference are devoted to the study of devices that are extremely small -- in one, two or all of their dimensions.

# Decrease in transistor size since 1995 and projections to 2022



Current gate lengths are about 25 nm

Projected gate length in 2015 is 10 nm - only 40 times the diameter of a silicon atom!

[From 2007 International Technological Roadmap]

# Ultra-cold atoms

Although quantum mechanics is often crucial for understanding electrons, it is usually not necessary for describing the motion of atoms. **Atoms** are typically **10,000 times heavier than electrons**, and quantum mechanical motion is usually less important for heavier particles.

**Recently, it has become possible to trap a collection of atoms and cool them to incredibly low temperatures** (a billionth of a degree above absolute zero!). Under these conditions **quantum mechanics** becomes **very important**.

Also: **interactions may be important** even though the trapped atoms are very far apart.

# Ultra-cold atoms as a tool for learning about electron systems

Despite the huge difference between the masses of electrons and atoms, systems of ultra-cold atoms can display quantum phenomena similar to those in strongly interacting electron systems, such as the cuprate high temperature superconductors.

Experimental tools available in cold atom systems, may enable us to gain insights into the electron systems that have not been possible otherwise.

Systems of ultracold atoms, their quantum description, and their connection to phenomena in electron systems, are one of the major subjects of our Solvay Conference.

# Phases and Phase Transitions

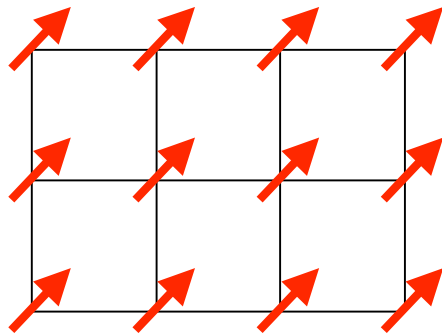
Materials can exist in different states, or “phases”, such as solids, liquids, and gases, with very different physical properties. A small change in conditions, such as a small change in temperature, can cause a solid, such as ice, to melt into a liquid, causing it to completely lose the property of rigidity. Such a change of state is called a “phase transition”.

Other phase transitions include: when a superconductor is heated above its critical temperature, or when a magnet such as iron is heated above a critical temperature, where it loses its magnetic properties.

Many phase transitions represent a change in ordering.

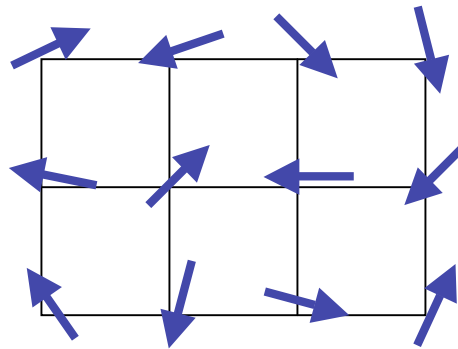
# Magnetic Phases

Arrangements of electron spins.



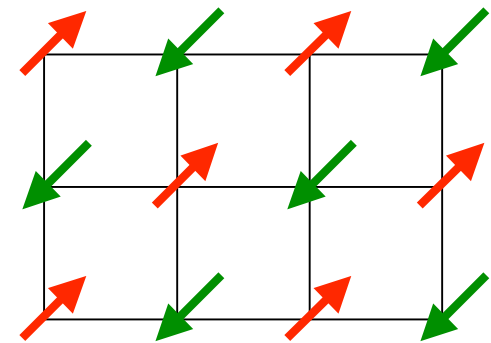
Ferromagnetic

(Iron at room temperature)



Disordered

(Non-magnetic materials; or iron above  $T_c$ .)



Anti-ferromagnetic

(Various other materials at low temperatures.)

# Exotic Phases and Phase Transitions

Many **other exotic phases** and **phase transitions** have been found to occur, particularly at low temperatures, in systems where quantum mechanics is important. Some of these phases are very difficult to describe in conventional language.

Fundamental questions discussed at this conference include:

**What new types of phases are yet to be discovered?** and  
**What would be the nature of the transitions between them?**

# Current Technologies based on Quantum Properties of Condensed Matter Systems include:

Integrated circuits and transistors..

Solid state lasers, used in medicine, communications, reading and writing of CDs, etc.

Photovoltaic devices for solar energy conversion. Storage batteries.

Magnetic memories and read-out sensors.

Catalysts for chemical reactions.

There surely will be many more applications in the future.

## Summary

The quantum theory of condensed matter is important both for the **fundamental questions it raises** and **for practical applications**.

Some topics central to the Solvay Conference, which we have briefly reviewed, include:

- **Superconducting materials**
- **Nano-scale devices**
- **Ultra-cold atoms**
- **Phases and phase transitions**