CONSUMER TECH

The Joy Of Condensed Matter Physics

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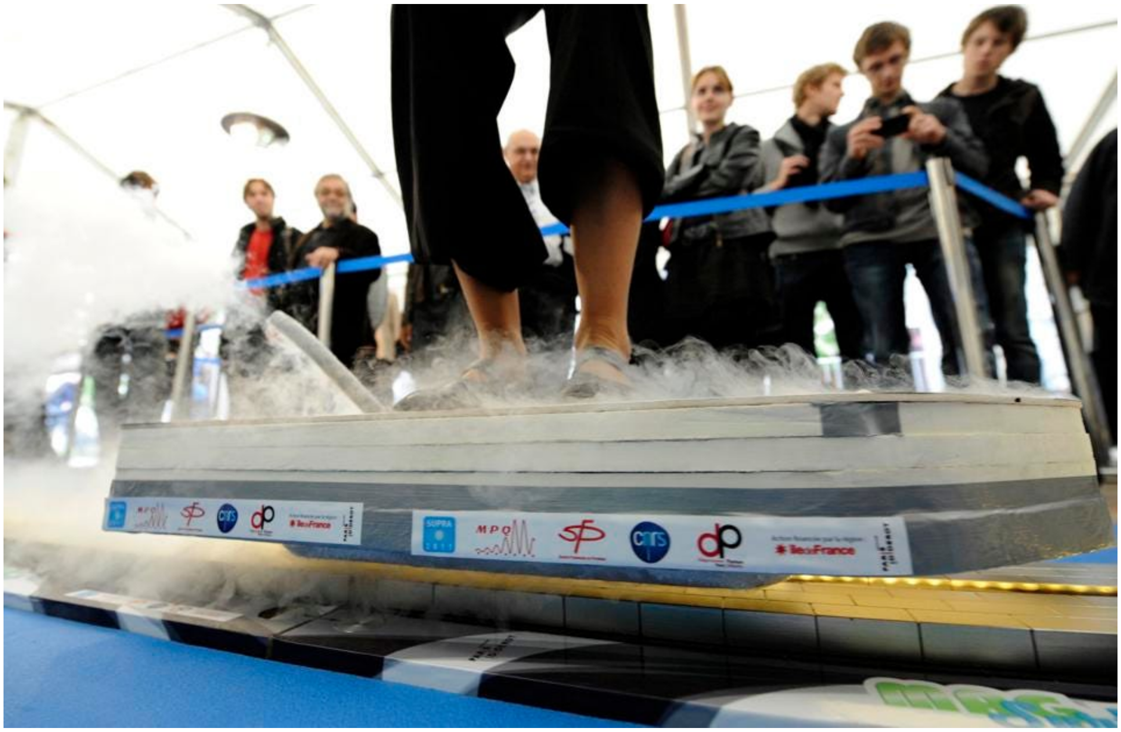

A person presents a MagFly superconductor skate during the Science Festival on October 12, 2011 in... [+]

Why is condensed matter physics interesting? originally appeared on Quora - the knowledge sharing network where *compelling questions are answered by people with unique insights.*

Answer by Inna Vishik, Assistant Professor of Physics at UC Davis, on Quora:

I am drawn to condensed matter physics because it is simultaneously useful and fundamental, simultaneously mundane and fantastical, simultaneously large and small, and most of all, some of the phenomena that are observed in condensed matter systems are just flipping cool.

First, a definition of condensed matter. This field studies many-atom systems that are condensed (i.e. not a gas) but not *too* condensed (i.e. not the inside of a neutron star). Condensed matter physics in its broadest definition encompasses many different subfields (cold atoms, biophysics, soft matter, solid-state physics, etc.). For this piece, I will focus on solid-state physics (the study of crystalline solids; also called hard condensed matter) with which I am most familiar.

With that disclaimer out of the way, back to our scheduled programming …

Condensed matter physics is both **useful** and **fundamental**. Many people who know a little bit about solid state physics know that it gave us microscopic understanding of silicon and its native oxide, which gave us solid-state transistors, which gave us every computer and smartphone on the planet. But those same semiconducting materials, when stacked on top of each other in a specific way, can produce a very pure 2-dimensional metal at the interface. When this specially-prepared material is cooled down to very low temperature (<4K, i.e. not useful) and subjected to a large magnetic field (several Tesla, not useful), it exhibits quantized conductance comprising the integer and fractional quantum Hall effect, both of which garnered Nobel prizes in physics. The former is used as a standard for electrical resistance (useful after all), and the latter exhibits electron-like quasiparticles that behave as if they have *fractional* charge (whaa??).

On that note, condensed matter systems manifest other quasiparticles (objects that behave like particles inside the solid but don't exist outside the solid) which are predicted in particle physics but never observed in free space, such as majorana fermions [1] and magnetic monopoles [2]. The quantum hall effect is the intellectual predecessor to a subfield of solid-state physics that is currently very trendy—topological materials, including topological insulators, Dirac semimetals and Weyl semimetals. These also connect to particle physics via quasiparticles that behave like massless Dirac and Weyl fermions (fundamental), and if they can be made superconducting in the proper way, it is predicted that they will also manifest majorana fermions which may be used for quantum computation [3] (potentially useful).

Condensed matter physics is simultaneously **mundane** and **fantastical**. I am typing this answer at my dining room table, and I can use condensed matter physics to explain why various objects in my vicinity behave the way they do: why my ceramic coffee mug is good for handling hot liquids and would break if I dropped it, why my stainless steel fork does not attract a paper clip right now but would if I held it up to a big honking magnet, why my diamond is so flawless (when at a loss for a third item on a list, quote Beyoncé).

These same materials can be implicated in my personal favorite phenomenon in condensed matter physics—superconductivity—in which a material suddenly loses its resistivity at low enough temperature and can conduct a dissipationless current (basically, a perpetual motion machine, if you can keep it cold enough). Some of the highest temperature superconductors out there are ceramic materials [4]. Iron (the main elemental constituent of steel) can be compressed (but not nearly as much as a neutron star) and become a superconductor [5]; or it can be alloyed with, say, arsenic and barium to make a different type of high-temperature superconductor [6]. And diamond becomes superconducting [7] if you dope it with an ample amount of boron.

This juxtaposition between the **mundane** and the **fantastical** also encompasses the ability of condensed matter physics to not only to describe nature, but also to manipulate nature. We live in one universe, but crystalline solids allow us to create or discover another universe with different properties. Do you want a universe where magnets only have a north pole, but no south pole? This was realized inside so-called Pyrochlore materials, which were synthesized in a lab and whose peculiar magnetic structure gives rise to *quasiparticles,* which behave like *magnetic monopoles* [8]. Do you want a two-dimensional universe? Maybe one with a slower speed of light—a slower cosmic speed limit? Both are realized in graphene, a fantastical material which is usually produced in the most mundane way possible: by taking a piece of scotch tape to a hunk of graphite rock mined out of the ground [9].

Condensed matter physics is simultaneously **large** and **small**. I mean this both in terms of the experiments (and calculations) that can be done and the science itself. Many experiments in condensed matter physics can be performed on a tabletop by a single student in a lab at a relatively low cost. Other experiments, however, are performed at large user facilities such as synchrotrons, neutron scattering research reactors and free electron-lasers, which require a full time support team and can cost more than a billion dollars to build (the good news is they can be used for many different experiments, not only in condensed matter physics, but in chemistry and biology too). On the theoretical side of the field, some people do pencil and paper calculations, while others apply for time on a supercomputer to numerically study systems of many-interacting particles. The science of condensed matter has a small number of tiny constituents: electrons, protons, and neutrons. But when many, many of them are put together, emergent properties can appear that encompass a macroscopic material and are often quite different from the sum of their parts.

And that brings me to the amazing phenomena that appear in condensed matter systems [10]. It should be noted that oftentimes these phenomena are discovered by surprise, not predicted beforehand. Previously, I discussed fractional charges in the fractional quantum hall effect and superconductivity (fun fact: the theory of the Higgs' Boson originates from the theory explaining why certain metals become superconductors at low temperature; all of physics is connected). Other cool phenomena include super-obese electrons in some rare-earth compounds who behave as if they have a mass 1,000 times that of a free electron [11], materials in which the resistance suddenly increases by a factor of 100,000 when subjected to a magnetic field [12], highly radioactive elements that undergo five different structural phase transitions in their solid state [13], fractal behavior (Hofstadter's butterfly) in graphene/boron nitride heterostructures, novel types of magnetic order such as skyrmions (the name alone…), just to name a few. And we are not limited to the phenomena we know about today: the smallest speck of crystalline solid contains over a septillian mutually interacting electrons and ions, which can be arranged in nearly limitless ways, so there is no shortage of astounding phenomena (some of which might be useful, too) waiting to be discovered/invented. It goes down in the CM, for sure.

A big thank you to Prof. Alexander F. Kemper, Dr. George Burkhard, and Noah Raman for helpful suggestions, improvements, and discussion on this piece.

Footnotes

[1] Observation of Majorana fermions in ferromagnetic atomic chains on a superconductor

[2] http://www.nature.com/nature/jou...

[3] http://www.nature.com/nphys/jour...

[4] High-temperature superconductivity

[5] http://www.nature.com/nature/jou...

[6] Iron Exposed as High-Temperature Superconductor

[7] https://arxiv.org/ftp/cond-mat/p...

[8] Dirac Strings and Magnetic Monopoles in the Spin Ice Dy2Ti2O7

[9] Minerals | Graphite

[10] The Theory of Everything

[11] Heavy fermion

[12] Thousandfold Change in Resistivity in Magnetoresistive La-Ca-Mn-O Films

[13] Allotropes of plutonium

[14] http://www.nature.com/nature/jou...

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