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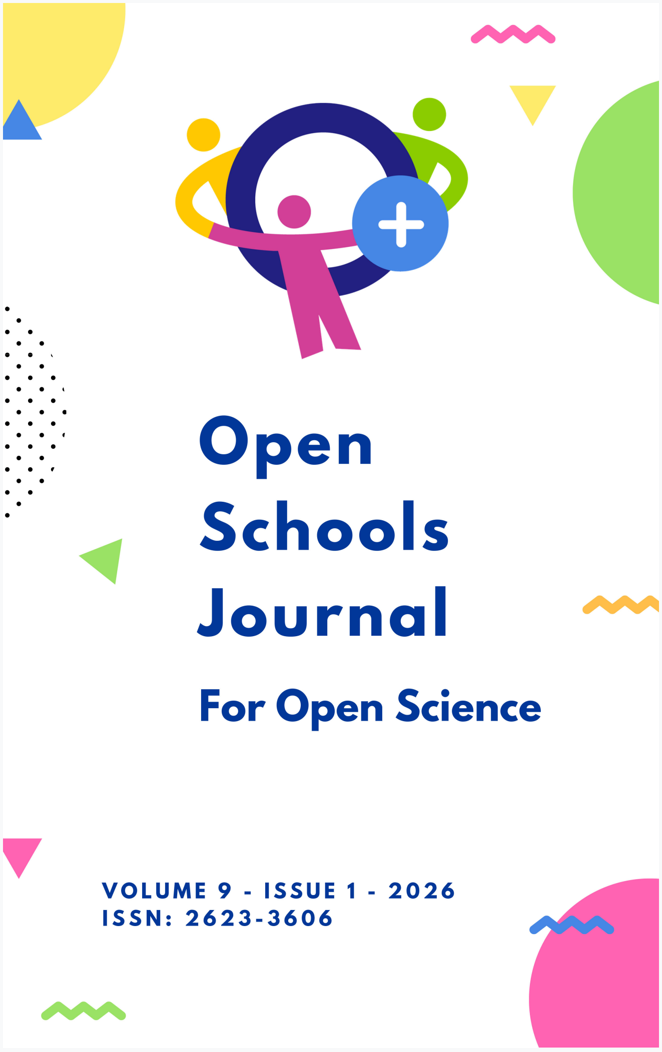

Exploring the world of quantum materials

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Exploring the world of quantum materials

Leon Gkougkoulias

Abstract:
Quantum materials possess exotic properties which are due to quantum mechanical effects. These properties encompass superconductivity, topological properties, and strong electron correlations, among others.
The main types of quantum materials are superconductors, topological insulators, and quantum spin liquids. Each of these exhibits exotic phenomena that classical physics cannot explain.
Superconductors offer zero resistance to electricity beneath a critical temperature, revolutionizing applications like MRI machines and maglev trains.
Topological Insulators are mainly insulators but conduct on the surface, protected by topological order, with applications in quantum computing. Quantum materials may enable breakthroughs in energy transmission, sensors, and quantum computing, with revolutionary technology spanning industries. Quantum materials bridge condensed matter physics and emerging technologies, opening up new possibilities for discovery and industrial development.

Introduction

The properties of materials obey the rules of physics, except when they don't. Quantum materials is an umbrella term used to include all materials that have properties that cannot be explained by classical physics. Quantum materials are fascinating, because they are the brick stones of future innovations.

What are Quantum Materials

Quantum Materials are materials that exhibit behaviours known in quantum mechanics, that is entanglement, quantum interference and topology. Entanglement is when particles remain correlated regardless of distance. Quantum interference means that in superposition that is when particles can exist in multiple states simultaneously, these states can interfere with each other. Topology is a new fundamental organization principle in addition to symmetry, because quantum states depend on global geometry and not in local symmetry.
It is very interesting to note that their electrons can behave collectively in exotic ways., because there is a strong electron correlation, as electrons do not act independently but interact strongly. For example, electrons in a viscous flow can achieve through cooperation what they cannot accomplish individually. In 2017 research reported signatures of fluid-like electron behaviour in graphene[1]. Electrons in the current were able to squeeze through the pinch points collectively, much like a fluid, rather than clogging, like individual grains of sand.
Most of the quantum materials are solid, such as graphene, cuprates and topological insulators. There are though also non solids like H_2S under high pressure which is a superconductor, Bose-Einstein Condensates and Fermi Gases.

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[1] https://news.mit.edu/2022/electron-whirlpools-physics-0706

Examples of Quantum Materials

Graphene is a 2D quantum material. This means that it consists of only one layer of atoms (some 2D materials are two atoms thick). So graphene is a single layer of carbon atoms arranged in a hexagonal pattern. Supposedly one can create graphene at home with just the use of scotch tape, a pencil and lots of patience to repeat the procedure with the tape until the required thickness is achieved. At least this is how Professors Andre Geim and Kostya Novoselov managed to isolate it for the first time[2]. Graphene is an amazing material because it is considerably more resistant than steel and lighter than aluminium. Ever since 2004 when it was first isolated it is used in sensors, electronics, batteries and other innovations.

Cuprates are also very interesting. They were discovered in 1986 they are layered materials with one or more crystal planes consisting of Cu and O atoms (two O per Cu), and charge reservoirs between them.

Superconductivity

The Cuprates mentioned above are amazing superconductors. In superconductors, below a critical temperature, resistance drops to zero. Electrons form Cooper pairs via lattice vibrations (phonons). These pairs condense into a single quantum state that flows without energy loss. The Meissner effect expels magnetic fields from the superconductor's interior.
This practically means that these materials are ideal conductors as they conduct electricity without resistance at low temperatures[3].

Their applications include but are not limited to Maglev trains, MRI machines, Quantum circuits.

Topological Insulators

The bulk is insulating, but surfaces host conducting states protected by topology, or in short insulating inside conductive on the outside[4]. These edge states arise due to band inversion and spin-orbit coupling. Surface electrons have locked spin-momentum, resisting scattering and disorder. Topology guarantees robustness of surface conduction under perturbations. This means that the conductivity is protected even in case of surface impurities. Topological insulators are used in Quantum computing and in spintronics, which is a new field of electronics that uses the spin of electrons to create new devices.

Uses of Quantum Materials

Spintronic devices have advantages like higher speed, less power consumption and some memory devices can even retain information even when powered off. In sensors quantum materials offer higher precision magnetometers and gyroscopes. Superconducting cables reduce energy loss in transmission. Quantum materials are especially useful in quantum computing. QLEDs and QRLEDS have sharper colours and better efficiency[5].

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[2] https://www.graphene.manchester.ac.uk/learn/discovery-of-graphene/
[3] https://hoffman.physics.harvard.edu/materials/organic/background.php
[4] https://spectrum.ieee.org/a-beginners-guide-to-topological-materials
[5] https://hkust.edu.hk/news/hkusts-next-gen-qrleds-transform-smartphone-tvs-ultra-bright-and-color-rich-displays

The Future

Every day scientists around the world discover new quantum materials with unexpected properties that might very soon change fundamentally our technology. Reading about these wonderful discoveries, such as the Nodal Line Semimetals which exhibit nonsymmorphic symmetry and could be the next day of power devices and computers is interesting and opens a window to look into the future.

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