Altermagnets: A new chapter in magnetism and thermal science

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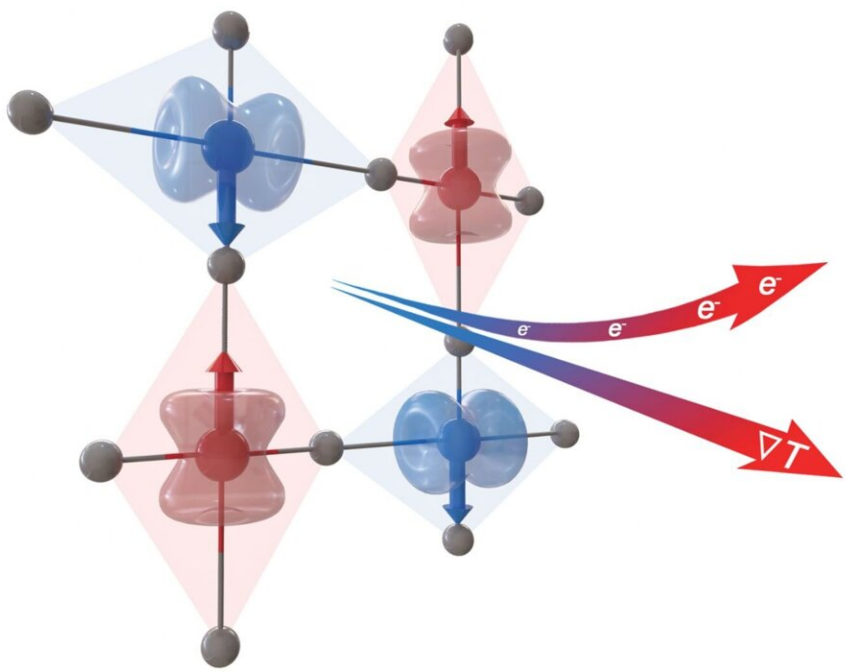

Crystal thermal transport in altermagnets. The left part, which includes the balls, arrows, and spin density isosurfaces, represents a typical altermagnet. When a temperature gradient field is applied, charge and thermal currents are induced in a perpendicular direction, illustrating crystal thermal transport, as shown in the right part. Credit: Zhou et al/*Physical Review Letters*. DOI: 10.1103/PhysRevLett.132.056701.

In a new study, scientists have investigated the newly discovered class of altermagnetic materials for their thermal properties, offering insights into the distinctive nature of altermagnets for spin-caloritronic applications.

Magnetism is an old and well-researched topic, lending itself to many applications, like motors and transformers. However, new magnetic materials and phenomena are being studied and discovered, one of which is altermagnets.

Altermagnets exhibit a unique blend of magnetic characteristics, setting them apart from conventional magnetic materials like ferromagnets and antiferromagnets. These materials exhibit properties observed in both ferromagnets and antiferromagnets, making their study enticing.

The current research, published in *Physical Review Letters*, explores the thermal properties of altermagnets and was led by Prof. Wanxiang Feng and Prof. Yugui Yao from the Beijing Institute of Technology.

Speaking of their motivation behind exploring altermagnets, Prof. Feng told Phys.org, "Magnetism is an ancient and fascinating topic in solid-state physics. While exploring non-collinear magnets over the past decades, we encountered a new type of collinear magnet, the altermagnet."

Prof. Yao added, "With a dual nature resembling both ferromagnets and antiferromagnets, altermagnets intrigued us with the potential for novel physical effects. Our motivation stemmed from the desire to understand and unlock the unique properties of these magnetic materials."

The emergence of magnetism

Magnetic properties emerge from the behavior of atoms, particularly the arrangement and movement of electrons within a material.

"In magnetic materials, due to the exchange interaction between atoms, the spin magnetic moments arrange parallel or antiparallel, forming the most common ferromagnets and antiferromagnets, respectively, which have been studied for over a century," explained Prof. Feng.

Altermagnets defy conventional norms by embodying a dual nature—resembling antiferromagnets with zero net magnetization and ferromagnets with non-relativistic spin splitting.

In altermagnets, collinear antiparallel magnetic order combines with non-relativistic spin splitting, resulting in zero net magnetization akin to antiferromagnets and ferromagnetic spin dynamics simultaneously.

This unique behavior emerges from the intricate interplay of atoms within the crystal structure. For instance, ruthenium dioxide, the subject of this research, showcases spin degeneracy induced by nonmagnetic oxygen atoms, breaking spatial and time symmetries. This leads to the unique magnetic properties of the material.

Additionally, altermagnets exhibit a unique spin polarization. The term "spin polarization" means that a preponderance of electron spins tends to align in a particular direction.

The spin polarization is noteworthy in altermagnets because it occurs in the physical arrangement of atoms (real space) and in the momentum space, where the distribution of electron spins in the material is considered.

Nernst and Hall effects

The researchers focused on studying the emergence of crystal Nernst and crystal thermal Hall effects in rubidium dioxide (RuO_2), chosen as a showcase representative of altermagnetism.

The crystal Nernst effect (CNE) observed in altermagnets is a result of their distinctive magnetic nature. In simple terms, as the material experiences a temperature difference across its dimensions, it leads to the emergence of a voltage perpendicular to both the temperature gradient and the magnetic field. This phenomenon reveals that the material's magnetic properties influence its response to temperature changes, providing insights into the intricate connection between thermal and magnetic behaviors in altermagnets.

In altermagnets, this effect is significantly influenced by the direction of the Néel vector, which represents the direction in which neighboring magnetic moments align. This adds an extra layer of complexity to the thermal response.

Similarly, the crystal thermal Hall effect (CTHE) sheds light on how heat moves in altermagnets. Like the traditional thermal Hall effect, it occurs perpendicular to the temperature gradient and magnetic field. In altermagnets, the CTHE shows significant variation depending on the Néel vector direction. This anisotropy is a central factor in understanding the thermal transport behavior unique to altermagnetic materials.

Thermal properties of RuO_2

The research methodology employed a dual strategy, combining symmetry analysis and cutting-edge first-principles calculations, to unravel the thermal transport properties of RuO_2. Symmetry analysis played a crucial role in unraveling the fundamental reasons behind the emergence of altermagnetism.

Through two symmetry operations involving spatial inversion, time reversal, and lattice translation, the study showcased the intricate interplay of atoms within the crystal structure, demonstrating how nonmagnetic oxygen atoms induced non-relativistic spin splitting in energy bands.

This process resulted in the breaking of crystalline time-reversal symmetry, giving rise to distinct crystal thermal transport properties.

"Through detailed analysis, we identified three physical mechanisms contributing to crystal thermal transport: Weyl pseudo-nodal lines, altermagnetic pseudo-nodal planes, and altermagnetic ladder transitions," said Prof. Yao.

In simple terms, the Weyl pseudo-nodal lines are pathways that guide heat within the material, altermagnetic pseudo-nodal planes can be pictures as designated zones influencing heat flow, and altermagnetic ladder transitions can be thought of as the material's way of climbing a heat ladder.

These findings are exciting as they play a significant role in how heat travels within altermagnets.

The researchers discovered an extended Wiedemann-Franz law in RuO_2, linking the material's unusual thermal and electrical transport characteristics. Contrary to conventional expectations, this extended law operates over a broader temperature range, extending beyond 150 Kelvin.

Spin caloritronics

The researchers believe that altermagnets could have a pivotal role in spin caloritronics, a field of research that explores the interplay between spin and heat flow, which are not achievable with ferromagnets or antiferromagnets. This field has potential applications in developing new technologies for information processing and storage.

"Altermagnetic materials with collinear antiparallel magnetic order exhibit faster spin dynamics and lower sensitivity to stray magnetic fields compared to ferromagnetic materials. This makes them promising for achieving higher storage density and faster spin caloritronic devices," explained Prof. Feng.

The researchers also intend to investigate higher-order crystal thermal transport and magneto-optical effects in the future.

Speaking of this, Prof. Yao said, "We are curious about the differences in higher-order crystal thermal transport and high-order magneto-optical effects in altermagnets compared to antiferromagnets or ferromagnets. We are in the early stages of this technology, and there's a long journey ahead before it becomes practically achievable."

More information: Xiaodong Zhou et al, Crystal Thermal Transport in Altermagnetic RuO2, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.132.056701. On *arXiv*: DOI: 10.48550/arxiv.2305.01410

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