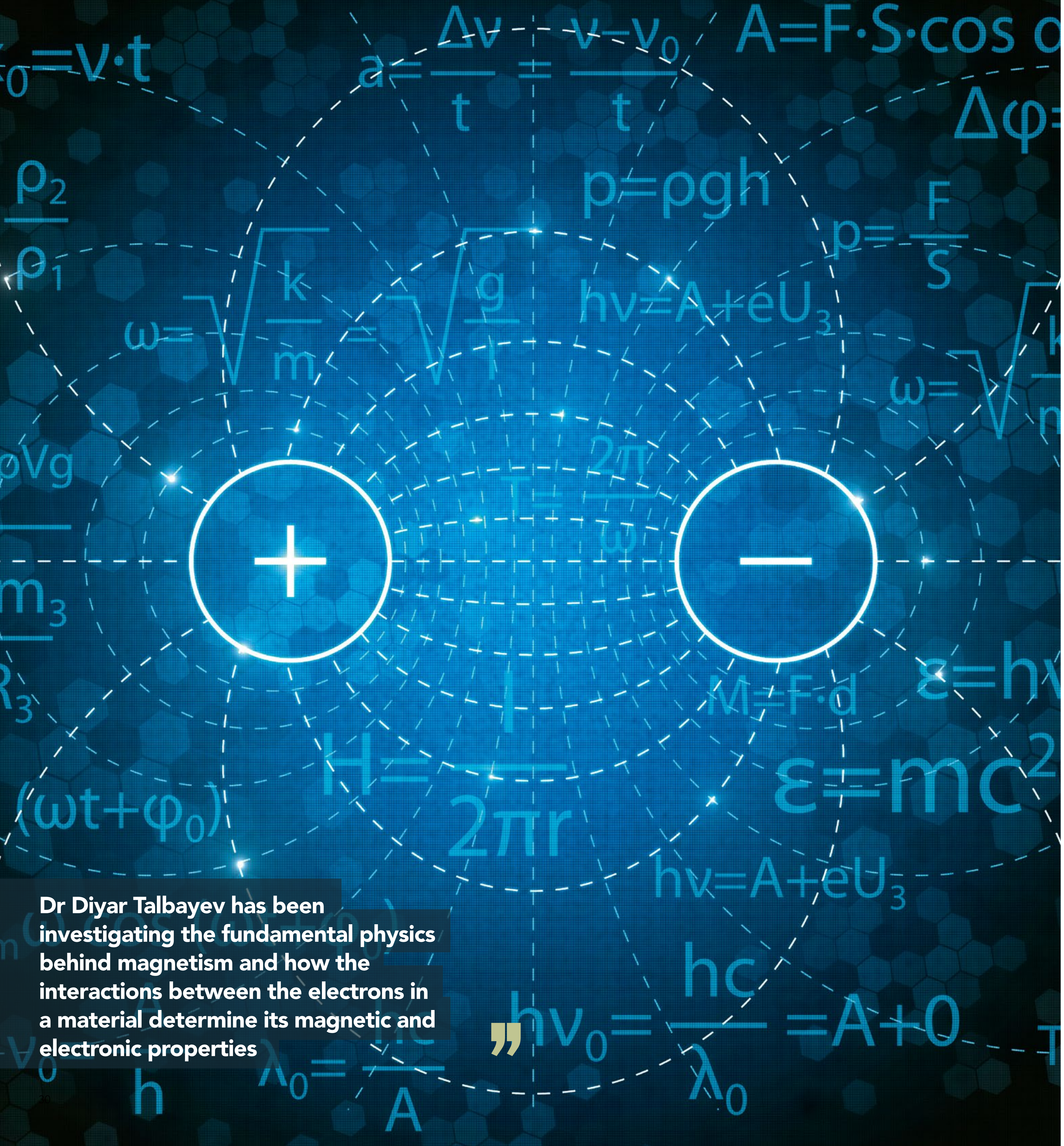


Dr Diyar Talbayev has been investigating the fundamental physics behind magnetism and how the interactions between the electrons in a material determine its magnetic and electronic properties

Electronic behaviour in magnetic matter: insights from femtosecond and terahertz spectroscopy

Magnetism in materials arises from the strange and exotic properties of the electrons within the material. There are a huge class of materials, including many rare earth elements, that are of particular use in a variety of computing applications, such as information storage and processing. By using novel experimental technologies to generate very short pulses of light in the terahertz region, **Dr Diyar Talbayev**, and his group at Tulane University, have gained an unparalleled insight into the magnetic dynamics of solid materials and the fundamental physics underlying these processes.

When thinking about magnetic materials, iron is probably the first to spring to mind. Iron was the first material found to exhibit permanent magnetism, which is why permanent magnetism is also known as ferromagnetism, after the Latin word for iron – 'ferrum'.

However, there are many more kinds of magnetism than just ferromagnetism, as well as a huge variety of compounds that show these exotic types of magnetic behaviours. Many of these are compounds that contain either heavy metals or rare earth metals that, at a microscopic level, form crystalline lattices with regular, periodic structures.

Dr Diyar Talbayev at Tulane University has been investigating some of the fundamental physics behind magnetism and, in particular, how the interactions between the electrons in a material determine its magnetic and electronic properties.

UP OR DOWN?

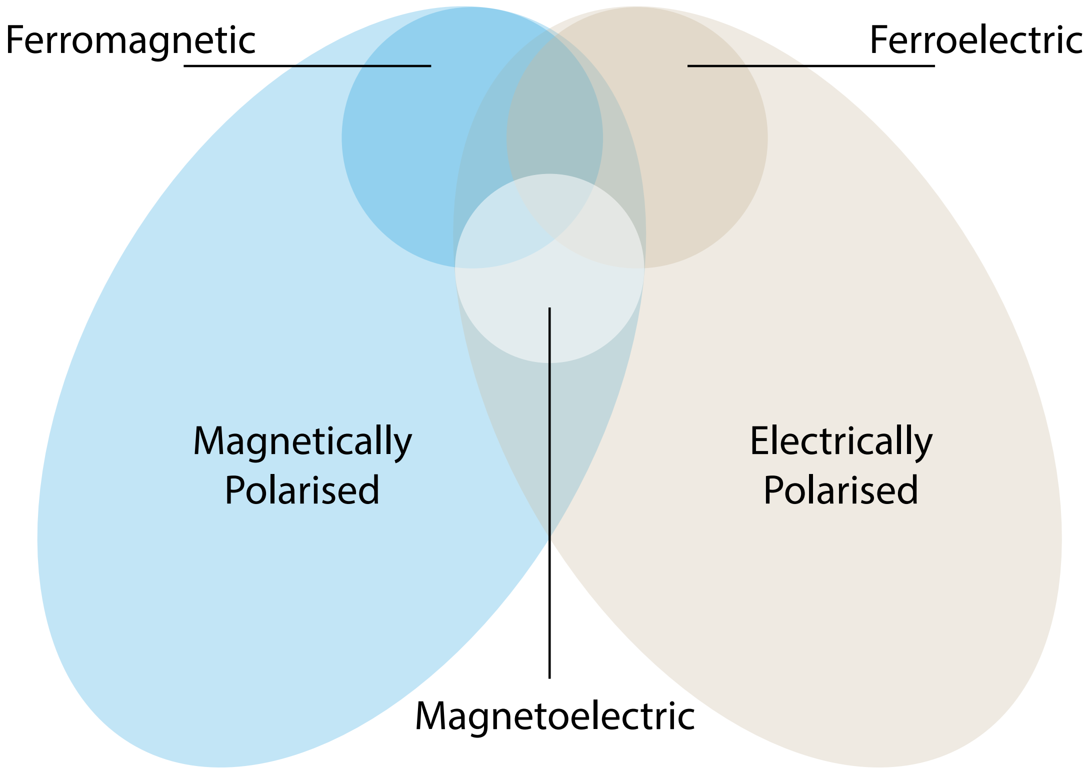
There are many kinds of magnetism that are dependent on the properties of the electrons present in the material. Electrons have a property known as 'spin', which is really a quantum mechanical effect, but can be thought of very crudely as the orientation of the electron as it rotates, where it can be either 'up' or 'down.'

Although spin is an incredibly complex phenomenon, it is a very important property in determining the interaction of the electron with external electric or magnetic fields, or with other electrons. In most neutral molecules, electrons are typically found in pairs, with opposite spins. As there are an equal number of electrons with up and down spins, the overall net spin is zero. However, in ferromagnetic materials, like common iron bar magnets, there are some unpaired electrons. If all the atoms in an area, known as a magnetic domain, have their spins aligned, there is an overall spin in the material that results in ferromagnetism.

SPIN DYNAMICS

However, it is possible to change the orientation of spin of individual electrons, or lose the overall alignment of magnetic domains. If you hit an iron magnet hard enough, it can lose its magnetism because the magnetic domains become scrambled and there will be no overall spin alignment.

Brute force is not the only thing that can interfere with the behaviour of magnetic materials. In the presence of an external



electric field, the orientation of the spins can change in magneto-electric materials. Dr Talbayev's group are particularly interested in an unusual type of magnetic behaviour known as antiferromagnetism. Here, the neighbouring ions have opposite spin alignments to each other. Antiferromagnetic and magneto-electric materials show very different properties to ferromagnets, but the ability to manipulate these using external electric fields means they show promise for potential applications in computer memory for the read/write processes involved in data management.

However, probing spin states of electrons and determining their magnetic interactions has proved somewhat challenging. Nonetheless, Dr Diyar Talbayev is making use of terahertz light to do exactly that.

THE THZ REGIME

Terahertz radiation is an electromagnetic wave which has a longer wavelength than microwaves but shorter than infrared light. Historically, it has been very difficult to generate light in this region of the electromagnetic spectrum. However, it is ideally suited to observing information on the spin states and dynamics of the electrons in materials and offers very high resolution information. This is because the energy of the radiation is comparable to the energy difference between the spin states of electrons in the material, so it can be used to selectively look at their quantum mechanical behaviour.

THE ELECTRON MOVIE

Dr Talbayev has been combining the utility of terahertz radiation with femtosecond laser pulses to perform time resolved terahertz spectroscopy (TRTS). Femtoseconds are incredibly short units of time that correspond to many of the timescales involved in the physics and chemistry of materials. These pulses are sufficiently quick to capture snapshots of motion of the electrons in the material.

The pulse durations produced by a femtosecond laser are so short in time that the instantaneous power delivered by the laser is huge and easily able to perturb the electronic equilibrium of the material of interest – thus exciting the electrons and causing them to move. As well as being responsible for the magnetic properties of a material, the movement of electrons is what allows the flow of charge, which is why certain materials are conductive. For example, in metals, electrons can typically move freely around the material, rather than being localised to a single atom, meaning they can conduct electricity.

Dr Talbayev has been using this to study the properties of the electron flow in magnetic metals. By probing the motion of electrons at different times after their excitation by a femtosecond laser pulse, information can be obtained on how the conduction process works. As such, Dr Talbayev has been particularly interested in how these excited electrons are scattered on their journeys through the metal by ions of the crystalline lattice and by spin fluctuations.

By using broadly applicable techniques such as TRTS, Dr Talbayev and his group have been able to look at a very diverse range of magnetic materials and really understand the role of the humble electron in shaping the materials' magnetic and electronic properties.

By using broadly applicable techniques such as time resolved terahertz spectroscopy, Dr Talbayev and his group have been able to look at a very diverse range of magnetic materials

Q&A

What types of materials tend to show antiferromagnetic properties?

Most crystalline materials that contain transition metal ions tend to show antiferromagnetic properties. Antiferromagnetism is more ubiquitous in nature than ferromagnetism. Ferromagnetism is a more obvious property, as a ferromagnet sticks to a refrigerator, while an antiferromagnet does not. Both these kinds of magnetism represent an ordered magnetic state.

What will be the biggest breakthroughs arising from a more complete understanding of magnetic dynamics?

Some of the biggest breakthroughs will be in the area of manipulation of ferromagnetic and antiferromagnetic domains by femtosecond light pulses. A femtosecond light pulse will be used to write and erase information in magnetic memories. This can potentially speed up the writing of information in computer memories by thousands of times. Another exciting area for ground-breaking discoveries is the manipulation of antiferromagnetic domains using the magnetic field of terahertz pulses. Terahertz pulses are not sufficiently strong for this yet, as outlined below in the final question.

What types of applications will there be for antiferromagnetic materials?

Antiferromagnets are used and will continue to be used in magnetic computer memories and data storage.

What are the current experimental limitations in trying to understand magnetic behaviours in materials?

One experimental limitation is the weakness of the magnetic field of terahertz radiation. If made sufficiently strong, this magnetic field can potentially be used to control the electronic spin orientations via the interaction known as Zeeman interaction. However, more experimental development is needed to achieve a sufficiently strong magnetic field in a terahertz wave. A thousand-fold increase in this magnetic field is needed.

What are your future plans for this research?

My future plan is to investigate materials that are antiferromagnetic and also ferroelectric at the same time, or composite materials that are made of antiferromagnetic and ferroelectric constituents. Ferroelectricity is also a very useful property for data storage and processing. Ferroelectric domains are switched by an electric field. The marriage of magnetism and ferroelectricity promises fundamentally new kinds of devices, such as a memory bit with more than the usual two 'up' and 'down' states. My ultimate dream is to use the electric and/or magnetic field of a terahertz pulse to manipulate (read and write) magnetic and ferroelectric memory bits.

The marriage of magnetism and ferroelectricity promises fundamentally new kinds of devices

Detail

RESEARCH OBJECTIVES

Dr Talbayev's current research focuses on the optical and electronic properties of complex materials. He and his research team use time-resolved optical and terahertz spectroscopy to determine the magnetism and conduction of electrons in complex materials.

FUNDING

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COLLABORATORS

- Professor Keshav Dani (Okinawa Institute of Science and Technology Graduate University)
- Professor Jiangfeng Zhou (The University of South Florida)

BIO

Diyar Talbayev was born in Almaty, Kazakhstan. He received a BS degree in Applied Mathematics and Physics from Moscow Institute of Physics and Technology in 1998, and a PhD from Stony Brook University in 2004. Since 2011, he has been an Assistant Professor at Tulane University.

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