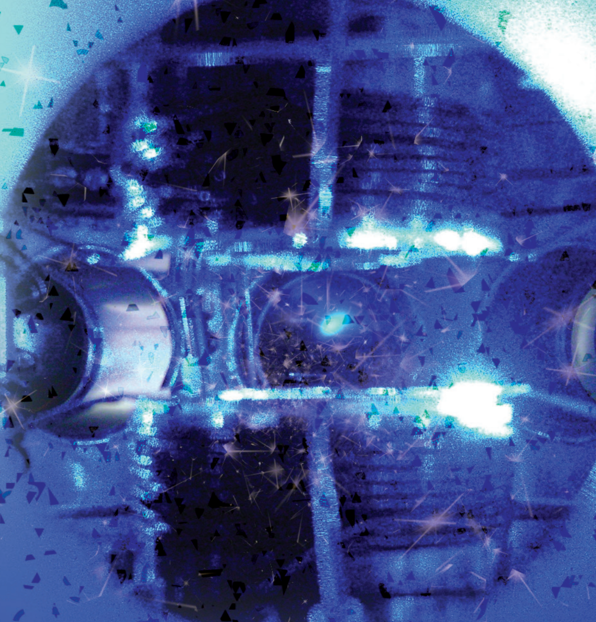


Cooled using laser beams to five-thousandths of a degree above absolute zero, the bright glowing ball in the centre is a cloud of over 1 million strontium atoms that are held in place by a magnetic field produced by the coils visible at the top and bottom.

DR MATTHEW JONES

A quantum state of matter

Dr Matthew Jones discusses his pioneering work investigating atomic interactions, which aims to provide a new research platform to study quantum systems and answers to a number of open questions

Could you outline the primary objectives of your research group?

Our research group aims to learn more about the behaviour of quantum systems that are strongly correlated, or in other words where interactions play a strong role. The physics of strong correlations governs the properties of many technologically relevant materials, such as high-temperature superconductors, and is also relevant to areas such as quantum information. We carry out experiments using laser-cooled strontium atoms, where we aim to engineer strongly correlated quantum systems in a controlled way.

On a personal level, how did you develop an interest in this field?

At the end of my undergraduate studies, I felt quite strongly that I did not 'understand' quantum mechanics. I found out that atomic physics provides one of the few systems where quantum states can be prepared and manipulated in experiments, and so I chose this field for my PhD. Over time, I realised that this lack of understanding wasn't just my own ignorance, but also reflected deep and exciting open questions regarding large-scale quantum systems.

Could you tell us a little about the project's background? What led to its formation?

I started work on strontium atoms after moving to Durham in 2006. At this point, my colleague Professor Charles Adams had already realised the huge potential of Rydberg states for creating strongly correlated quantum systems, and he persuaded me that this was an intriguing direction to take. Over the next few years, several groups published exciting theory papers that predicted the existence of Rydberg crystals and supersolids, and it became clear that we had the ideal experiment to test these ideas.

Why are strongly correlated materials difficult to model, and how do you overcome this challenge?

Many-particle quantum systems contain a vast amount of information. For example, let's consider just 100 electrons: electrons carry spin, which is like an arrow that can point up or down. Because these electrons are described by quantum mechanics, the spin can also point up *and* down. To completely describe the state of 100 electrons, we must store 2×2^{100} numbers, requiring over a billion billion terabytes of storage!

So we can't solve the basic equations of quantum mechanics directly – we must make approximations. The usual method which assumes that each particle interacts with a 'mean field', made up of the average effect of all the other particles, breaks down in a strongly correlated material. Our approach to this problem is to let atoms model the electron spins – making a quantum rather than a classical simulation.

What is a Rydberg supersolid and what would be the implications of observing one?

Supersolids are fascinating because they are a contradiction. In a solid, we think of the atoms as being fixed in place (in a crystal lattice, for example). Exactly the opposite happens in a superfluid like liquid helium – the atoms are free to move around with no resistance at all. A supersolid combines these two properties – the atoms have spatial order, like a crystal, but can also flow with no resistance. Recent theoretical work has shown that a superfluid phase could be observed by adding the long-range interactions between Rydberg atoms to a superfluid Bose-Einstein condensate.

Have you made any interesting or exciting discoveries so far that you wish to highlight?

Recently, with Dr Thomas Pohl's group at the Max-Planck Institute for Complex Systems in Dresden, we have shown theoretically that the strong correlations responsible for supersolid formation could be used to enhance the performance of optical atomic clocks based on strontium atoms. The interaction responsible for supersolid formation creates entangled states of the atoms in the clock, leading to a significant improvement in the signal-to-noise ratio. Strontium lattice clocks are currently under consideration as the next generation of time standard, so this work could have important practical consequences.

How do you predict the field will evolve over the next few years?

I think the field will also follow this exciting path of using the strong correlations introduced by Rydberg interactions for applications in quantum information and quantum measurement. An intriguing example is provided by recent results from several groups showing that the strong interaction can be mapped on to single photons.

Search for a supersolid

Research into the use of strontium Rydberg atoms in the Department of Physics at the University of Durham, UK is breaking new ground in an attempt to realise the potential of a fascinating and contradictory state of matter

AS THEORETICAL AND experimental physicists probe deeper into the quantum nature of reality, technological advances made in recent years have allowed for a consistent narrowing of the gap between the two approaches. The development and refinement of laser cooling and trapping has expanded the possibilities of manipulating matter at an atomic level. At the same time, the ability to observe and control hitherto theoretical states of matter is fostering an increasing interest in the nature and behaviour of large-scale quantum systems – in particular, supersolids – and the mysteries that surround high temperature (high-T) superconductivity.

SUPERSOLIDS

A supersolid phase of an isotope of helium (He) was first predicted in 1970. In this bizarre state of matter, atoms are locked in place in the familiar, ordered patterns of a crystalline solid and yet simultaneously free to move with the frictionless flow of a superfluid. Fraught with difficulties and controversy, the search for a supersolid in helium has proved inconclusive.

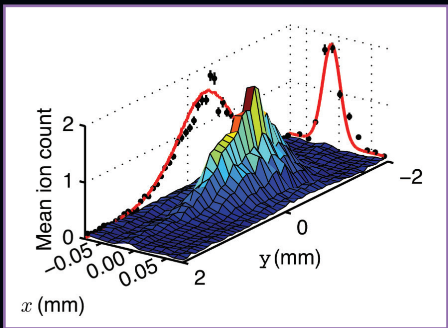
Recent theoretical work has shown that it may be possible to observe a supersolid in a different way by using laser-cooled atoms. In so doing, researchers hope to shed some light on the key question of the interplay of crystalline order and superfluidity in materials like high-T superconductors, where simple computer models cannot be solved for more than a handful of particles.

At the forefront of this research, Dr Matthew Jones from the University of Durham in the UK is leading a team that is exploring strongly correlated materials with long-range order and superfluidity. By cooling the atoms present in a gas to a temperature close to absolute zero the researchers can form a Bose-Einstein condensate (BEC). Within the BEC, the atoms form a superfluid. Crucially, the internal state of each atom can be completely controlled. By using a laser pulse it has become possible to highly excite the outer electron, known as the valence electron, switching on a controllable long-range interaction between the atoms.

RYDBERG ATOMS

This highly excited condition is known as a Rydberg state, which the team first observed in 2007 using electromagnetically induced transparency (EIT). As Jones explains, this state allows for far greater interaction: "The size of the atom in these highly excited states is magnified nearly a thousand times, and as a result Rydberg atoms interact very strongly with each other over distances of several microns". A unique aspect of their work is the use of strontium (Sr) atoms, which contain two valence electrons, providing new approaches to detecting and manipulating Rydberg atoms.

Strengthened by the technological and human resources available at Durham University, Jones and his group intend to discover whether strong correlations can lead to the dynamic emergence of long-range order and whether this can coexist with superfluidity in a Rydberg



A two-dimensional map of the spatial distribution of Rydberg excitations obtained using scanning autoionisation microscopy.

supersolid: "A Rydberg supersolid provides a model system for studying the interplay between superfluidity and interactions," elucidates Jones. "Combining cold atoms and Rydberg excitation is now a very hot topic in atomic physics."

SUPERATOMS

The study has four major objectives. Firstly, the researchers intend to obtain high-resolution images using a scanning microscope based on autoionisation. Importantly, as the Rydberg atoms are excited and interact within their cold dense cloud, a characteristic length scale emerges (known as a dipole blockade radius) in which the Rydberg excitation is delocalised and the strongly correlated atoms within the blockade sphere entangle to form a superatom. Using a tightly focused laser beam, the team has developed a new technique to excite the second valence electron leading to autoionisation in this small region of the sample. The ions can then be extracted using an electric field and detected using a microchannel plate (MCP). As Jones explains: "An image is formed by scanning the focus of the laser over the cloud of atoms and measuring the number of ions at each position". In this way, they will be able to gauge the density distribution of the Rydberg atoms while setting the spatial resolution by adjusting the size of the laser spot.

RYDBERG CRYSTALS

This scanning technique opens the possibility of observing the emergence of long-range order and spatial correlations while using tailored light pulses to form Rydberg crystals, representing a major aim of the project. "If you try to excite Sr atoms in a laser-cooled gas, where the atoms are essentially randomly positioned, then you find that this interaction causes the Rydberg atom to form a periodic crystal of excitation probability," outlines Jones. The observation of dynamical crystallisation would provide a significant test of the group's understanding of the complex many-body dynamics in a strongly correlated system and could prove an important resource for future experiments, including the creation of non-classical states of light, or to assist in the investigation of quantum transport effects.

CUTTING THROUGH THE NOISE

The third objective involves the dressing of the Rydberg atoms using off-resonant coupling. By first mapping the dipole blockade onto a BEC of ground state (non-Rydberg) Sr atoms, the off-resonant coupling to the Rydberg state mixes a small, controllable amount of Rydberg character into the BEC, allowing for a reduction in the effective decay rate, more in line with a timescale appropriate to the BEC dynamics. Crucially, the team's use of Sr atoms enables the dressed interaction to be observed by eliminating other background collisions between ground state atoms.

TOWARDS A SUPERSOLID

Finally, the team intends to test the theoretical assertion that the dressed potential of the Rydberg atoms would lead to dramatic effects on the BEC. In particular, they wish to examine the prediction that dynamical control of the strength of the dressing can lead to the emergence of long-range spatial order, with the condensate breaking up into a crystalline arrangement of droplets which remain superfluid. Moreover, at lower temperatures tunnelling is predicted to occur between these droplets, which would lead to bulk superfluidity and consequently a Rydberg supersolid phase. Pivotally, the researchers will be able to image both spatial and momentum distributions to test the existence of the Rydberg supersolid directly.

> The ability to observe and control hitherto theoretical states of matter is fostering an increasing interest in the nature and behaviour of large-scale quantum systems – in particular, supersolids

The existence of such a supersolid phase has been an open question for 40 years; therefore the observation of it in a cold atoms system would represent a significant advance in the field. As cold Rydberg gases represent the forefront of atomic physics research, the investigations being conducted at Durham University could well shape the future direction not only of quantum simulation but of a myriad of related sciences as well. Indeed, Jones' investigation is contributing to the emergence of a dynamic new field surrounding condensed matter and atomic physics.

INTELLIGENCE

RYDBERG CRYSTALS AND SUPERSOLIDS

OBJECTIVES

To learn more about the behaviour of quantum systems that are strongly correlated. The team carries out experiments using laser-cooled strontium atoms, where they aim to engineer strongly correlated quantum systems in a controlled way.

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