Spontaneous Bose-Einstein condensation of excitons

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Excitons are pairs of electrons and holes inside a solid material that together behave like a single particle. It has long been suspected that when many such excitons exist in the same piece of matter, they can form a single giant quantum state called a Bose-Einstein condensate – the same process which is responsible for a metal losing all its electrical resistance when it becomes a superconductor, for example. However, actually proving that Bose-Einstein condensation of excitons occurs in any real material has been a challenge for physicists for decades. An experiment done at the University of Illinois at Urbana-Champaign, carried out in collaboration with UvA-Institute of Physics researcher Jasper van Wezel, has uncovered evidence that this elusive state of matter really does exist. Their results were published in *Science* this week.

In the early 20th century, physicists discovered that the world around us consists of two types of particles: bosons and fermions. The main difference between these particles is how they behave when one tries to bring them into the same physical state, with the same position, the same velocity, and so on. While for two fermions (such as electrons) it is fundamentally impossible to ever be in the exact same state, two or more bosons (such as photons, particles of light) can be in the same state at the same time without any problems. In fact, at low enough temperatures, collections of bosons will prefer such a situation: the particles have the tendency to all occupy the same state, in a process known as Bose-Einstein condensation.

Excitons

For most types of bosons, Bose-Einstein condensation takes place at very low temperatures, near the absolute temperature minimum of 273 degrees below zero on the Celsius scale. An exception to this rule could be the behavior of excitons in a crystal. Excitons are combinations of negatively charged electrons and so-called holes - the absence of an electron somewhere in the crystal, leading to a local surplus of positive charge. Pairs of electrons and holes can be bound together and behave like a single bosonic particle, the exciton.

It was predicted in the 1960s that just like other bosons, excitons can form Bose-Einstein condensates. Moreover, this should happen at much higher temperatures than for most other particles – in theory it could happen even at room temperature. Since higher temperatures are much easier to reach in a laboratory setting, excitons could provide an accessible setting in which both the unusual quantum properties of the Bose-Einstein condensates themselves, as well as the unique material properties they bestow upon their host crystals, can be investigated.

M-EELS

Despite the relatively high temperature at which the effect described in the *Science* article occurs (only 100 degrees centigrade or so below room temperature), and despite the presence of excitons having been suspected for many years, proving beyond doubt that excitons really do form a Bose-Einstein condensate turned out to be surprisingly difficult. The main reason is that there is a different physical phenomenon which is hard to distinguish from a Bose-Einstein condensate of excitons: the formation of a so-called Peierls state, where electrons inside a crystal structure spontaneously

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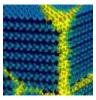

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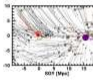

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organize in a wave-like manner, with alternating peaks and troughs of electron density. Such a wave has many of the same physical characteristics expected for a Bose-Einstein condensate of excitons.

A new experiment carried out at the University of Illinois at Urbana-Champaign, in collaboration with researchers at the University of Oxford, and the University of Amsterdam, has now shown that the newly developed experimental technique of Momentum-resolved Electron Energy-loss Spectroscopy (M-EELS for short) does allow them to distinguish unique signatures of condensed excitons in a material called titanium diselenide. This technique was developed at the University of Illinois in Urbana-Champaign, and for the first time allows researchers to measure low-energy bosonic particles made of electrons and holes, regardless of their momentum. With this unique capability, the researchers were able to prove that excitons in titanium diselenide spontaneously agglomerate into a Bose-Einstein condensate when the material is cooled down to below 100 degrees centigrade below room temperature.

These measurements for the first time give compelling evidence for the fact that excitons can form a Bose-Einstein condensate at relatively high, easily accessible temperatures. Moreover, they show that M-EELS is a powerful and versatile new technique with many potential future applications. The results have been published in *Science* this week.

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More information: Anshul Kogar et al. Signatures of exciton condensation in a transition metal dichalcogenide, *Science* (2017). **DOI: 10.1126/science.aam6432**

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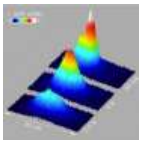

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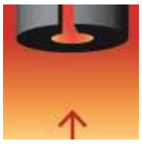

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