Marrying superconductors, lasers, and Bose-Einstein condensates

June 17 2016, by Sheri Ledbetter

Chapman University Institute for Quantum Studies (IQS) member Yutaka Shikano, Ph.D., recently had research published in *Scientific Reports*. Superconductors are one of the most remarkable phenomena in physics, with amazing technological implications. Some of the technologies that would not be possible without superconductivity are extremely powerful magnets that levitate trains and MRI machines used to image the human body. The reason that superconductivity arises is now understood as a fundamentally quantum mechanical effect.

The basic idea of quantum mechanics is that at the microscopic scale everything, including matter and light, has a wave property to it. Normally the wave nature is not noticeable as the waves are very small, and all the waves are out of synchronization with each other, so that their effects are not important. For this reason, to observe quantum mechanical behavior experiments generally have to be performed at a very low temperature, and at microscopic length scales.

Superconductors, on the other hand, have a dramatic effect in the disappearance of resistance, changing the entire property of the material. The key quantum effect that occurs is that the quantum waves become highly synchronized and occur at a macroscopic level. This is now understood to be the same basic effect as that seen in lasers. The similarity is that in a laser, all the photons making up the light are synchronized, and appear as one single coherent wave. In a superconductor the macroscopic wave is for the quantum waves of the electrons, instead of the photons, but the basic quantum feature is the same. Such macroscopic quantum waves have also been observed in Bose-Einstein condensates, where atoms cooled to nanokelvin temperatures all collapse into a single state.

Up until now, these related but distinct phenomena have only been observed separately. However, as superconductors, lasers, and Bose-Einstein condensates all share a common feature, it has been expected that it should be able to see these features at the same time. A recent experiment in a global collaborative effort with teams from Japan, the United States, and Germany have observed for the first time experimental indication that this expectation is true.

They tackled this problem by highly exciting exciton-polaritons, which are particle-like excitations in a semiconductor systems and formed by strong coupling between electron-hole pairs and photons. They observed high-energy side-peak emission that cannot be explained by two mechanisms known to date: Bose-Einstein condensation of exciton-polaritons, nor conventional semiconductor lasing driven by the optical gain from unbound electron hole plasma.

By combining the experimental data with their latest theory, they found a possibility that the peak originates from a strongly bound e-h pairs, which can persist in the presence of the high-quality optical cavity even for the lasing state. This scenario has been thought to be impossible since an e-h pair experiencing weakened binding force due to other electrons and/or holes breaks up in high-density. The proposed scenario is closely related to the BCS physics, which was originally introduced by John Bardeen, Leon Cooper, and John Robert Schrieffer to explain the origin of superconductivity. In the BCS theory, the superconductivity is an effect caused by a condensation of weakly bound electron pairs (Cooper pairs). In the latest theory of e-h pairs plus photons (e-h-p), bound e-h pairs' survival can be described in BCS theory of e-h-p system as an analogy of Cooper pairs in superconductivity.

"Although a full understanding of this observation has not yet been reached," said Dr. Tomoyuki Horikiri at Yokohama National University, and one of the authors on the study. "The discovery provides an important step toward the clarification of the relationship between the BCS physics and the semiconductor lasers. The observation not only deepens the understanding of the highly-excited exciton-polariton systems, but also opens up a new avenue for exploring the non-equilibrium and dissipative many-body physics. In such practical application studies, there are still many quantum foundational questions."

More information: Tomoyuki Horikiri et al, High-energy side-peak emission of exciton-polariton condensates in high density regime, *Scientific Reports* (2016). DOI: 10.1038/srep25655

Provided by Chapman University