Marrying superconductors, lasers, and Bose-Einstein condensates

Superconductivity is 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 themselves very small, and all the waves are out of phase with each other, so that their effects are not noticeable. For this reason to observe quantum mechanical behavior generally experiments have to be performed at very low temperature, and 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 here is that the quantum waves become in-phase and occurs 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 in-phase, 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 to 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 anticipated that we should be able to see a type of hybrid system containing characteristics of superconductors, lasers, and Bose-Einstein condensate. A recent experiment in a global collaborative effort from teams in Japan, the United States, and Germany have observed for the first time experimental indication that this expectation is true.

Dr. Tomoyuki Horikiri at Yokohama National University together with Dr. Makoto Yamaguchi and Dr. Kenji Kamide forms an international collaboration team including Tim Byrnes at New York University, Yutaka Shikano at Institute for Molecular Science, National Institutes of Natural Sciences, Tetsuo Ogawa at Osaka University, Alfred Forchel at Universität Würzburg, and YoshihisaYamamoto at Stanford University and National Institute of Informatics. They tackled this problem by strongly 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, and 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 signal originates from a strongly bound e-h pairs, which can persist in 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 experiences a weakened binding force due to other electrons, or that holes breaks up in high-density. The proposed scenario is closely related to BCS physics, named after 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 reached,” says Dr. Horikiri, “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. The paper is published in *Scientific Reports*, one of the journals in Nature Publishing Group.

Reference:
Title: High-energy side-peak emission of exciton-polariton condensates in high density regime
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