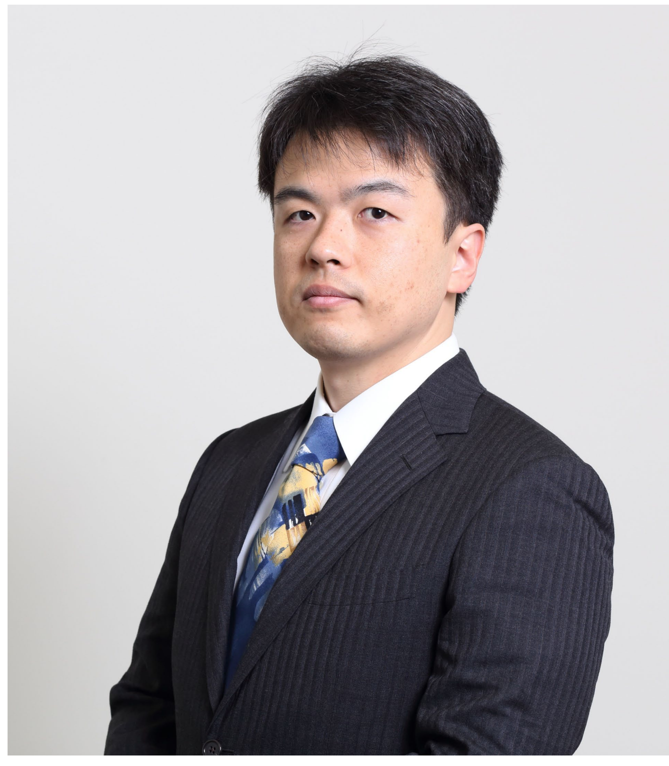
The Sir Martin Wood Prize Lecture

Realisation of Bose-Einstein condensation of excitons



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Biography

2003:
B. S., Department of Applied Physics, The University of Tokyo

2005:
M. S., Department of Applied Physics, The University of Tokyo

2007-2010:
Research Associate, Assistant Professor, Department of Applied Physics, The University of Tokyo

2010:
Assistant Professor, Photon Science Center, The University of Tokyo

2010-2015:
Assistant Professor, Department of Physics, The University of Tokyo

2012:
Ph. D., Department of Physics, The University of Tokyo

2015:
Lecturer, Department of Physics, The University of Tokyo

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Associate Professor, Photon Science Center, The University of Tokyo

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Max Planck Institute for Solid State Science

Lecture Hall 2D5

When light is absorbed by a semiconductor crystal at low temperatures, conduction electrons and their corresponding holes form excitons. These hydrogen-like neutral quasiparticles with finite lifetimes are expected to behave as bosons. They are cooled via thermal contact with the phonon bath. Excitons have been of interest since the 1960s as potential systems for realising Bose-Einstein Condensation (BEC). In the bulk semiconductor Cu_2O, there exists a 1s paraexciton state with a uniquely long lifetime, making it a prime candidate for BEC. Despite decades of experimental pursuit, evidence of BEC had not been observed.

This study first sought to understand why BEC was absent. Based on measurements of the 1s-2p induced absorption spectrum in the mid-infrared wavelength region, the absolute density and temperature of excitons were evaluated from the low-density limit. We discovered that paraexcitons were annihilated through inelastic two-body scattering even at lower densities than initially assumed, effectively shortening their lifetime. This made it impossible to satisfy BEC conditions in the traditional experimental condition of around 2 K. We also proposed that setting the BEC critical temperature in the sub-kelvin temperature region could be effective.

Subsequently, we cooled a Cu_2O single crystal using a cryogen-free ^3He refrigerator, and we formed a strain-induced trap potential that allowed for capturing and accumulating paraexcitons. We achieved an exciton temperature of 800 mK, and successfully exceeded the BEC critical density. The BEC transition was observed in the spatially resolved luminescence spectrum as a relaxation explosion, where the two-body inelastic scattering rate in the condensate increased in a threshold manner. To prepare a stable BEC, we cooled the crystal using a cryogen-free dilution refrigerator. By exploiting the activation of paraexciton-TA-phonon scattering in the strain-induced trap, the world's lowest exciton temperature of approximately 100 mK was achieved. We realised 1s-2p mid-infrared absorption imaging of trapped paraexcitons, resulting in direct observation of the exciton BEC. While the exciton-exciton elastic scattering in the condensate exhibited well-understood behaviour, there were unexplained features, such as small condensate fractions, indicating the importance of this model physical system for future developments in the study of quantum many-body phenomena in non-equilibrium open systems.

Excitons are exotic atoms that exist in the many-body electron systems of solids. We have also realised laser cooling of positronium, an exotic atom composed of an electron and a positron in a vacuum. Through precision laser spectroscopy and observation of quantum statistical states of these simple atomic systems governed by electromagnetic interactions, we aim to contribute to the development of quantum many-body physics and unravel the mysteries of the universe.

Associate Professor Yoshioka was awarded the Sir Martin Wood Prize at the Millennium Science Forum which took place in November 2024. The Millennium Science Forum was established in 1998 to promote scientific exchange between Britain and Japan and recognize the work of outstanding young Japanese researchers. The prize is named after Sir Martin Wood, founder of Oxford Instruments.