Citation of the 2020 Nishina Memorial Prize

1) Awardee

Dr. Kazushi KANODA

Professor, Department of Applied Physics, the University of Tokyo

Title of Research Achievement:

"Study of strongly correlated quantum liquids in organic conductors"

Abstract of Research Achievements:

Electrons in solids have duality as waves propagating through the crystalline lattices composed of atoms or molecules and as moving particles avoiding each other by the repulsive Coulomb force. Their competition induces collective phenomena, which are unique to interacting electrons but not possible for independent electrons. For example, when the Coulomb energy between electrons on the same atom or molecule far exceeds the kinetic energy of interatomic (intermolecular) electron hopping, localization of electrons results in the Mott insulating state, where the spin degree of freedom of electrons is responsible for a wide variety of magnetism. Application of pressure to Mott insulators shrinks the lattice and promotes electron hopping, thereby causes an insulator-to-metal phase transition (the Mott transition). Anisotropic superconductivity is often observed in the neighborhood of the Mott transitions. Studies of diverse phenomena caused by the electron-electron interaction have made an active research field, physics of strongly correlated electrons. Although traditionally, the main target of this field is inorganic materials, organic conductors composed of organic molecules have been recently playing important roles. Dr. Kanoda discovered the following important quantum phenomena in organic conductors by taking advantage of the structural diversity of molecular crystals and their excellent controllability with pressure: the long-sought quantum spin liquids on a triangular lattice, quantum critical liquids near the Mott transitions, and novel correlation effects in a quasi-two-dimensional electron system with cone-shaped energy bands.

The ground state of Mott insulators in most cases shows a magnetic order with fixed spin directions such as ferromagnetic or antiferromagnetic states. In 1973, P. W. Anderson proposed that antiferromagnetic quantum spins on a triangular lattice would become a quantum spin liquid, where quantum fluctuations prevent spin order even at absolute zero temperature, because the magnetic frustration prohibits the stable antiparallel spin configuration on every bond. In spite of continued efforts over many years, realizing the spin liquid state in real materials has been extremely difficult and subsequent theoretical studies have posed doubt on the original Anderson's proposal. This situation was changed by the discovery by Dr. Kanoda. From nuclear magnetic resonance and other magnetic and thermal experiments, he found that the organic molecular crystal κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$, in which dimers of BEDT-TTF molecules hosting a localized spin 1/2 form a triangular lattice, shows no magnetic order down to very low temperatures [1, 2]. This work has stimulated extensive research on quantum spin liquids on triangular and related lattices. It is now recognized that quantum spin liquids can have various degrees of freedom beyond the Anderson's original proposal. The research on quantum spin liquids has grown into a rich field of physics, which is intimately related to the topological quantum phenomena.

The properties of the series of BEDT-TTF based molecular crystals are strongly influenced by pressure and relatively low pressures are required to induce Mott transition compared with inorganic materials. By measuring the electrical resistivity of several BEDT-TTF based conductors under precise control of pressure, Dr. Kanoda discovered a universal quantum critical scaling relation for the temperature and pressure dependence of the resistivity near the Mott transition, irrespective of the details of the ground states. This indicates the emergence of quantum critical liquids fluctuating between localized and itinerant states in the neighborhood of the Mott transition.

The layered organic conductor α-(BEDT-TTF)$_2$I$_3$ with low symmetry of the crystal structure shows a charge ordered insulating state at ambient pressure and becomes conducting under pressure. Unlike conventional metals, the high-pressure phase of α-(BEDT-TTF)$_2$I$_3$ is known to have cone-shaped energy bands (often called a massless Dirac electron system). By performing nuclear magnetic resonance experiments on this Dirac electron system, Dr. Kanoda in collaboration with theoretical colleagues discovered novel correlation effects originating from suppressed electrical screening due to vanishing density of states at the vertex of the cone and the chirality of the wave functions. From the local spin susceptibility obtained by site-selective NMR measurements combined with the renormalization-group analysis, they first demonstrated strong sharpening of the cone compared with the calculated band structure [4]. This result confirms the theoretical prediction for logarithmic divergence of the electron velocity toward the vertex of the cone. They further found anomalous increase of the nuclear relaxation rate at low temperatures, which would be ascribed to the fluctuations of electron-hole exitonic pair condensation [5]. This implies dynamic mass acquisition by the interaction between chiral particles.

The discoveries of quantum spin liquid, metal-insulator quantum critical liquid, and novel correlation effects in a quasi-two-dimensional electron system with cone-shaped energy bands by Dr. Kanoda have brought new prospect in the physics of strongly correlated electrons. It is remarkable that these different emergent phenomena occur in the same series of BEDT-TTF based materials with only difference in the spatial arrangement of the molecule. This is a clear message that flexibility of the lattice geometry is the source of diverse quantum phenomena and plays important roles in the physics of strongly correlated electrons.

References

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2) Awardee

Dr. Kazuma NAKAZAWA

Senior Professor, Faculty of Education, and Graduate School of Engineering, Gifu University, Tokai National Higher Education and Research System

Title of Research Achievement:

"Study of double strangeness nuclei using nuclear emulsion plate"

Abstract of Research Achievements:

Major objectives of nuclear physics are to understand the synthesis and evolution of matter in the universe by exploring unknown nuclei as well as to understand the formation of atomic nuclei by studying the microscopic origin of the nuclear force. For those purposes, there have been theoretical and experimental investigations on the nuclear structure, the nuclear force and the nuclear properties far from stability. In recent years, studies on hypernuclei which contain strange quark(s) open a possibility to shed new light on the origin of the baryon-baryon interactions (the nuclear force between nucleons and hyperons) in terms of quarks and gluons.

Dr. Nakazawa is a leading experimentalist searching for the hypernuclei with the use of the nuclear emulsion plate, which is a specialized photographic film to record tracks of charged particles with an accuracy of 1 μm or less. Ξ^- hyperons produced via the (K^-, K^+) reactions in a primary target are captured by nuclei in the plate, where various hypernuclei can be formed. With an optical microscope, the tracks of Ξ^- are scanned through the plate to find out traces of formation and decay of the hypernuclei. To speed up the scanning process, the emulsion-counter hybrid method has been developed, in which incident positions of the Ξ^- are determined from the tracking information of K^- and K^+ recorded by an electrical counter system, so that the scanning of Ξ^- can be performed in the limited area. Using this technique, the sequential weak decay of a double Λ hypernucleus was directly observed at KEK 176 experiment [1].

Using the same technique with further various improvements, a clear and unambiguous event, called the NAGARA event, was observed at KEK E373 experiment [2]. From the kinematical analysis of all the tracks found in the event, the possible formation and decay modes are thoroughly investigated. It is then identified uniquely as the sequential decay of ${}^{6}_{\Lambda\Lambda}He$, the hypernucleus made of helium and two Λ particles, for the first time. Furthermore, from the determination of the mass of ${}^{6}_{\Lambda\Lambda}He$, the Λ-Λinteraction is found to be weakly attractive with the energy of $\Delta B_{\Lambda\Lambda}$=0.67±0.17 MeV [2,3].

The scanning technology has been improved further and full volume scan of the nuclear emulsion plate has become possible (the overall-scanning method). With this new method, they have found a new event, the KISO event, out of 8 million images of the nuclear emulsion plate. It corresponds to the formation and decay of a Ξ hypernucleus [4]. Kinematical analysis has shown that the Ξ^- is deeply bound in nitrogen nucleus forming a Ξ hypernucleus, which indicates for the first time that the nuclear force between Ξ^- and nucleon is attractive [4].

The experimental studies by Dr. Nakazawa and his collaborators have revealed that the Λ-Λ interaction is weakly attractive, providing crucial information on the study of the baryon-baryon interactions and the cooling of neutron stars. Also the experimental finding on the attraction between Ξ and the nucleon provides crucial information for the studies of the hyperon mixing in the interior of neutron stars as well as the equation of state for high density matter. Moreover, those experimental results provide important information in understanding the origin of the nuclear force in terms of quantum chromodynamics. Dr. Nakazawa and his collaborators are currently working at J-PARC E07 experiment seeking new double strangeness nuclei and have already found a double Λ Be nucleus, ${}^{11}_{\Lambda\Lambda}Be$ [5].

References

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