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 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 are 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 types of magnetism. Application of pressure to Mott insulators shrinks the lattice and promotes electron hopping, thereby causing an insulator-to-metal phase transition (the Mott transition). Anisotropic superconductivity is often observed in the neighborhood of the Mott transitions. Studies of the diverse phenomena caused by the electron-electron interactions have become an active research field, i.e., the physics of strongly correlated electrons. Although, traditionally, the main target of this field has been inorganic materials, organic conductors composed of organic molecules have been recently playing important roles. By taking advantage of the structural diversity of molecular crystals and their excellent controllability with pressure, Dr. Kanoda discovered the following important quantum phenomena in organic conductors: 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.

In most cases, the ground state of Mott insulators 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 would prevent spin order even at absolute zero temperature, because the magnetic frustration would prohibit the stable antiparallel spin configuration on every bond. Despite 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 Anderson's original proposal. This situation changed due to the discovery by Dr. Kanoda. Using 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 Anderson's original proposal. 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, in comparison to inorganic materials, relatively low pressures are required to induce Mott transition. By measuring the electrical resistivity of several BEDT-TTF based conductors with 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 a crystal structure having low symmetry shows a charge ordered insulating state at ambient pressure and becomes conductive 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 as compared to 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 could be ascribed to the fluctuations of electron-hole exitonic pair condensation [5]. This would imply dynamic mass acquisition by the interaction between chiral particles.

The discoveries by Dr. Kanoda 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 have brought new perspectives 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 differences in the spatial arrangement of the molecule. This is a clear sign that flexibility of the lattice geometry is the source of diverse quantum phenomena and plays an important role in the physics of strongly correlated electrons.

References

[1] Y. Shimizu, K. Miyagawa, K. Kanoda, M. Maesato, and G. Saito, "*Spin Liquid State in an Organic Mott Insulator with a Triangular Lattice*", Phys. Rev. Lett. **91**, 107001 (2003).

[2] H. F. L. Pratt, P. J. Baker, S. J. Blundell, T. Lancaster, S. Ohira-Kawamura, C. Baines, Y. Shimizu, K. Kanoda, I. Watanabe, and G. Saito, "*Magnetic and non-magnetic phases of a quantum spin liquid*", Nature **471**, 612 (2011).

[3] T. Furukawa, K. Miyagawa, H. Taniguchi, R. Kato, and K. Kanoda, "*Quantum criticality of Mott transition in organic materials*", Nature Phys. **11**, 221 (2015).

[4] M. Hirata, K. Ishikawa, K. Miyagawa, M. Tamura, C. Berthier, D. Basko, A. Kobayashi, G. Matsuno, and K. Kanoda, "*Observation of an anisotropic Dirac cone reshaping and ferrimagnetic spin polarization in an organic conductor*", Nature Commun. **7,** 12666 (2016).

[5] M. Hirata, K. Ishikawa, G. Matsuno, A. Kobayashi, K. Miyagawa, M. Tamura, C. Berthier, and K. Kanoda, "*Anomalous spin correlations and excitonic instability of interacting 2D Weyl fermions*", Science **358**, 1403 (2017).

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 plates"

Abstract of Research Achievements:

Two major objectives of nuclear physics are to understand the synthesis and evolution of matter in the Universe by exploring unknown nuclei, and to understand the formation of atomic nuclei by studying the microscopic origin of nuclear forces. For those purposes, there have been theoretical and experimental investigations on nuclear structure, nuclear forces and the nuclear properties far from stability. In recent years, studies on hypernuclei that contain strange quark(s) have opened up possibilities 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 these hypernuclei with the use of a nuclear emulsion plate, which is a specialized photographic film that records tracks of charged particles with an accuracy of 1 μm or less. Ξ^- hyperons produced via (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 traces of the formation and decay of the hypernuclei. To speed up the scanning process, an 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 the KEK 176 experiment [1].

Using the same technique with various further improvements, a clear and unambiguous event, called the NAGARA event, was observed at the KEK E373 experiment [2]. From the kinematical analysis of all the tracks found in the event, the possible formation and decay modes were thoroughly investigated. The sequential decay of ${}^{6}_{\Lambda\Lambda}He$, the hypernucleus made of helium and two Λ particles, was identified uniquely for the first time. Furthermore, from the determination of the mass of ${}^{6}_{\Lambda\Lambda}He$, the Λ-Λ interaction was 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 a full volume scan of the nuclear emulsion plate has become possible (the overall scanning method). With this new method, a new event, the KISO event, has been found, 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 baryon-baryon interactions and the cooling of neutron stars. In addition, the experimental finding on the attraction between Ξ and the nucleon has provided crucial information for 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 have provided important information in understanding the origin of nuclear forces in terms of quantum chromodynamics. Dr. Nakazawa and his collaborators are currently working at the J-PARC E07 experiment, seeking new double strangeness nuclei, and have already found a double Λ Be nucleus, ${}^{11}_{\Lambda\Lambda}Be$ [5].

References

[1] S. Aoki et al., “Direct Observation of Sequential Weak Decay of a Double Hypernucleus”, Progress of Theoretical Physics **85** (1991) 1287-1298.

[2] H. Takahashi et al., “Observation of a ${}^{6}_{\Lambda\Lambda}He$ Double Hypernucleus”, Physical Review Letters **87** (2001) 212502 (1-5).

[3] J. K. Ahn et al., “Double-Λ hypernuclei observed in a hybrid emulsion experiment”, Physical Review C **88** (2013) 014003 (1-10).

[4] K. Nakazawa et al., “The first evidence of deeply bound state of Xi^- - ${}^{14}N$ system”, Progress of Theoretical and Experimental Physics **2015** (2015) 033D02 (1-11).

[5] H. Ekawa et al., “Observation of a Be double-Lambda hypernucleus in the J-PARC E07 experiment”, Progress of Theoretical and Experimental Physics **2019** (2019) 021D02 (1-11).