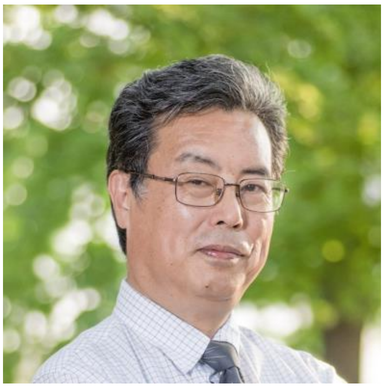
2024 (70th) Nishina Memorial Prize

1) Dr. Susumu Shimoura

Professor Emeritus, The University of Tokyo



"Experimental study of four-neutron states"

Whether nuclei or gathered states composed entirely of neutrons exist or not is one of the important questions in nuclear physics that has remained unanswered for many years. It is known that the nuclear force between two neutrons, although being attractive, is weaker than that between a proton and a neutron. In fact, a proton and a neutron are bound together to form a nucleus called the deuteron, while two neutrons are barely unbound. Then, what happens to a system of three or more neutrons? In general, nuclei with an even number of neutrons have lower energy per each neutron than those with an odd number. Thus, a four-neutron nucleus (tetraneutron) is expected to exist as a bound metastable nucleus or as a resonance state where four neutrons are gathered only for a certain time. Various studies have been conducted both experimentally and theoretically for about 60 years, but no conclusion has been reached so far. The main reason is that it is extremely difficult to put four neutrons in the same place.

Dr. Shimoura devised experiments to produce tetraneutrons (4n) efficiently without background by the nuclear reaction

$$^{8}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be} + 4\mathrm{n},$$

in which a beam of neutron-rich unstable ^{8}He nuclei is injected to a ^{4}He target. In this reaction, two protons in the target ^{4}He are replaced by two neutrons, leaving four neutrons almost at rest without recoil. The ^{8}He in the beam turns into ^{8}Be, and by measuring the energy of the ^{8}He and ^{8}Be, the energy of the remaining 4-neutron system can be determined. (Because the ^{8}Be immediately splits into two ^{4}He nuclei, the energy of both ^{4}He nuclei should be measured.)

He led these experiments at RI Beam Factory (RIBF) in RIKEN. Accelerated ^{18}O beam was directed at a beryllium target, and produced ^{8}He nuclei were separated from other nuclei and injected into a liquid helium target. Two ^{4}He nuclei ejected from the target were analyzed by the SHARAQ spectrometer, giving the energy of the 4n system. A peak indicating the presence of tetraneutrons with 4 counts (with a statistical significance of 4.9σ) was observed about 1 MeV above the total mass of the four neutrons in the energy spectrum [1].

To confirm this result, he proposed another reaction,

$$^{8}\text{He} + \text{p} \rightarrow \text{p} + {}^{4}\text{He} + 4\text{n},$$

called the α-knockout reaction in which an α-particle (^{4}He nucleus) of a ^{8}He nucleus is knocked out and four neutrons are gently left behind. This can produce tetraneutrons efficiently without background, because the ^{8}He nucleus has a structure of four neutrons loosely bound around an α-particle. This experiment was also conducted at RIBF.

A beam of ^{8}He was injected into a liquid hydrogen target, and the emitted ^{4}He and p were analyzed with the SAMURAI spectrometer. In the obtained energy spectrum of the 4-neutron system, a high-statistics (about 60 counts) peak with a statistical significance more than 5σ was observed, with an energy of 2.37 ± 0.38 (statistical error) ± 0.44 (systematic error) MeV and a width of 1.75 ± 0.22 (statistical error) ± 0.30 (systematic error) MeV. This is consistent with the result of the first experiment. It has been confirmed, therefore, that the tetraneutron exists as a resonance state (or a strongly correlated state) with a width of about 2 MeV and at about 2 MeV above the 4-neutron mass, and not as a bound state [2].

These experiments were conducted with many researchers in Japan and abroad, and the key to the success lies in the well-thought-out nuclear reactions and the strong leadership of Dr. Shimomura. Various theoretical calculations are being made on tetraneutrons, but the results seem to remain inconclusive so far. His experiments open a new research area, “nuclear physics for multi-neutron systems,” which is expected to play a significant role in understanding the structure of extremely neutron-rich nuclei and neutron stars through further experimental and theoretical studies.

References

[1] K. Kisamori et al., “Candidate Resonant Tetraneutron State Populated by the ^{4}He(^{8}He,^{8}Be) Reaction” Phys. Rev. Lett. **116**, 052501 (2016).

[2] M. Duer et al., “Observation of a correlated free four-neutron system” Nature **606**, 678 (2022).

2) Dr. Dai Aoki

Professor, Institute for Materials Research, Tohoku University

"Pioneering research on unconventional superconductivity in actinoid compounds"

Superconductivity represents one of the most striking macroscopic quantum phenomena in physics. The microscopic mechanism underlying this state involves the formation of Cooper pairs—bound states of two electrons. In conventional superconductors, this pairing is mediated by electron-phonon interactions, a process well described by the BCS theory, where electrons with opposite spins form pairs in a spin-singlet state. Historically, ferromagnetism and superconductivity were considered mutually exclusive phenomena, like oil and water.

In certain f-electron systems, particularly compounds containing rare-earth or actinoid elements, localized f-electrons hybridize with conduction electrons to form a strongly correlated metallic state. These strong correlations lead to a dramatic enhancement of the electron effective mass, often reaching values 100–1000 times that of the bare electron mass. Such systems, termed heavy-fermion materials, remain an active area of research in quantum materials. When these heavy-fermion materials undergo a superconducting transition, the conventional BCS electron-phonon coupling mechanism is unlikely to be responsible for the Cooper pair formation. Instead, magnetic interactions, stemming from strong Coulomb interactions between f-electrons, are hypothesized to provide the pairing mechanism.

Against this backdrop, Dr. Aoki's pioneering research on uranium-based systems led to several groundbreaking discoveries. Most notably, he discovered URhGe, the first material to exhibit microscopic coexistence of ferromagnetism and superconductivity at ambient pressure [1]. Prior to this discovery, UGe_2 had been identified as a material displaying coexistence of these phenomena. However, research progress was hindered by the requirement of high pressure to induce superconductivity and its low transition temperature. In contrast, URhGe exhibits its highest superconducting transition temperature when ferromagnetic fluctuations are enhanced under pressure [2]. Subsequent investigations revealed an extraordinary phenomenon known as re-entrant superconductivity: the superconducting state is initially suppressed by an applied magnetic field but remarkably re-emerges at higher field strengths. These experimental observations strongly suggest that the superconductivity in this system is mediated by ferromagnetic fluctuations, with Cooper pairs forming in the spin-triplet state with parallel spin alignment—a hallmark of ferromagnetic superconductivity. This discovery has fundamentally challenged our understanding of the interplay between magnetic order and superconductivity in strongly correlated electron systems.

In 2019, UTe_2 was identified as a spin-triplet superconductor in the USA. Subsequently, he made the remarkable discovery of multiple superconducting phases in this material under the combined conditions of high pressure and magnetic field [3,4]. These distinct phases are characterized by different superconducting symmetries, drawing parallels to the multiple phases observed in superfluid helium-3. UTe_2 has emerged as a focal point of international research in quantum materials and he keeps a leading position in its investigation.

Dr. Aoki's achievements stem from his expertise in two critical areas: the growth of high-quality single crystals of actinoid compounds and precise measurements of their physical properties at ultra-low temperatures. His work has been particularly acclaimed for revealing novel superconducting states that coexist with ferromagnetism, effectively exploiting the unique properties of 5f electrons in actinoid systems. This research has significantly advanced our understanding of strongly correlated electron systems and unconventional superconductivity.

References

[1] D. Aoki, A. Huxley, E. Ressouche, D. Braithwaite, J. Flouquet, J.-P. Brison, E. Lhotel, and C. Paulsen, "Coexistence of superconductivity and ferromagnetism in URhGe" Nature **413**, 613 (2001).

[2] D. Braithwaite, D. Aoki, J.-P. Brison, J. Flouquet, G. Knebel, Ai Nakamura, and A. Pourret, "Dimensionality driven enhancement of ferromagnetic superconductivity" Phys. Rev. Lett. **120,** 037001 (2018).

[3] D. Aoki, A. Nakamura, F. Honda, D. Li, Y. Homma, Y. Shimizu, Y. J. Sato, G. Knebel, J.-P. Brison, A. Pourret, D. Braithwaite, G. Lapertot, Q. Niu, M. Valiska, H. Harima, and J. Flouquet, "Unconventional superconductivity in heavy fermion UTe_2" J. Phys. Soc. Jpn. **88**, 043702 (2019).

[4] D. Aoki, F. Honda, G. Knebel, D. Braithwaite, A. Nakamura, D. Li, Y. Homma, Y. Shimizu, Y. J. Sato, J.-P. Brison, and J. Flouquet, "Multiple superconducting phases and unusual enhancement of the upper critical field in UTe_2" J. Phys. Soc. Jpn. **89**, 053705 (2020).

3) Dr. Shuichi Murakami

Professor, Department of Physics, Institute of Science Tokyo

“Theory of spin Hall effect and topological materials”

The spin Hall effect is a phenomenon in which a spin current is generated in a material in a direction perpendicular to both applied electric field and spin moment. In the conventional Hall effect, electrons are subject to the Lorentz force in a magnetic field, creating a potential difference perpendicular to both electric current and magnetic field. In contrast, the spin Hall effect requires spin-orbit interaction instead of a magnetic field.

Electrons behave like waves in crystalline solids, and their energy spectra as functions of crystal momentum are called energy bands. In the momentum space, the Berry curvature, a geometric quantity calculated from the Bloch functions of electrons, plays a role of a “magnetic field.” Dr. Murakami and his coworkers showed that in semiconductors such as GaAs, where spin-orbit interaction is important, a crossing point of two energy bands can be regarded as a magnetic monopole, and the “Lorentz force” from the “magnetic field” of the monopole causes the spin Hall effect [1]. This versatile theory can be widely applied to non-magnetic materials, and the spin Hall effect has been actively studied both experimentally and theoretically for a variety of metals and semiconductors.

The theory of Murakami and his coworkers was followed in 2005 by a theoretical prediction of the quantum spin Hall effect by a group in the USA. In this effect, quantized spin currents are carried by spin-up and -down electrons moving in opposite directions along the edge of a two-dimensional insulator with strong spin-orbit interaction. Materials which exhibit this effect are also called two-dimensional topological insulators. In 2006, he proposed thin films of bismuth as a candidate material [2], which was experimentally verified in 2013. Since then, various atomic-layer materials consisting of Bi, Sb, Sn, etc. were identified as two-dimensional topological insulators. In 2006, HgTe/CdTe quantum wells were also predicted to be a two-dimensional topological insulator by a group in the USA. This was verified in experiments in

2007, earlier than Bi thin films.

In 2007, he studied the phase transition between ordinary insulators and topological insulators in three dimensions and showed that in non-centrosymmetric materials, a metallic state called the Weyl semimetal always appears as an intermediate phase between the two insulating phases [3]. Weyl semimetals have an even number of band-crossing points, called the Weyl points, in the momentum space. Near such Weyl points, the electronic states can be regarded as relativistic massless fermions described by the Weyl equation and the Berry curvature corresponds to either a monopole or an anti-monopole. Since then, many Weyl semimetals have been discovered, such as TaAs and Co_3SnS_2, and their unique properties, such as surface Fermi arcs, chiral anomalies, and magnetoresistance, have been actively studied both theoretically and experimentally.

His theoretical study has been extended to various new phenomena, associated with electronic states having nontrivial topology, including topological crystal insulators, semimetals, the thermal Hall effect in ferromagnets, and non-Hermitian systems. The theoretical achievements of Dr. Murakami have made important contributions to our understanding of the spin Hall effect and topological materials.

References

[1] S. Murakami, N. Nagaosa, and S.-C. Zhang, "Dissipationless quantum spin current at room temperature", Science **301**, 1348 (2003).
[2] S. Murakami, "Quantum Spin Hall Effect and Enhanced Magnetic Response by Spin-Orbit Coupling", Phys. Rev. Lett. **97**, 236805 (2006).
[3] S. Murakami, "Phase transition between the quantum spin Hall and insulator phases in 3D: emergence of a topological gapless phase", New J. Phys. **9**, 356 (2007); (Corrigendum) New J. Phys. **10**, 029802 (2008).