2021 Nishina Memorial Prize

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“Discovery and Exploration of Spin-Induced Multiferroics”

Magnetism and dielectricity are among the most fundamental properties of materials. Application of magnetic fields induces magnetization in many materials as a result of uneven electronic spin distribution. Application of electric fields, on the other hand, produces a flow of electrons (electric current) in metals and, in insulators, asymmetric distribution of electronic and ionic charge, resulting in electric polarizations. The electromagnetic effect, where application of magnetic fields (electric field) induces electric polarization (magnetization), has been known in certain materials since 1960s. However, this effect was very weak and had never grown into a major research field.

This situation has changed significantly in this century. Dr. Takahisa Arima and Dr. Tsuyoshi Kimura discovered in 2003 together with coworkers that a change of magnetic structure induces a ferroelectric state in the magnetic insulator $TbMnO_3$ [1]. This material had been known to show an incommensurate magnetic order of Mn^{3+} spins below the Neel temperature T_N=41 K. The ferroelectric order with a spontaneous polarization along *c*-axis of the crystal was observed at zero magnetic field below T_C=27 K, at which a change of the magnetic structure had been suggested. Furthermore, this polarization along c-axis was suppressed by magnetic fields along *b*-axis, which in turn induced a polarization along *a*-axis. “Ferroics” is the term to collectively describe the states, in which microscopic magnetic or electric moments of atoms and ions are ordered in a macroscopic scale, such as ferro- (antiferro-) magnetic and ferro- (antiferro-) electric states. This discovery indicated the presence of an unknown coupling between two different ferroics.

Because of the relativistic spin-orbit interaction, the shape of electronic orbital relevant to the superexchange interaction of Mn-O-Mn bonding in $TbMnO_3$ depends on the relative orientation of two Mn spins. For non-collinear spin arrangements, it was theoretically shown by Katsura, Nagaosa, and Balatsky that the distorted orbital shape should lead to the spontaneous electric polarization unless the vector connecting the two spins is orthogonal to the spin plane. Subsequently, Dr. Arima and coworkers investigated the spin structure of $TbMnO_3$ by neutron diffraction experiments and confirmed a collinear spin structure above T_C with a sinusoidal modulation in the amplitude of Mn moments and a non-collinear cycloidal spin structure below T_C, consistent with the theory [2].

Since non-collinear spin structures are rather ubiquitous for magnets with competing exchange interactions, coexistence of ferroelectricity and magnetic order has been confirmed in a large number of frustrated magnets after the discovery in $TbMnO_3$. Many of these materials enable us to control electric polarization by magnetic fields or magnetization by electric fields, which are also important for application. Thus multiferroics has rapidly grown into a major field of condensed matter physics.

Dr. Takahisa Arima has continued to contribute to the development of multiferroics through precise structural analysis by X-ray and neutron diffraction and through proposal of a new mechanism for the electric polarization in $CuFeO_2$, which has a proper screw spin structure [3, 4]. Dr. Tsuyoshi Kimura has succeeded in synthesizing many new multiferroic materials, including a hexaferrite system exhibiting magnetoelectric effects at room temperature and low magnetic fields, demonstrating universality of multiferroics and possibility for applications [5−7].

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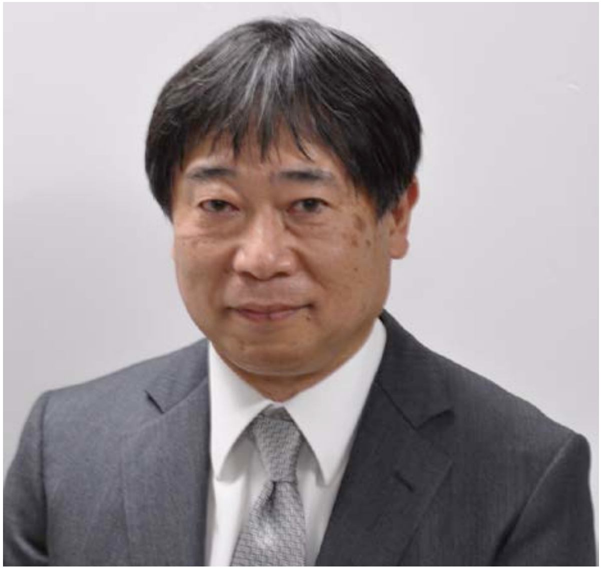

Dr. Masato Takita
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"Establishment of the sub-PeV gamma ray astronomy and elucidation of the origin of galactic cosmic rays"

Modifying an observational instrument for cosmic-ray induced air showers located at 4,300 m in Tibet, China and observing high-energy cosmic gamma rays, Dr. Masato Takita and his collaborators succeeded in detection of sub-PeV (10^{14} eV – 10^{15} eV = 100 TeV – 1 PeV) gamma rays for the first time in the world and elucidated that PeV cosmic rays originate in our Galaxy. These achievements have led to the establishment of the sub-PeV gamma-ray astronomy.

As cosmic rays have an electric charge and they are bent by the galactic magnetic field in our Galaxy, high-energy gamma rays from π^0 produced by accelerated cosmic rays colliding with the interstellar medium have been attracting attention as a means to elucidate their origin.

Dr. Takita proposed and applied a method to separate a cosmic-ray induced muon-rich air shower from a gamma-ray induced muon-poor air shower by installing a large (3,400 m^2 in area) water Cherenkov-type muon detector (large water tanks with 20-inch-in-diameter photomultiplier tubes), at 2.4 m underground of the Tibet ASγ air shower surface detector array (65,700 m^2 in area).

In 2019, the Tibet ASγ experiment succeeded in the first detection of gamma rays beyond 100 TeV from the Crab Nebula at a 5.6 σ significance (Ref. [1]). Following the first detection, the Tibet ASγ experiment observed gamma rays above 100 TeV not only from the two sources (TASG J2019 +368 and TASG J2032 +414) in the Cygnus constellation direction (Ref. [2]), but also from a supernova remnant G106.3+2.7 for the first time (Ref. [3]). Especially, the gamma rays from G106.3+2.7 are identified as those of the π^0 origin produced by cosmic-ray, based on discussions on their origin (not from the pulsar, but from the overlapping molecular clouds), other-wavelength observations, and the energy budget. Thus, the observation demonstrates for the first time that G106.3+2.7 is a potential candidate object that accelerates cosmic rays up to PeV energies.

Furthermore, in 2021, the Tibet ASγ experiment discovered many diffuse gamma rays with energies between 400 TeV and 1 PeV, coming ubiquitously along the Galactic disk at a 5.9 σ significance, and what is more surprising, their directions turned out to be away from the known TeV gamma-ray sources in our Galaxy (Ref. [4]). The detected gamma rays are concluded to be produced by collisions of PeV cosmic rays emitted from cosmic-ray sources in our Galaxy with interstellar medium in the Galactic disk and their features are consistent with theoretical predictions. This is the first experimental evidence for the belief since 1958 that PeV cosmic rays originate in our Galaxy.

Although these research achievements belong to a Japan-China international joint research group, the Tibet ASγ collaboration, Dr. Takita, who directs the collaboration, played an essential role in these discoveries, and his contribution is judged to be sufficiently significant.

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Dr. Satoshi Miyazaki
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"Observational cosmology through the development of wide field cameras for Subaru Telescope"

Dark matter and dark energy are major mysteries confronting physics and cosmology in the 21st century. Investigating their distribution and temporal changes in the universe by analyzing the distribution of galaxies over the cosmological scale could be a clue for understanding their nature.

In the 1990s, Dr. Satoshi Miyazaki began developing large format CCD devices in collaboration with the members of the Lincoln Laboratory of Massachusetts Institute of Technology. For observations of galaxies in distant universe, the high sensitivity in the near infrared is an important advantage due to cosmological redshift. He succeeded in developing a large, back-illuminated CCD device with four times the sensitivity of conventional CCDs at 950 nm together with his collaborators. The CCD device has a rectangular form and keeps high sensitivity up to the edge in three directions. Ten such devices are arranged in a mosaic configuration such that wide field imaging is possible with almost no gaps. His group completed this unique camera, Suprime-Cam, in 2000 in time for the first light of the Subaru Telescope. This camera has become an unrivaled instrument in the world [1] and has made significant achievements in the studies of galaxies in the early universe and the identification of the cosmic reionization epoch.

Based on this successful operation, he proposed developing an ambitious Hyper Suprime-Cam (HSC) with a field of view seven times larger than that of Suprime-Cam. The successful fabrication of the HSC in 2013 [2] was led by incorporating, (1) the development of a CCD that doubles the sensitivity at a wavelength of 1 micron by dramatically increasing the thickness of the depletion layer, (2) the development of a corrective lens system and atmospheric dispersion correction mechanism to achieve high resolution images over a wide field of view, and (3) the development of a lightweight ceramic housing tube of the camera that enables mounting on the Subaru Telescope.

The cosmic background radiation observation satellite WMAP, launched in 2001, has verified the overall validity of the standard cosmic evolution model called the ΛCDM model. However, the number of galaxy clusters predicted by this model is known to be much larger than the numbers identified by X-rays. He proposed a project to search for faint clusters of galaxies by measuring systematically the "weak gravitational lensing effect" caused by the gravitational field of dark matter in the clusters. His group succeeded to identify the distribution of dark matter using high quality images from Suprime-Cam [3]. In the latest study using the HSC, 95% of the detected dark matter halos are confirmed to have corresponding faint clusters of galaxies. However, the number count of galaxy clusters is still lower than the theoretical prediction, which might indicate the need to revise the standard cosmic evolution model.

In 2014, he proposed a strategic plan to survey distant universe using the HSC over a total of 330 nights, as a representative of an international joint observation project involving the National Astronomical Observatory of Japan, the Kavli Institute for the Physics and Mathematics of the Universe, and Princeton University to study dark matter and dark energy. The survey group has already published 40 papers from the first 90 nights of data in a special issue of the Publications of the Astronomical Society of Japan, in January 2018.

In addition to the aforementioned study on the identification of dark matter haloes using weak gravitational lensing, his group revealed a larger-scale three-dimensional spatial distribution of dark matter haloes from a study of weak gravitational lensing at different times over billions of years. As a result, they revealed how dark matter haloes coalesced into clusters over the billion years of cosmic time [4].

His group also succeeded for the first time in determining the parameters of the cosmic evolution model from the analysis of the power spectrum of the weak gravitational lensing effect seen in the HSC data at redshifts up to about 1. The results suggest that there may be a deviation from the parameters of the standard cosmological model obtained from the analysis of the cosmic background radiation at redshift 1000 [5].

Although most of these studies are the results of collaborative research, they were not possible without the contribution of Dr. Satoshi Miyazaki, who made a large amount of data with the world's highest image quality and maximum sensitivity available to the science community with his meticulous efforts to minimize systematic errors in HSC images. He not only led the production of the mosaic CCD camera, but also performed various data calibration analyses and released high-quality image data to provide astronomers around the world with opportunities to use the Subaru Telescope for science. He has led a strategic observation program to elucidate dark matter and dark energy and thereby has made a significant contribution to the advancements of astrophysics and astronomy.

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