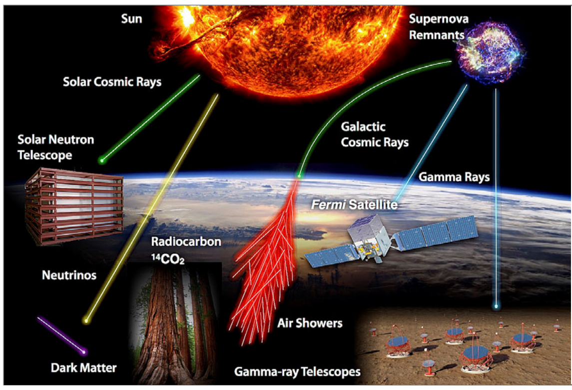
Division for Cosmic-Ray Research



- Acceleration and propagation of cosmic rays
  – Cosmic gamma-ray observations
  – Solar neutron observations
- Cosmic-ray interactions with the Earth's atmosphere
  – Hadron interactions of very-high-energy cosmic rays
  – Past solar activities probed by cosmogenic nuclides
- Particle astrophysics and non-accelerator physics
  – Dark matter and neutrino physics
- Wide-field transient survey by an optical telescope

Cosmic rays (CRs), which are mostly protons with small amounts of charged particles, such as electrons or nuclei, and neutral particles, such as gamma rays or neutrinos, are produced in space and propagate through interstellar and interplanetary magnetic fields before reaching the Earth. The Division for Cosmic-Ray Research performs cosmic gamma-ray observations using the Fermi Gamma-ray Space Telescope (Fermi satellite) and the Cherenkov Telescope Array (CTA), as well as high-altitude solar neutron observations, to reveal the CR acceleration mechanisms as common space plasma phenomena.

CRs also provide hints for ultra-high energy phenomena and unknown particles that cannot be explored in a laboratory. We conducted the Large Hadron Collider forward (LHCf) and the Relativistic Heavy Ion Collider forward (RHICf) experiments to study the hadronic interactions of ultra-high energy CRs using accelerators such as LHC or RHIC. This division also conducts neutrino physics research with the Super-Kamiokande experiment and promotes the Hyper-Kamiokande project as a future prospect. The group intensively works for direct dark matter searches in the XMASS liquid xenon experiment at the Kamioka Observatory and has recently started a new commitment to the XENONnT experiment in LNGS in Italy.

CRs deeply penetrate the atmosphere, producing ionization and cosmogenic nuclides. Our division studies past solar activities and sudden changes in CR flux that are recorded in the carbon-14 (^{14}C) fractions of ancient tree rings and other cosmogenic nuclides from Antarctic ice cores.

In addition, this division conducts the MOA experiment with a dedicated 1.8-m wide-field optical telescope at Mt. John University Observatory in Tekapo, New Zealand. It conducts surveys of gravitational microlensing due to massive astrophysical compact halo objects (MACHOs) or exoplanets and optical follow-up observations of gamma-ray bursts, super-nova neutrino detections, and gravitational wave events.

Main Activities in FY2019

Search for dark matter and research on the origin of cosmic rays using gamma-ray observations

Cosmic gamma rays are expected to be produced through the interactions of dark matter, CRs, and the interstellar medium. This makes gamma rays a useful probe to search for dark matter and investigate the properties and distribution of CRs and the interstellar medium.

We are developing the next-generation gamma-ray observatory, the CTA, to observe cosmic gamma rays in an energy range from well below 100 GeV to above 100 TeV. We are in charge of the development of silicon photomultipliers (SiPMs) for the Gamma-ray Cherenkov Telescope (GCT), which is one of three telescope designs for small-sized telescopes (SSTs) in the CTA. The GCT camera was selected as the final SST camera and we are in charge of the SiPM procurement and calibration. Meanwhile, we studied the properties of the origin of SiPM optical crosstalk in detail, where it produces additional signals to the incident photon signal. We found a relatively high rate of delayed crosstalk, which requires further careful study of its effects.

We also studied the feasibility of replacing the photomultipliers (PMTs) with SiPMs for the medium-sized telescopes (MSTs) of the CTA. Originally, PMTs were selected as they were less expensive for covering the area required for the MST camera. However, as SiPM costs became comparable to PMT costs, SiPMs became an attractive alternative because they can operate under moonlight, which can double the observation time of the MST. Simulation studies, combined with experimental verification at several wavelengths, found that an SiPM can collect 62% more signal photons and 6.53 times more background photons than a PMT. Since the signal tends to be blue while the background tends to be red, the simulation found that the signal and background photons for the SiPM are similar to those of the PMT with proper color filtering. These results confirm that we can use SiPMs for the MST.

Acceleration mechanism of solar energetic particles

We observe solar neutrons produced by the interaction of accelerated ions with the solar atmosphere to study the acceleration mechanism of solar energetic particles. It is expected that understanding the acceleration mechanism of solar energetic particles could help to elucidate the acceleration mechanism of cosmic rays in space. Since neutrons are not deflected by interplanetary magnetic fields, they keep the information on the time when charged particles are accelerated at the solar surface. It is essential to measure the energy of neutrons because they have mass, and the period of flight of a neutron from the Sun to the Earth differs depending on its energy. ISEE has developed a worldwide network of solar neutron telescopes to detect solar neutrons (>100 MeV) over an entire day..

We obtained the energy spectra of neutrons from more than 10 events, if we assume neutrons are produced at the same time as electromagnetic waves on the solar surface. The energy spectra obtained indicate that very efficient acceleration, such as shock acceleration, does not work in the case of neutron-producing solar flares. To derive a conclusive understanding of the acceleration mechanism, we need to observe a solar neutron event in which the energy spectrum of the neutrons can be determined without assuming the production time of the neutrons. For this purpose, we need a solar neutron telescope with better sensitivity to neutrons and a higher energy resolution than the one which ISEE developed.

A new solar neutron telescope was installed at the Mt. Sierra Negra volcano (4,580 m above sea level) in Mexico. The new detector is called the SciBar Cosmic Ray Telescope (SciCRT). SciBar was used in accelerator experiments, and this installation was realized with support from Kyoto University, the High Energy Accelerator Research Organization (KEK), the National Autonomous University of Mexico, and the National Institute for Astrophysics, Optics and Electronics in Mexico. SciCRT uses 15,000 scintillator bars to measure particle tracks, providing much better sensitivity to neutrons, and better energy resolution and particle discrimination. The performance of SciCRT was investigated using Monte Carlo simulation, and we can discriminate the production time of neutrons, whether it is instantaneous or continues for more than 5 minutes, while discriminating between shock acceleration and stochastic acceleration. As for the worldwide network of solar neutron telescopes, the operation at Gornergrat in Switzerland ceased in the fiscal year (FY) 2017. The operation at Mauna Kea in Hawaii also ceased in FY 2018.

The activity of solar cycle 24 reached a maximum in February 2014 and has since decreased. At the end of FY 2019, it is just between the end of solar cycle 24 and the beginning of solar cycle 25. No solar neutron events were detected in FY2019. Since the installation of SciCRT, no large solar flares with which solar neutrons are expected have yet occurred. The procedure to search for solar neutrons is under developing in association with solar flares, which are not strong enough for neutrons to be produced in usual.

This study was performed in collaboration with Chubu University, Shinshu University, the National Astronomical

Observatory of Japan, RIKEN, the Institute for Cosmic Ray Research (ICRR) of the University of Tokyo, the Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency (ISAS/JAXA), the Japan Atomic Energy Agency (JAEA), the National Defense Academy, the Aichi Institute of Technology, and many other institutions around the world.

Cosmic-ray interaction-focused accelerator experiment

Where and how are cosmic-ray particles accelerated to high energies? To answer this question, many observations and studies of cosmic rays have been performed worldwide. In particular, ultra-high energy cosmic rays (UHECRs) with the energies above 10^{19} eV, whose sources are expected to be highly energetic objects in the universe such as active galactic nuclei, are actively studied. These cosmic rays are observed using the so-called air-shower technique; the observation of particle cascades caused by interactions between cosmic rays and atmospheric atomic nuclei, using particle detectors and/or fluorescence telescopes. A precise understanding of the hadronic interactions between cosmic-ray particles and the atmosphere is key to estimating primary cosmic-ray information from the observed air showers. Therefore, we studied high-energy interactions at the large particle colliders, LHC and RHIC, located at the European Organization for Nuclear Research and the Brookhaven National Laboratory (BNL).

This year, we continued our analyses of the data obtained from these operations at LHC and RHIC, and accelerated preparations for our future operations. Preliminary results for the production cross-section of very forward neutral pions at proton–proton collisions, with a center of mass energy of 13 TeV, were reported at the 36th International Cosmic Ray Conference (ICRC2019). A neutral pion produced at a collision decays immediately into a photon pair. Our calorimeter detector detects the photon pair simultaneously, and the kinematics of the pion can be reconstructed from the results. This measurement is very important for understanding air-shower development in the atmosphere because most of the particles in air showers originate from neutral pions produced during cosmic-ray interactions. We are now attempting to improve the analysis methods for better measurement precision. Additionally, we are planning new measurements at both LHC and RHIC for further understanding of these interactions. Our international collaboration for measurement at LHC, LHCf, submitted a "Technical Report," including our operation and detector upgrade plans, to the LHC committee in June, and the proposals for the new operations in 2021 and 2023 have been approved. We will accelerate preparations for these operations.

Cosmic neutrinos and dark matter

Super-Kamiokande (SK) is the 50-kton water Cherenkov detector housed underground at the Kamioka Observatory, Gifu, dedicated to the observation of neutrinos and possible proton decay. SK has been preparing for the observation of supernova relic neutrinos emitted by all the supernova explosions by adding gadolinium (Gd) to the pure water in the detector. In 2019, the preparation of the Gd-water system was completed and the detector is now ready for the Gd-loading operation, which has been suspended owing to the COVID-19 situation. The analysis of neutrino/anti-neutrino separation techniques using decay-electrons or tagged neutron information have been carried out. A new analysis on non-standard neutrino interactions through atmospheric neutrino oscillation is also underway. We have also started real-time analysis with gravitational wave alerts to search for possible coincidences of neutrino events in SK. In addition, we have initiated intensive efforts to develop a new atmospheric neutrino flux modeling code to refurbish the Honda -model to cope with the newest hadronic interaction models.

Hyper-Kamiokande (HK) is the next generation of large-scale 260-kt water Cherenkov detector, with a fiducial volume nearly eight times larger. We have been making continuous contributions to starting and promoting the project by delivering intensive seminars in overseas institutions (four Taiwanese institutions in April and four Australian institutions in May). Since the beginning of 2020, the project has been officially approved by the government, and has proceeded to the construction phase.

The XMASS experiment is a direct dark matter search using a single-phase liquid xenon detector. In February 2019, the experiment had completed the data collection phase. Analysis is ongoing to finalize these dark matter search results, using a few years of continuous operation data.

Historic cosmic-ray intensity variation with cosmogenic radioisotopes

Cosmic rays falling on the Earth interact with the atmosphere and produce various secondary particles. Among them, long-lived cosmogenic nuclides, such as ^{14}C and ^{10}Be, are used as excellent proxies for past cosmic-ray intensities. We measured ^{14}C concentrations in tree rings and ^{10}Be and ^{36}Cl concentrations in ice cores to investigate historic cosmic-ray variations. From such analyses of cosmogenic nuclides, we found cosmic-ray increase events in 774/775 CE and 993/994 CE. A possible cause of these cosmic-ray events is solar energetic particle (SEP) events, and the scale of these SEP events is estimated to be tens of times larger than the largest event on record. We aim to clarify the frequency of such extreme SEP events by searching for other cosmic-ray events.

This year, we revealed the detailed ^{14}C variations of a cosmic-ray event in ~660 BCE using earlywood-latewood separated ^{14}C analyses of a Choukai-cedar tree sample. We showed that the duration of this event was longer than the two cosmic-ray events mentioned above, 41 months at the longest (Sakurai et al., 2020). We also measured ^{10}Be and ^{36}Cl concentrations in ice cores from the Antarctic Dome Fuji station to clarify the cause of a cosmic-ray event in ~5480 BCE. We presented the cosmogenic evidence of past extreme SEP events and the detailed ^{10}Be variations around 5480 BCE at the 36th International Cosmic- Ray Conference (ICRC2019) ICRC2019 and the 8th East Asia Accelerator Mass Spectrometry Symposium (EA-AMS 8), respectively.

We have been developing automated graphitization equipment for ^{14}C analyses with the ISEE Technical Support Division. This year, we confirmed its operation and evaluated its performance. The developed graphitization equipment is capable of fully automatic graphite sample preparation and samples can be processed in a lower background environment than the existing manual equipment allows. In addition, we tested methods of separating tree rings (microtome method and plate-state cellulose extract method) for ^{14}C analysis with high temporal resolution of less than one year. We also introduced pretreatment equipment for ice-core ^{10}Be analysis and evaluated its performance. It was confirmed that the ^{10}Be treatment can be performed with a sufficiently low background level.

Wide-field optical surveys for gravitational microlensing and gravitational sources

In 2018, we detected 448 microlensing events and issued real-time alerts to follow-up groups. Several extrasolar planet candidates have been found, and their analyses are in progress. Follow-up observations of gravitational waves in the O3 observation period are in progress.