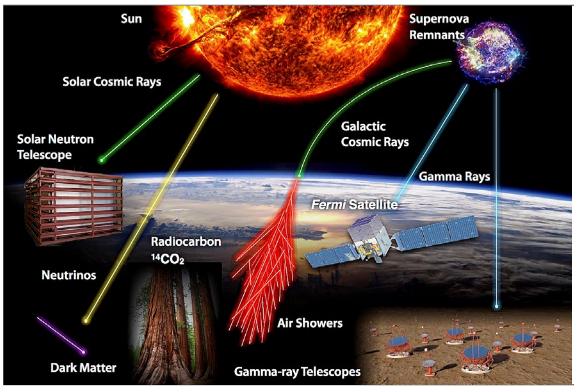
Division for Cosmic-Ray Research



- Acceleration and propagation of CRs
  – Cosmic gamma-ray observations
  – Solar neutron observations
- CR interactions with the Earth's atmosphere
  – Hadron interactions of very-high-energy CRs
  – Past solar activities probed by cosmogenic nuclides
- Particle astrophysics and non-accelerator physics
  – Dark matter and neutrino physics
- Widefield transient survey using 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 IMFs 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), and 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 large hadron collider forward (LHCf) and relativistic heavy ion collider forward (RHICf) experiments to study the hadronic interactions of ultra-high-energy CRs using accelerators such as the LHC or RHIC. This division also conducted neutrino physics research with the Super-Kamiokande experiment and promoted the Hyper-Kamiokande project as a future prospect. The group intensively worked on 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 Gran Sasso National Laboratory (LNGS) in Italy.

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

Main Activities in FY2020

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

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

We are developing a 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 oversee the development, procurement, and calibration of silicon photomultipliers (SiPMs) for the small-sized telescope in the CTA. One of the problems with the operation of the SiPM is optical crosstalk, which produces additional signals to the incident photon signal. In the past, we successfully reduced the optical crosstalk by more than an order of magnitude. To understand the origin of the remaining optical crosstalk, we studied delayed crosstalk, which is produced by a different mechanism from normal optical crosstalk. (Normal optical crosstalk coincides with the original signal, whereas the delayed crosstalk occurs approximately 10 ns later.) Precise measurements of the delay time distribution of the delayed crosstalk revealed that early delayed crosstalk was misidentified as normal crosstalk because the delay was too short to resolve the delayed signal from the original signal. We found that the misidentified delayed crosstalk rate accounted for almost all the remaining crosstalk. We are now discussing measures to reduce the delayed crosstalk with a manufacturer. We also studied the increase in the optical crosstalk in neighboring SiPM sensors due to reflection by the protection glass window of the camera. We found that the optical crosstalk increased by a factor of four or more owing to the presence of the protection window. We are currently investigating the effects of this crosstalk.

Acceleration mechanism of solar energetic particles

We studied the acceleration mechanism of solar energetic particles by observing solar neutrons with energies greater than 100 MeV on the ground. Solar energetic particles are accelerated in association with energetic solar flares. These accelerated ions produce neutrons through interactions with the solar atmosphere. It is expected that observing neutrons is better for understanding the acceleration mechanism of solar energetic particles than observing accelerated ions directly because neutrons are not reflected by the interplanetary magnetic field. Neutrons are attenuated in Earth's atmosphere. Therefore, the ISEE has developed a worldwide network of solar neutron detectors at high mountains in different longitudes.

Thus far, more than 10 solar neutron events have been obtained. The energy spectra of neutrons at the solar surface are obtained if we assume that neutrons are produced at the same time as electromagnetic waves produced in association with the same solar flares. The obtained spectra indicate that stochastic acceleration occurs when energetic neutrons are produced on the Sun. 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. The sensitivity to neutrons and energy resolution of the solar neutron detectors used in the worldwide network is not sufficient to conclude the acceleration mechanism of solar energetic particles.

A new solar neutron telescope was installed at the top of Sierra Negra (4580 m above sea level) in Mexico. The new detector is called the SciBar Cosmic Ray Telescope (SciCRT). SciBar was used in the accelerator experiments, and this installation was realized with support from Kyoto University, the High Energy Accelerator Research Organization, the National Autonomous University of Mexico, and the National Institute for Astrophysics, Optics and Electronics in Mexico. SciCRT uses 15000 scintillator bars to measure particle tracks, providing much better sensitivity to neutrons, 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 min, while discriminating between shock and stochastic acceleration.

The activity of the solar cycle shifted from cycle 24 to cycle 25 in 2020. The data obtained by SciCRT amounted to approximately 1 Terra Byte per month. Researchers in Mexico City pick up data at Sierra Negra and carry the data to Mexico City every two to three months. In the fiscal year 2020, the COVID-19 pandemic occurred worldwide. People in Mexico City could not visit Sierra Negra for a long time, and the operation of SciCRT had to stop for approximately six months because the hard disk at the mountain was full. Finally, it became possible to visit Sierra Negra in February 2021. SciCRT has been continuously operated since then. Fortunately, the Sun was inactive during the fiscal year 2020, and no energetic solar flare occurred.

This study was performed in collaboration with Chubu University, Shinshu University, the Institute for Cosmic Ray Research of the University of Tokyo, ISAS/JAXA, the Japan Atomic Energy Agency, the National Defense Academy, the Aichi Institute of Technology, and many other institutions worldwide.

Study of neutrinos and dark matter in underground experiments

Neutrinos are neutral elementary particles that interact with matter only through weak interactions. The neutrino oscillations caused by the mixing of the three flavor states of neutrino can be useful tools to investigate their properties, such as their masses. The Cosmic Ray Research Division conducts neutrino research in Super-Kamiokande at the Kamioka Underground Observatory, and is also promoting the future Hyper-Kamiokande experiment, which has an eight times larger effective mass.

This year, the results of the search for neutrino-nonstandard interactions using atmospheric neutrino oscillations have finally been produced as a Ph.D. thesis for the joint degree program at the University of Edinburgh. We have also made efforts to upgrade the existing Honda flux, the atmospheric neutrino production model, using hadronic interaction data obtained from various accelerator-based experiments, and comparing their central values and systematic uncertainties.

Dark matter in the universe is considered as yet-undiscovered particles, which are heavy neutral particles that are difficult to observe owing to their weak interactions. Many experiments are underway globally to detect these particles. We directly searched for dark matter in the XENONnT experiment using a double-phase xenon time projection chamber (TPC) at the Gran Sasso underground laboratory in Italy. This year, the construction of the detector at the site was completed, and commissioning was successfully undertaken despite the COVID-19 pandemic. Although trips to the site were inhibited, we engaged in remote monitoring shifts of liquid xenon introduction and analysis of the commissioning data of the TPC and neutron veto detectors. We are also conducting various research and development studies for the future DARWIN project, which is planned to build a 40-ton double-phase xenon TPC. We have developed an electrode made of a quartz plate coated with a thin layer of high-resistivity transparent material. We successfully demonstrated electron drift using a small drift tube as a drift electrode. We also evaluated the performance of the SiPM photodetector at the liquid xenon temperature and developed a new hybrid photomultiplier tube using SiPM for photoelectron amplification.

Developing an electrode with a quartz plate using a thin layer of high-resistivity transparent material.

CR interaction-focused accelerator experiments

Where and how are CR particles accelerated to high energies? To answer this question, many observations and studies of CRs have been performed worldwide. CRs are observed using the air-shower technique, which involves observing particle cascades caused by interactions between CRs and atmospheric atomic nuclei using particle detectors or fluorescence telescopes. A precise understanding of the hadronic interactions between CR particles and the atmosphere is key to estimating the primary CR information from the observed air showers. The interpretation of chemical composition observables is strongly dependent on the hadronic interaction model used in the air-shower simulation. Therefore, we studied high-energy interactions of large particle colliders, LHC and RHIC, located at the European Organization for Nuclear Research and the Brookhaven National Laboratory.

We performed LHCf and RHICf experiments to observe energetic photons and neutrons produced in the very forward region of proton-proton collisions in the LHC and RHIC. Both experiments have been undertaken internationally. This year, we continued our analyses of the data obtained from these LHC and RHIC operations and accelerated preparation for our future operations. One of the data analyses, a combined analysis of LHCf with ATLAS, progressed well this year. The contribution of forward photon production to diffractive collisions was measured by selecting forward photon events without particle production in the central region. The result was largely inconsistent with some of the model predictions, and model improvement by fine-tuning it with our results is expected in the future.

For future operations, we are upgrading a new readout system with the Italian group in LHCf, and we started the design of a new detector using silicon pixels and pads for the next RHICf operation. COVID-19 has had an unavoidable impact on the schedules; however, we are trying to minimize this and accelerate the preparation of future research.

Historic CR intensity variation with cosmogenic radioisotopes

CRs falling on Earth interact with the atmosphere and produce various secondary particles. Among them, long-lived cosmogenic nuclides, such as ^{14}C and ^{10}Be, have been used as excellent proxies for CR intensities in the past. We measured ^{14}C concentrations in tree rings and ^{10}Be and ^{36}Cl concentrations in ice cores to investigate past CR variations. From such analyses of cosmogenic nuclides, we found increased CR events in 774/775 CE, 993/994 CE, and ~660 BCE. Possible causes of these CR events include 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. However, intermediate-scale SEP events, which occur between extreme events found in cosmogenic nuclides and the largest events on record, have not yet been detected. To detect such an intermediate-scale SEP event using cosmogenic nuclides, improving the measurement uncertainty and isolating the nuclide variation due to other factors is essential. We aim to clarify the frequency of extreme SEP events by searching for other CR events and detecting such intermediate-scale SEP events.

This year, to detect such intermediate-scale SEP events, we succeeded in measuring ^{14}C concentrations in tree rings with 1/3-year resolution by adopting intra-annual separating methods for tree rings (microtome and plate-state cellulose extract methods). In addition, we performed a high-precision ^{14}C measurement around the Carrington event (1859) as a candidate for an intermediate-scale SEP event.

We also performed quasi-annual analyses of ^{10}Be and ^{36}Cl concentrations using the Antarctic Dome Fuji ice core for ~100 years at approximately 5480 BCE. We discussed the causes of the CR increase event reported around 5480 BCE by comparing the results with the ^{10}Be and ^{36}Cl variations around the 775 CE event.

We provided some of the annual ^{14}C data previously obtained by our research group on the age calibration curve IntCal20, which is used as the world standard value for ^{14}C (Reimer et al. 2020). The annual increase in ^{14}C, such as the 775 CE event, can be applied to ultra-high-precision dating as a time marker. IntCal20 focuses on ^{14}C events and annual resolution ^{14}C data. Our annual ^{14}C data for the SEP event search contributed significantly to the fields of dating and stratigraphy.