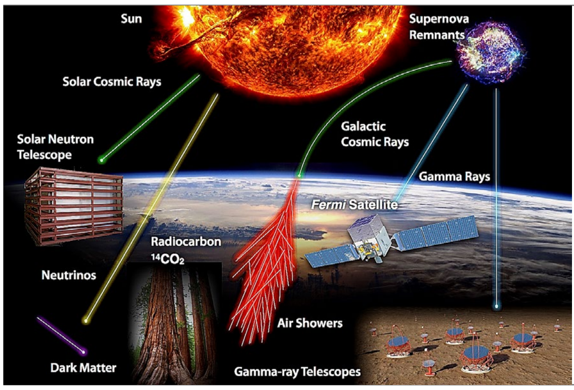
Division for Cosmic-Ray Research



- 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 FY2021

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

Cosmic gamma rays are produced through interactions of dark matter, CRs, and the interstellar medium. Therefore, gamma rays are useful probes 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, 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 small-sized telescopes in CTA. One advantage of the SiPM is its ability to operate under moonlight, which can increase the observation time by a factor of two. We studied the behavior of the SiPM under intense background light. Under intense background light, the SiPM current increases, the voltage drops across the series resistor of the bias circuit, and the drift of the breakdown voltage due to the temperature rise are expected to reduce the pulse amplitude. In addition, the pulse amplitude of the SiPM output signal can be reduced if the SiPM detects photons while recovering from detecting previous photons owing to the background light. When the series resistor is at a minimum, the pulse amplitude drop is measured to be approximately 7%, with a background light intensity equivalent to that of the full moon. We found that the temperature increase had the largest effect on the pulse amplitude at 4%, whereas the effect of the voltage drop across the series resistor was 1.5%. These two effects accounted for 5.5% and 7% of the measured amplitude reduction, respectively. The simulation of pulse overlap during the recovery time indicates that this effect can fully explain the remaining 1.5%.

The CTA is now considering employing the SiPM for the large-sized telescope to take advantage of the higher photon detection efficiency, smaller pixel size, and ability to operate under moonlight. However, the SiPM suffers from higher background light owing to better photon detection efficiencies in the red region, where the background light is bright. We proposed the application of a red filter on the surface of a light concentrator to reduce background light. We developed a prototype light concentrator and verified its characteristics. We also performed simulation studies on the gamma-ray detection efficiencies and found that the red filter improved the efficiency by more than 20% at a gamma-ray energy of 20 GeV. By reducing the pixel size by half, the improvement can be as much as 30%.

Acceleration mechanism of solar energetic particles

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

Thus far, more than 10 solar neutron events have been reported. The energy spectra of neutrons at the solar surface can be obtained if we assume that neutrons are produced simultaneously with electromagnetic waves produced in association with the same solar flares. The obtained spectra indicate that stochastic acceleration occurs when energetic neutrons are produced at the Sun. To derive a conclusive understanding of the acceleration mechanism, we must 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 the energy resolution of the solar neutron detectors used in the worldwide network are not sufficient to determine the acceleration mechanism of solar energetic particles.

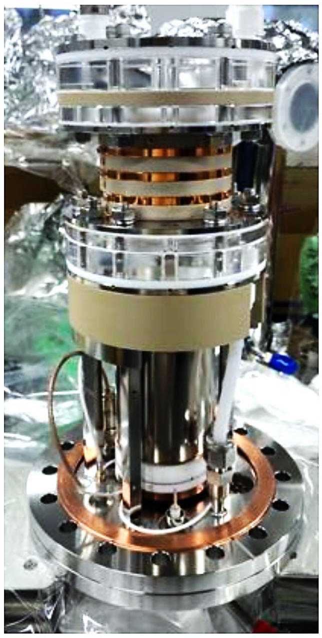
A new solar neutron telescope was installed at the top of Sierra Negra (4,580 m above sea level) in Mexico. The new detector is called the SciBar Cosmic Ray Telescope (SciCRT). SciBar was used in the accelerator experiments and this installation was realized with support from Kyoto University, the High Energy Accelerator Research Organization (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, 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 instantaneous or continuous for more than 5 min, while discriminating between shock acceleration and stochastic acceleration. At the same time as the observation of solar neutrons, the variation in the intensity of cosmic rays from various directions was monitored using SciCRT.

SciCRT has been maintained by scientists in Mexico City. Unfortunately, starting in the fiscal year 2020, people in Mexico City could not visit Sierra Negra due to the COVID-19 pandemic and the stable operation of SciCRT was not possible. In February 2022, scientists in Mexico City could once again reach Sierra Negra and cosmic ray intensities were monitored from February 2022. It was not possible to start the observation of solar neutrons in the fiscal year 2021 owing to some minor technical problems. The operation of solar neutron observation is planned to start early in the fiscal year 2022.

This study was performed in collaboration with Chubu University, Shinshu University, 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 other institutions worldwide.

Study of neutrinos and dark matter in underground experiments

Neutrinos are elementary particles with almost no mass, are neutral, and interact only through weak interactions. Neutrino oscillations caused by the mixing of three flavors of neutrino allow us to probe neutrino properties, such as neutrino masses or the mixing matrix. The Cosmic Ray Research Division conducts neutrino research at the Super-Kamiokande experiment in the Kamioka underground observatory and promotes the Hyper-Kamiokande experiment, a future water Cherenkov detector with a fiducial volume eight times larger than that of the Super-Kamiokande. In 2022 , the performance of a new 50 cm photomultiplier tube with a box-and-line-type dynode was studied for the construction of the Hyper-Kamiokande. In addition to the signal test of the delivered PMT at the Kamioka site, a test bench was set up in the laboratory to evaluate the signal stability. We also developed a new atmospheric neutrino simulation based on the Honda code, utilizing existing hadron production data from accelerator experiments.



Developing a 0.1 L prototype liquid xenon chamber with a hermetic quartz vessel inside.

Dark matter is yet-undiscovered heavy neutral particles that are difficult to observe owing to their weak interactions. Many experiments are currently underway 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, we analyzed the data currently being acquired for the first time. We also measured the environmental tritium at the site, which may be a background source for the recently claimed excess of electron recoil events by XENON1T. In addition, for the future liquid xenon dark matter experiment DARWIN, we are developing a hermetic liquid xenon detector using a quartz chamber and built a 0.1 L prototype to verify its radon shielding capability. In addition, we measured the photoelectric efficiency of metal surfaces under ultraviolet light and developed a hybrid photomultiplier tube using SiPM for photoelectron amplification.

Historic CR intensity variation with cosmogenic radioisotopes

CRs that fall 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 at 774/775 CE, 993/994 CE, and ~660 BCE. Possible causes of these CR events are solar energetic particle (SEP) events and the scale of these SEP events is estimated to be tens of times larger than the largest event recorded. Such large-scale SEP events pose a major threat to the current space-exploration era. We aimed to search for other signatures of CR events and clarify the frequency of extreme SEP events by measuring ^{14}C concentrations in tree rings over the past 10,000 years.

This year, we reported a new CR event in 5410 BCE detected by ^{14}C analyses using tree samples from the U.S., Finland, and Switzerland (Miyake et al., 2021). The origin of the 5410 BCE event may be also an extreme SEP event because the ^{14}C variations are very similar between the 5410 BCE event and other reported SEP-driven events. We also confirmed a regional difference in ^{14}C data, that is, higher latitudes trees show higher ^{14}C concentrations, which has been reported in previous studies.

We performed quasi-annual analyses of ^{10}Be and ^{36}Cl concentrations using the Antarctic Dome Fuji ice core around 5480 BCE and investigated the causes of the CR increase event reported at approximately 5480 BCE by comparing the results with the ^{10}Be and ^{36}Cl variations around the 775 CE event. The results showed that the cosmogenic nuclide data around 5480 BCE can be explained by a variation in galactic CRs (Kanzawa et al., 2021). An extreme grand solar minimum can be considered as a possible cause. Further investigation using ^{10}Be and ^{36}Cl data from other ice cores is important.

CR interaction-focused accelerator experiments

To understand where and how CR particles accelerate to higher energies, many observations and studies on CRs have been conducted 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 observed air showers. The interpretation of the chemical composition observables is strongly dependent on the hadronic interaction model used in the air shower simulation. Therefore, we studied the high-energy interactions of large-particle colliders, LHC and RHIC, located at the European Organization for Nuclear Research and the Brookhaven National Laboratory.

Beam test of the LHCf detectors at CERN−SPS.

We performed LHCf and RHICf experiments to observe the energetic photons and neutrons produced in the very forward region of proton-proton collisions in LHC and RHIC. Both experiments were conducted internationally. This year, we analyzed the data obtained with proton-proton collisions at the center-of-mass energy of 510 GeV at RHIC in 2017 and published the results of production cross-section measurements for very forward photons. The spectra were compared with the results of the LHCf experiment at 7 and 13 TeV and we confirmed the collision-energy scaling law, the so-called Feynman scaling, within the experimental error.

Both the LHCf and RHICf plan their next operations in the coming years. The LHCf will have an operation in September 2022, and we are accelerating the preparation. One of the milestones is the beam test of the detectors at CERN-SPS to test the aging effect of the detectors, new read-out system, and performance of joint operation with the ATLAS-ZDC detector. The test was completed in September, although there were some difficulties due to COVID-19.