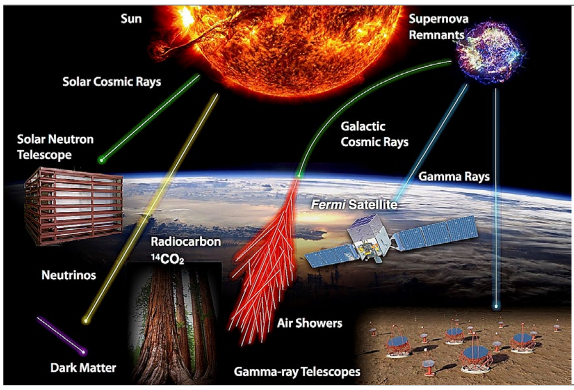
Division for Cosmic-Ray Research



- 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

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 core

Main Activities in FY2022

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

Cosmic gamma rays are produced through interactions between dark matter, CRs, and the interstellar medium. Therefore, they can serve as indicators to search for dark matter and investigate the properties and distribution of CRs and interstellar media.

We are currently developing a next-generation gamma-ray observatory, called the CTA, to observe cosmic gamma rays in the energy range from well below 100 GeV to above 100 TeV. This involves overseeing the development, procurement, and calibration of silicon photomultipliers (SiPMs) for small-sized telescopes (SSTs) installed in the CTA. In the design finalization stage of the SST camera, the avalanche cell size was one of the most important specification parameters for SiPMs because it affects the amplification gain, photon detection efficiency, optical crosstalk, and power consumption. We selected a cell size of 50 μm instead of 75 μm owing to its lower power consumption. Although a 75-μm cell offers 10% better photon detection efficiency, its gain is higher by a factor of two, resulting in higher current, power, and optical crosstalk. The heat produced in the SiPMs is conducted through a heat sink attached to the posterior of the SiPM module using a heat conductive adhesive. A heat conductive (~1 W/m/K) substrate was selected for the module loaded with SiPMs and their bias circuits. After finalizing the SST camera design, we initiated the procurement of components for the engineered camera, which is the first of the 42 cameras planned to be installed in the CTA; this camera will be assembled in 2023. The nominal lead time for SiPM module production was six to eight months. However, owing to the limited supply of heat conductive substrates for printed circuit boards, the lead time was extended to 15 months.

Meanwhile, we prepared a test to measure the infant mortality rate and lifespan of the SiPMs. The test included accelerated aging tests using a high current under high-temperature and high- humidity condition.

Acceleration mechanism of SEPs

The acceleration mechanism of SEPs, which are accelerated owing to energetic solar flares, was studied through ground observations of solar neutrons with energies greater than 100 MeV. These accelerated ions produce neutrons through interactions with the solar atmosphere. It is considered that neutron observations can provide a better understanding of the acceleration mechanism of SEPs than directly observing accelerated ions because neutrons are not reflected by the interplanetary magnetic field and are attenuated in the Earth’s atmosphere. Therefore, the ISEE program has developed a worldwide network of solar neutron detectors located on high mountains at different longitudes.

To date, more than 10 solar neutron events have been reported. The energy spectra of neutrons at the solar surface can be obtained based on the assumption that neutrons are produced simultaneously with the electromagnetic waves during solar flare events. The obtained spectra indicate that stochastic acceleration occurs when energetic neutrons are produced by the sun. To comprehensively understand the acceleration mechanism, we must observe a solar neutron event wherein the energy spectrum of neutrons can be determined without assuming their production time. However, the neutron sensitivities and energy resolutions of solar neutron detectors used worldwide are insufficient for determining the acceleration mechanism of SEPs.

A new solar neutron telescope, called the SciBar Cosmic Ray Telescope (SciCRT), has been installed at the top of Mt. Sierra Negra (4,580 m above sea level) in Mexico. The SciBar detector was used in the accelerator experiments. This installation was realized with the support of 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 employs 15,000 scintillator bars to measure particle tracks, providing significantly better sensitivity to neutrons, energy resolution, and particle discrimination. The performance of SciCRT was investigated using Monte Carlo simulations, which showed that it can identify the production time of neutrons, whether instantaneous or continuous, for more than 5 min, and also discriminate between shock and stochastic accelerations. In addition to solar neutron observations, CR intensity variations in different directions were simultaneously monitored using the SciCRT.

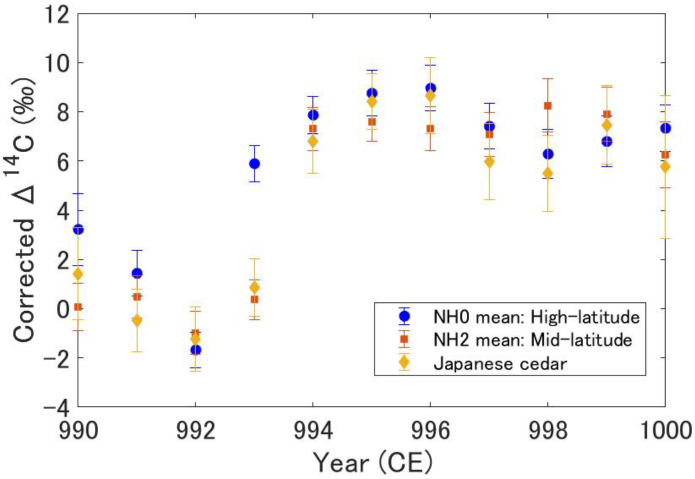
However, maintaining a worldwide network of solar neutron detectors is challenging. There were seven solar neutron detectors worldwide in 2003; however, this number has decreased recently, with two stations remaining in the fiscal year 2022: SciCRT in Mexico and Chacaltaya (5,250 m above sea level) in Bolivia. Both are maintained by the respective scientists in both countries and are expected to detect solar neutron events during the current solar cycle 25, which started in 2020.

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

Historic CR intensity variation measurements using cosmogenic radioisotopes

The CRs reaching the Earth interact with the atmosphere to produce secondary particles. Among them, long-lived cosmogenic nuclides, such as ^{14}C and ^{10}Be, have been conventionally used as excellent indicators for determining CR intensity. Therefore, we measured ^{14}C concentrations in tree rings and ^{10}Be concentrations in ice cores to investigate past CR variations. These analyses of the cosmogenic nuclides revealed that CR events increased during 774/775 CE, 993/994 CE, and ~660 BCE. The possible causes of these CR events are SEP events at scales estimated to be tens of times larger than the largest recorded event. Such large-scale SEP events pose a major threat in the current space exploration era. Therefore, we aimed to identify 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 investigated the period from 4000 to 3000 BCE and detected several event candidates (^{14}C increases).

We reported that there are clear regional differences in the timings of increases in ^{14}C concentrations during the 993 CE cosmic ray event based on the re-measurement results of Japanese cedar located on Yaku-island (Miyake et al., 2022, Fig. *). As shown in Fig.*, ^{14}C concentrations in mid-latitude trees, including the Japanese cedar, increased one year later than that in high-latitude trees. However, further research is required to determine whether these differences are because of atmospheric transport or variations in the timing of carbon fixation in trees.



Differences in ^{14}C variations for the 993 CE cosmic ray event (Miyake et al. 2022, High-latitude, mid-latitude, and Japanese cedar)

We also investigated the geographical distribution of ^{10}Be concentrations in Antarctica using snow samples to understand the background variation exhibited in ^{10}Be data from Antarctic ice core.

Study of neutrinos and dark matter through underground experiments

Super-Kamiokande (SK) is a 50-kton underground water Cherenkov detector located at the Kamioka Observatory dedicated to neutrino and possible proton decay observations. Gadolinium (Gd) was added to the pure water in the SK to prepare it for observing supernova relic neutrinos emitted by all supernova explosions. In the summer of 2022, an additional 0.02% of Gd was successfully introduced to increase the total to 0.03% without significantly impacting the detector performance. A new Honda neutrino flux model was developed by employing hadron production models tuned using existing accelerator data. The initial results were compared with those of the new Bartol neutrino flux model, which were discussed at a dedicated annual workshop on atmospheric neutrino production (WANP2023). Additionally, the construction of the Hyper-Kamiokande (HK) detector is ongoing. In 2022, the access tunnel to the main cavern was completed, and excavation of the main cavity is ongoing. The Nagoya Group has contributed intensively to study the performance of the new 136 20” B&L PMTs installed in the SK tank in 2018. This is the first extensive long-term test in the water. We confirmed that the new HK-PMTs worked as expected through a previous study conducted in air.

Dark matter constitutes undiscovered heavy neutral particles that are difficult to observe because of their weak interactions. We directly searched for dark matter during the XENONnT experiment using a double-phase xenon time-projection chamber (TPC) located at the Gran Sasso Underground Laboratory, Italy. After successful construction and commissioning of the detector from spring 2020 to spring 2021, the first set of scientific data “SR0” were obtained over 97.1 days, from July 6 to November 10, 2021. In this year, we analyzed this data and obtained more sensitive rejection of possible electron recoil excess previously reported in the preceding XENON1T experiment, with a background improvement by a factor of five. We also released the result of the first WIMP search from SR0, providing 2.58×10^{-47} cm^2 as the upper limit of the WIMP-nucleon cross section. We are also conducting various R&D studies on the DARWIN 50-ton liquid xenon TPC for future direct dark matter detections. We built a dedicated setup to measure the quantum efficiency (QE) of the electrode materials in liquid xenon using a dedicated VUV light system and found that by applying a thin layer, such as MgF2, helps reduce the QE of electrode materials by a factor of 10. We also developed a hermetic liquid-xenon TPC, wherein the inner volume of the TPC was enclosed by a quartz vessel, which prevented radon emanation from the detector material. We expect that this technology can play a key role in building a DARWIN-sized dark matter detector with radon background improved by one order of magnitude.

CR interaction-focused accelerator experiments

Many studies on CRs have been conducted worldwide to understand where and how CR particles accelerate to higher energies. CRs are observed using the air shower technique, which involves the observation of 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 essential for estimating primary CR information from observed air showers. The interpretation of the chemical composition is strongly dependent on the hadronic interaction model used in the air shower simulation. Therefore, we studied the high-energy interactions at large-particle colliders, LHC and RHIC, located at the European Organization for Nuclear Research and Brookhaven National Laboratory.

The LHCf experiment was conducted in September 2022, wherein proton beams were accelerated to 6.8 TeV and collided to produce photons and neutrons in the very forward region of the collisions, which were measured using LHCf calorimeter detectors. The center-of-mass collision energy was 13.6 TeV, which corresponded to CR interactions with an energy of 10^{17} eV. Owing to the high-energy collisions close to the ultra-high-energy cosmic ray energy of 10^{20} eV, the obtained data are crucial for studying CR interactions. The detectors were installed in the LHC tunnel in September, and the data were obtained during a successful 4-day operation, from 23– 27 September. We obtained statistics seven times larger than those of the previous operation conducted in 2015. These high-statistics data can be used to obtain a new measurement of the forward K0 meson that may help solve the muon puzzle, which is a critical problem in high-energy CR observations on the ground. Additionally, this operation included a joint operation with the ATLAS experiment.