【Grant-in-Aid for Transformative Research Areas（A）】

Investigation on the Origin and Evolution of Matter in the Universe by Extremely Rare Events: Frontier of Creating a New insight on the Matter in the Universe

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Purpose and Background of the Research

●Outline of the Research

The universe, originating as a high-temperature, high-density fireball, has evolved to its present state, leaving critical questions unresolved: "Why did only matter survive?", "What is dark matter, which outnumbers ordinary matter by five times?", and "How were heavy elements created and dispersed?" This research area seeks to address these enigmas by exploring extremely rare phenomena with the best sensitivity, including neutrinoless double beta decay, direct dark matter detection, and supernova neutrino observations. Our objectives are to reshape our understanding of 'matter'—a concept often overlooked—and to develop a new perspective on it.

●Backgrounds

The ultimate goals of particle and nuclear physics are the unification of forces and the elucidation of the origins of matter. These goals are pursued through three primary approaches: the high energy frontier, the high intensity frontier, and the cosmic frontier. The high energy and high intensity frontiers use accelerators to explore new phenomena and conduct precision measurements, respectively, while the cosmic frontier focuses on deriving particle properties through cosmic observations.

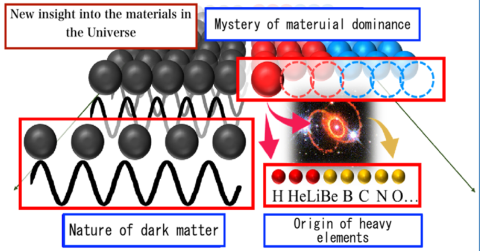

Figure 1. Conceptual image of the area

Recent developments have led to the emergence of new research areas, particularly underground particle physics, which utilizes low-radiation underground environments to study rare events that traditional approaches could not fully address. Beginning with the Kamiokande experiment, neutrino observations have expanded to include observations from various neutrino sources such as supernovae, the Sun, the atmosphere, accelerators, reactors, and the Earth. These observations have yielded significant achievements ranging from the discovery of neutrino oscillations to the precise measurement of neutrino oscillation parameters, and even measurements of the Earth's internal heat energy sources through Earth neutrino observations. Behind these accomplishments lies the development and refinement of "ultra-low-background techniques," which enable the detection of extremely rare signals with certainty. Currently, cutting-edge research on "the origins of matter" is conducted worldwide, based on these ultra-low-background techniques. What started as research originating in Japan has now grown into a field of global competition. We aim to further develop and expand this field as the "rare event frontier" of particle and nuclear physics.

●Goal

Previous research indicates that the universe's material evolved as follows: 1) At the universe's inception, only a small amount of matter survived from an equal amount of matter and antimatter; 2) this residual matter was just a quarter of the dark matter that formed galaxies; and 3) from initial elements like hydrogen, helium, and lithium, other elements were synthesized, constituting 20% of known matter today. Yet, mysteries persist regarding why only matter remained, the true nature of dark matter, and the synthesis and dispersal of elements. Our research focuses on unraveling these enigmas: the dominance of matter, the identity of dark matter, and the element synthesis in supernova explosions. By solving these, we aim to offer new insights into the material universe, potentially shifting the current paradigm of our material understanding.

Expected Research Achievements

●Baryon asymmetry

Understanding matter dominance may hinge on verifying neutrinos as Majorana particles, their own antiparticles. Neutrinoless double-beta decay ($0\nu\beta\beta$) is the sole practical test for this, potentially explaining neutrinos' tiny masses and their role in matter's dominance over antimatter. Such a discovery could propel our knowledge beyond the standard model, toward force unification. The KamLAND experiment (A01) seeks to detect $0\nu\beta\beta$ directly, while the CANDLES project (A02) advances future technologies like laser isotope enrichment and scintillation bolometer development. Even if $0\nu\beta\beta$ remains undetected, using highly sensitive equipment will still expand scientific boundaries by establishing new limits.

●Dark matter search

Dark matter, consisting of unknown elementary particles, may significantly enhance our understanding of particle physics if identified, potentially extending beyond the Standard Model (BSM). We are conducting direct experimental searches for dark matter candidates, particularly WIMPs and axions. The XENONnT project (B02) is focused on improving its detection capabilities to maintain global sensitivity leadership, while we (B02) also developing advanced detectors with directional sensitivity. Additionally, the new project B01 will utilize cryogenic and superconducting technologies to search for axions, aiming to comprehensively explore dark matter candidates.

●Supernova neutrinos

SK-Gd (C01) aims to achieve the world's first detection of cosmic background neutrinos from past supernovae. Additionally, SK-Gd collaborates with KamLAND to predict supernova explosions hours or days in advance. Should a supernova occur within the Milky Way, SK-Gd will rapidly notify global observatories of the neutrino origin, contributing to multi-messenger astronomy. Furthermore, in observing supernova neutrinos, a detailed analysis will be conducted using neutrino flavor data from various detectors (SK-Gd, KamLAND, XENONnT), and exploring reactions involving neutral currents like ^{16}O, advancing our understanding beyond insights from the SN1987A.

●New technology and theory

Each research project focuses on extremely rare events, supported by "rare event technologies" such as creating ultra-low radioactivity environments. We've developed a unique technological collaboration system that crosses research fields and experimental groups to enhance the use of these technologies, accelerating our research into the origins of matter. Additionally, we aim to unravel the three major mysteries of matter in the universe throughout cosmic history. By combining results from individual projects with theoretical studies, we seek to understand the history of cosmic matter and develop new insights into the nature of matter.

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