Gifu University
Japan Atomic Energy Agency (JAEA)
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The first determination of the Xi hypernuclear mass

New insights toward understanding of the origin of nuclei and structure of neutron stars

An international team of 97 researchers from 26 institutes of 6 countries, Japan, Korea, USA, China, Germany, and Myanmar led by Kazuma Nakazawa, a senior professor of Gifu University, observed the decay of a Xi hypernucleus in a nuclear-emulsion experiment carried out at J-PARC, Tokai, Japan.

In the observed event as shown in Fig. 1, which is named "IBUKI" after Ibuki Mountain in Gifu, a Xi-minus particle[1)], which contains two strange quarks, was bound to a Nitrogen-14 nucleus. By a detailed analysis of the decay products observed in the emulsion, the Xi hypernucleus mass could be precisely determined for the first time. The precise mass measurement of Xi hypernuclei gives information on "strong interaction[2)]" between a Xi-minus particle and a nucleus, and underlying interaction between a Xi particle and a proton/neutron. Since particles containing strange quark (hyperons[1)]), such as a Xi-minus particle, are predicted to appear in the core of neutron stars, which are the densest objects in the Universe, then the strength of the interaction leads to an understanding of which hyperons appear in which densities in neutron stars, and hence the structure like the radius and pressure inside. This result, therefore, is expected to contribute the understanding how the matter was formed from quarks, the elementary particles, and what is the structure of interior of neutron stars which are often described as giant nuclei. The result was published online in "Physical Review Letters (PRL)" on Friday 12 February, 2021 (Japan time). The paper was selected as an Editors' Suggestion and the commentary article was also published in Physics Synopsis (https://physics.aps.org/articles/v14/s15). Microscope image (Fig.1 left) was shown in the cover page of PRL Volume 126 Issue 6 issued on 12 February (USA time).

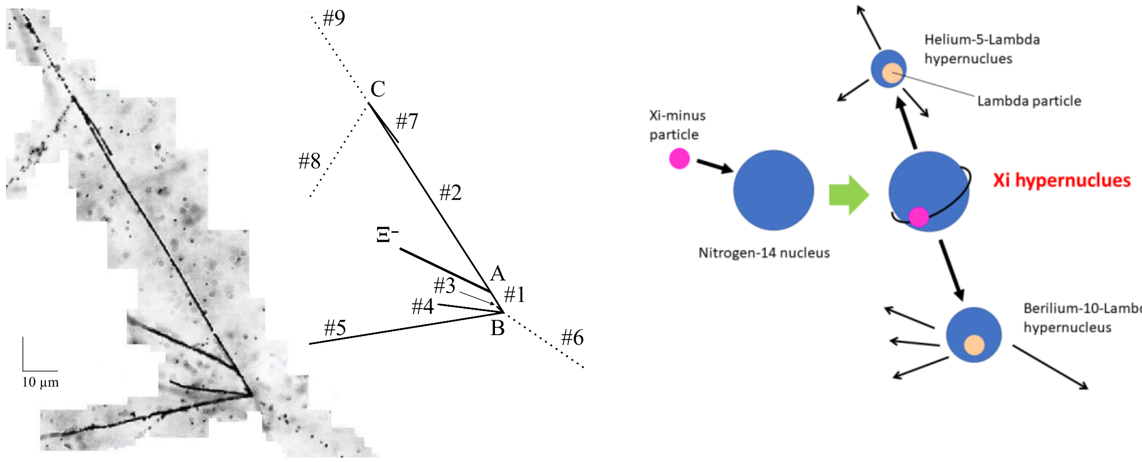

Fig. 1. Microscope image recorded in the emulsion and its schematic drawing of the IBUKI event.

A Xi-minus (Ξ^-) particle was absorbed by a Nitrogen-14 nucleus and formed a Xi hypernucleus at point A. It decayed into a Beryllium-10-Lambda hypernucleus (#1) and a Helium-5-Lambda hypernucleus

(#2). The Beryllium-10-Lambda hypernucleus decayed into several nuclei (#3-6) and several neutrons (no recorded tracks due to no charge) at point B. The Helium-5-Lambda hypernucleus decayed into a Helium-4 (#7) nucleus, a negative pion (#8), and a proton (#9) at point C.

[Points of Press Release]

- A Xi-hypernucleus was observed in the experiment at J-PARC.
- The existence of the Xi hypernucleus was first confirmed in our past experiment, but we were unable to determine its mass, uniquely. By the present observation, however, the mass of the Xi hypernucleus was precisely determined for the first time.
- Mass of the observed Xi hypernucleus gives information on strong interaction between a Xi-minus particle and a nucleus and the underlying interaction between a Xi particle and a proton (neutron). This is an important finding that will help us to understand how nuclei are formed from quarks, as well as the internal structure of the densest neutron stars in the Universe from a ground-based experiment.

[Text]

Highlights and Achievement

The research team was newly observed a Xi hypernucleus which contains a Xi-minus particle in the E07 experiment carried out at J-PARC, Tokai, Japan. In the detailed analysis of the emulsion sheets irradiated by Xi-minus particles produced by the accelerator beam, the Xi hypernucleus was identified as a bound state of Xi-minus particle and a Nitrogen-14 nucleus, and its mass was uniquely and precisely determined. The Xi-minus particle, which contains two strange quarks, does not exist naturally on the earth and its force with nuclei was not well known. The binding energy of the Xi-minus particle (which is a measure of the force between a Xi-minus and a Nitrogen-14 nucleus) was determined to be 1.27±0.21 MeV. This is the first and the most precise determination of the mass of Xi-hypernucleus and the binding energy of the Xi-minus particle. Similar to negative charged electrons, the Xi-minus particle can form the bound states with positive charged nuclei by Coulomb force (electromagnetic interaction). In the Coulomb case, the binding energy was calculated to be 0.39 MeV, which is quite different from 1.27±0.21 MeV given by IBUKI. The Xi hypernucleus observed in this research is bound deeper by the additional force, strong interaction, between the Xi-minus and the nucleus. The binding energy gives us the strength of the attractive strong interaction. The formed Xi hypernucleus decayed into two Lambda hypernuclei by the elementary conversion process that a Xi-minus particle and a proton go to two Lambda particles[1)]. If the conversion reaction is strong, the system decays before the Xi-minus reaching in the nucleus and forming the Xi hypernucleus. Thus, the present result indicates that the conversion process is weak. Strong interaction, which acts between a Xi-minus particle and nuclei or a Xi-minus particle and a proton (neutron), or occurs the above conversion process, is important to know in order to understand the origin of nuclei and structure of neutron stars, which are often described as giant nuclei. New insights of strong interaction have been obtained in this research.

Background

Xi-hypernuclei are nuclei in which a Xi particle is embedded in the ordinary nuclei composed protons and neutrons. Similar to a proton or a neutron, a Xi particle is composed by three quarks, two of them are strange quarks. They are short-lived and decay within 10 billionths of a second (10^{-10} s). Studies of hypernuclei, which contain strange quarks, lead to deep understanding of the origin and formation of nuclei. They, especially studies on Xi hypernuclei, are also particularly important in the understanding of neutron stars which are often described as giant nuclei. Neutron stars are the densest stellar objects in our universe known so far and have been formed as remnants after supernovae explosion. Their mergers have attracted attention in recent years as sources of the gravity wave, the birth place of heavy elements. In order to understand properties of neutron stars, such as a maximum mass, radius, density, and pressure etc., it is necessary to consider which particle appears at which density of the interior of neutron stars. The Xi particle is one of the particles that can be produced in neutron stars. Since the condition for production of the Xi depend on the strength of the forces of the Xi with the proton or neutron, it is necessary to determine the force by ground-based experiments. Experimental data on Xi hypernuclei have been waited for a long time.

The force by strong interaction, which acts between a Xi particle and nuclei, was suggested to be attractive by two experiments in 1990s. Research group led by Prof. Nakazawa reported the event of Xi hypernucleus (KISO event) for the first time in 2015. This event was found in the nuclear emulsion sheets irradiated in the past experiment carried out at KEK 12-GeV Proton Synchrotron (E373). The force between a Xi particle and a nucleus was turned out to be attractive. However, since KISO event has ambiguity whether a daughter Lambda hypernucleus was in the ground or the excited states, the mass of the Xi hypernucleus, and hence the strength of the force were not uniquely identified. Since the production of the Xi hypernucleus is rare event, a lot of Xi hypernuclear events are necessary to be observed in order to determine the mass of the Xi hypernucleus and obtain details of strong interaction of the Xi particle. The research team planned a new experiment at J-PARC, where high-intensity beams are available, using newly developed techniques, which aims to observe 10-times events of those in the previous experiment at KEK 12-GeV Proton Synchrotron.

Experiment and analysis

The E07 experiment was carried out at Hadron Experimental Facility at J-PARC, Tokai, Ibaraki, Japan in 2016 and 2017. Using high-intensity and high-purity negative kaon[1)] beams produced by accelerator (the proton synchrotron at J-PARC), Xi-minus particles were generated and injected into totally 1500 emulsion sheets. After the photographic development of the irradiated emulsion sheets, Xi hypernuclei were searched for in the sheets using optical microscopes, which were developed by the research team. For efficient search, the position and direction of Xi-minus particles measured by the detectors were used in the scanning of the emulsion. The event was found and identified that a Xi-minus was absorbed in Nitrogen-14 nucleus and Xi hypernucleus was formed and finally decayed into 2 Lambda hypernuclei (Berilium-10-Lambda and Helium-5-Lambda hypernuclei). The binding energy of the Xi-minus particle was determined to be 1.27± 0.21 MeV without any possibility of the excited states of the daughter hypernuclei.

This event was named as "IBUKI" after Ibuki Mountain at west area of Gifu Prefecture, where Gifu University is located. It is the practice of the team to name the rare and important event after the place to be connected the institute or person who contributes to discover it.

Prospects

The present result is expected to contribute the understanding how the matter was formed from quarks, the elementary particles, and what is the structure of interior of neutron stars which are often described as giant nuclei.

New scanning method called "overall scanning" has been developed. This method enables us to search Xi hypernuclei produced by Xi-minus particles, which were not tagged with our detector systems, and more 10-times Xi hypernuclei, namely 100-times as those in the previous experiment, are expected to be found. The details of strong interaction of the Xi particle can be revealed through the systematic measurements on various nuclear species and energy states of Xi hypernuclei using a lot of Xi hypernuclear events.

[Article information]

Title: Observation of Coulomb-Assisted Nuclear Bound State of $\Xi^- - {}^{14}N$ System
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Journal name: Physical Review Letters
DOI: 10.1103/PhysRevLett.126.062501
Published URL : https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.062501

[International research team]

This research was carried out by the international research team formed by the following universities and institutes,

Facility of Education, Gifu University, Japan,
Graduate School of Engineering, Gifu University, Japan,
Advance Science Research Center, Japan Atomic Energy Agency (JAEA), Japan,
Department of Physics, Tohoku University, Japan
Institute of Particle and Nuclear Studies, High Energy Accelerator Organization (KEK), Japan,
Accelerator Laboratory, High Energy Accelerator Organization (KEK), Japan,
Department of Physics, Osaka University, Japan,
Research Center for Nuclear Physics, Osaka University, Japan,
Department of Physics, Kyoto University, Japan,
High Energy Nuclear Physics Laboratory, RIKN, Japan,
Meson Science Laboratory, RIKEN, Japan,
Center of Advanced Photonics, RIKEN, Japan,
Department of Physics, Nagoya University, Japan,
Department of Physics, Seoul National University, Korea
Korea Research Institute of Standards and Science, Korea
Department of Physics, Korea University, Korea,
Research Institute of Natural Science, Gyeongsang National University, Kore,
Department of Physics and Astronomy, University of New Mexico, USA,
Department of Physics & Astronomy, Ohio University, USA,
Helmholtz Institute Mainz, Germany,
Institute für Kernphysik, Johannes Gutenburg-Universität Mainz, Germany,
Institute of Nuclear Energy Safety Technology, Chinese Science Academy, China,
Institute of High Energy Physics, China,
Institute of Modern Physics, Shanxi Normal University, China,
Department of Physics, Lashio University, Myanmar,
Department of Physics, University of Yangon, Myanmar.

The members of above universities/instates contributed detector developments for the experiment and their operation during the beam exposure experiment. Production and photo developments of the nuclear emulsion sheets, and scanning of the sheets and the detection of the IBUKI event using the optical microscopes were carried out by the members of Gifu University. A member of JAEA contributed in the analysis of detector system to tag the Xi-minus particle and the detailed analysis of the microscope image to identify the Xi-nucleus and measure its mass.

Glossary

1) Strange quark, Lambda particle, Xi particle, hyperon, Kaons (K meson)

A baryon is a particle, which is composed by three quarks like a proton and a neutron. There are several particles other than the proton and the neutron in baryon family by considering the third quark, "strange (s)" quark, in addition to the "up (u)" and "down (d)" quarks. A Lambda particle contains a strange quark (uds), while Xi particles contain two strange quarks: Xi-minus (dss) or Xi-zero (uss). Baryon which contains strange quark(s) are called a "hyperon".

The nucleus which contains one or more hyperons is called a "hypernucleus". Lambda hypernuclei contain a Lambda hyperon, while double-Lambda hypernuclei contain two Lambda hyperons, Xi hypernuclei contain a Xi hyperon.

A meson is composed by a quark and an anti-quark. A negative kaon, K^- ($\bar{u}s$) is a meson which has a strange quark, where $\bar{u}$ is an anti-quark of the up quark. The Xi-minus particle is produced with a K^+ ($u\bar{s}$) meson in the reaction of the K^- beam and a proton in the diamond target.

$$K^- + \text{proton} \rightarrow \text{Xi-minus} + K^+$$

A Xi-minus particle reacts with a proton and converts it into two Lambda particles. This conversion reaction causes the Xi hypernucleus to decay. At this point, the two Lambda particles happen to bind together to form two Lambda hypernuclei, which is the IBUKI event observed here.

Xi-minus + proton → Lambda + Lambda

2) Strong interaction

It is often called "strong (nuclear) force". One of the four elementary interactions in the universe. (The others are weak interaction, electromagnetic interaction, and gravity.) The force acts between quarks and forms a nucleon (proton, neutron) from quarks or a nucleus from nucleons. To understand the nature and properties of strong interaction is one of the most important subjects in the modern physics. The forces between hyperon and hyperon, hyperon and nucleon, and hyperon and nuclei give crucial key. Thus, hyperons and hypernuclei, which do not exist naturally on the earth and are only produced with the accelerator beams, are studied intensively at J-PARC and other accelerator facilities in the world.