Tentative Translation

Interim Report on the EIC Project and Related New Developments in Nuclear Physics (Overview)

July 19, 2024
Expert Panel on the EIC Project and Related New Developments in Nuclear Physics

文部科学省

Current State of Nuclear Physics in Japan and Related Issues

- **Nuclear physics** is the **study of quantum dynamics of a wide hierarchy of levels**, from elementary particles (quarks and gluons) and nucleons (protons and neutrons) (approx. 10^{-15} m) to neutron stars (approx. 10^{4} m), using elementary particles as the basic unit, for the purpose of elucidating the creation and evolution of matter.
- In addition to its scientific significance, nuclear physics **contributes to the creation of innovation, stable supply of energy, and development of human resources.**
- **Through the development of large experimental facilities in Japan and participation in international collaborative experiments**, **outstanding research results have been produced**, including the discovery of quark-gluon plasma (the state in which matter was dissolved into a soup of elementary particles that is believed to exist in the early universe) and nihonium.
- Young researchers in Japan **are active in obtaining research posts to lead international joint research. The number of graduate students** aspiring to this field **has also increased in recent years.**
- On the other hand, **the number of researchers and the number of papers in the top 10% of citations are declining** in this field in Japan.

Research environment needs to be improved so that it attracts young researchers and encourages participation in this field, etc.

https://www.riken.jp/press/2016/20160108_4/

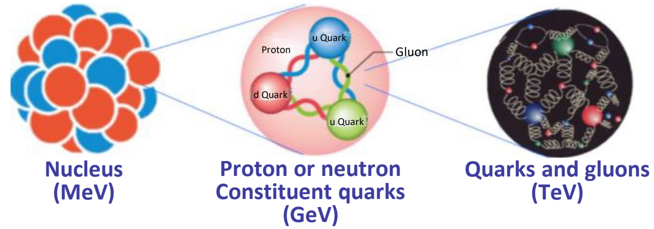
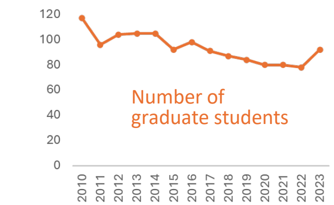
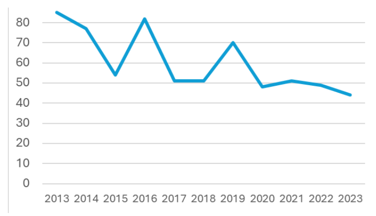


Image showing hierarchical levels of a nucleus

Membership of Nuclear Physics Forum (association of researchers in the field of experimental nuclear physics)



Number of Japanese papers in the top 10% of citations



Analysis by the Research Center for Nuclear Physics (RCNP), Osaka University

Japan's Participation in the EIC Project and Related New Developments in Nuclear Physics #1

[Direction of nuclear physics in Japan]

- **In quantum physics, progress has been made in our understanding at each level**: elementary particles, nucleons and nuclei, atoms and molecules, liquids and solids, and astronomical bodies and the universe. On the other hand, there are many problems that cannot be resolved simply with an understanding of each level, such as the appearance of high-temperature superconductivity in systems where there are strong bonds between electrons. **Having an understanding spanning multiple levels is essential.**
- **Nuclear physics** is a discipline that brings together the fundamental concepts of modern physics as it relates to a wide range of fields. It plays an **important role in utilizing quantum physics across a wide hierarchy of levels**.
- Aim is to create **"multiscale quantum dynamics research"** to elucidate universal laws of quantum dynamics that transcend hierarchical levels by integrating theoretical, experimental and computational science, starting from nuclear physics.
- Also contribute to the creation of innovation **in the fields of energy and quantum technology** [see Reference 1].

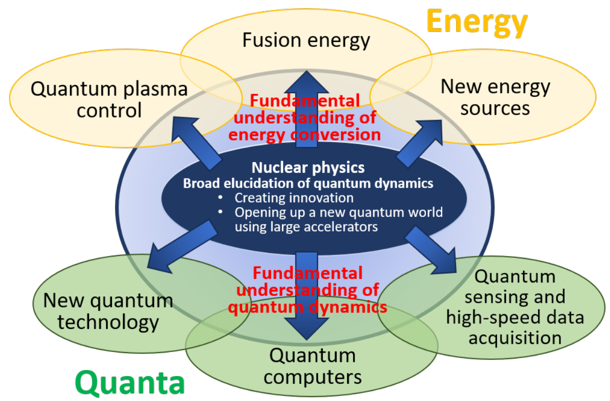


Image showing the expansion of nuclear physics

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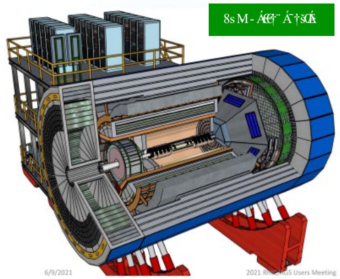
Japan's Participation in the EIC Project and Related New Developments in Nuclear Physics #2

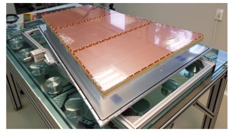
[New Developments in Nuclear Physics and the EIC Project]

- The Electron-Ion Collider (EIC) will be the world's first **collider** of polarized electrons with polarized protons/nuclei and will be built at the **Brookhaven National Laboratory (BNL) in the U.S.** [see Reference 2]. It will perform **precise measurements** of **three-dimensional structures** (position and movement of quarks and gluons) **inside protons and nuclei**. More than 850 people from 25 countries and regions are participating in the project.
- **Contributions will be made to promoting multiscale quantum dynamics research** by **utilizing the results of the EIC** to understand the properties of quantum interference (quantum robustness), phenomena and functions that first emerge when quanta are assembled in large numbers (emergence of quantum many-body systems), and quantum phenomena that appear in everyday environments (non-equilibrium phenomena in open quantum systems), etc.
- **A wide range of applications are expected**, including **scientific results such as elucidation of the origin of proton mass and spin**, the development of new energy sources, and contribution to the realization of quantum computers.

https://www.bnl.gov/eic/epic.php



https://alice-collaboration.web.cern.ch/menu_proj_items/O2-FLP



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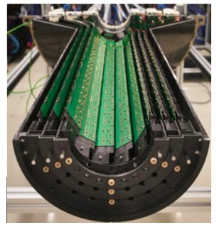
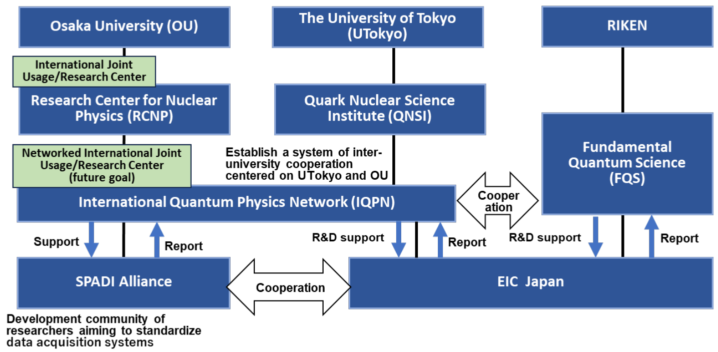


https://alice-collaboration.web.cern.ch/menu_proj_items/its

Image showing overall experimental instruments and the sensors and large-scale data acquisition system to be led by Japan

[Participation Framework for the EIC Project]

- Leveraging Japan's strengths, **the Japan Group—led by researchers in their 40s, together with many young researchers in their 30s**—will be in charge of experimental instruments and data acquisition/analysis systems that will be critical to the success of the project and **will take a leading role in the creation of scientific results.**
- **RIKEN: Establish an EIC base at BNL**, construct experimental instruments, implement a streaming data acquisition system, accept researchers from Japan, and **implement initiatives aimed at the creation of multiscale quantum dynamics research**, etc.
- **Universities: Consolidate the knowledge of academia in Japan, recruit and train excellent human resources** and dispatch them to BNL, and lead the **international standardization** of experimental instruments and data acquisition technology, etc.
  - ✓ Establish the **Quark Nuclear Science Institute (QNSI)** at **the University of Tokyo**. **Core organization** in Japan's EIC Project. Establish the **International Quantum Physics Network (IQPN)** to promote large-scale international research in a cohesive "all Japan" effort through **inter-university collaboration with Research Center for Nuclear Physics (RCNP), Osaka University**.
  - ✓ **Encourage the participation of diverse institutions** by utilizing the functions of **joint usage/research centers**, and **establish systems that facilitate the participation of researchers, including young researchers**.



EIC promotion structure

Overall Findings

- To actively promote the participation of Japanese universities and research institutions in the EIC Project as well as related new developments in nuclear physics, **the Ministry of Education, Culture, Sports, Science and Technology (MEXT) must actively support the efforts of relevant institutions and researchers of RIKEN, the University of Tokyo, Osaka University, etc.**
- Further discussions will be held on important matters such as the development of a system that enables young researchers to improve their skills by participating in various experiments in Japan and overseas.

Contributing to the Creation of Innovation through New Developments in Nuclear Physics

Reference 1

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Expected scientific findings:

◆ **Understanding the behavior** of quarks* and gluons* **inside protons and nuclei**

* Elementary particles (quanta) that make up a proton

➢ **A proton is thought to be composed of 3 quarks**, but making precise measurements using high-energy electrons reveals that it has **a complex structure composed of countless quarks and gluons**

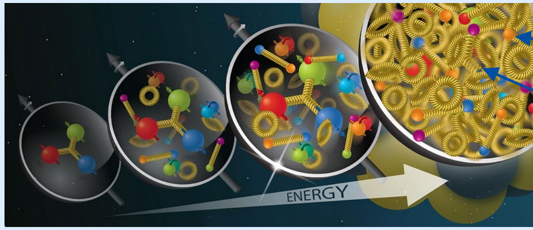


Image showing inside a proton at low → high energy

Understanding the origin of proton mass

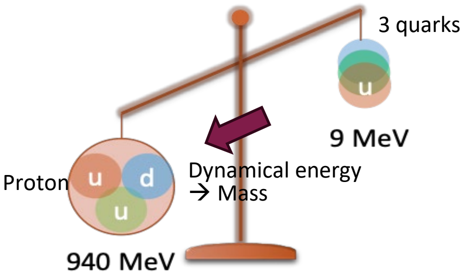
Understanding the origin of proton spin

Expected contributions in the field of energy

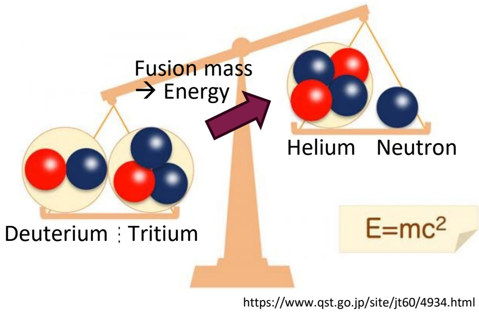
Fundamental understanding of mass/energy conversion ($E = mc^2$)

- Proton mass is about 100 times the mass of 3 quarks
  Elucidation of the **dynamical energy** of quarks and gluons, **which accounts for about 99%** of proton mass (mass and energy are equivalent)

➢ Contribution to the fundamental understanding of the **mechanism by which energy is produced** by fusion and fission, and to the development of **new fusion reactions**



Mass of a proton and of 3 quarks



Fusion reaction: Difference in mass is energy

✓ In addition, nuclear physics and nuclear fusion **share the same mathematical and experimental techniques**, and are expected to contribute to **solving common issues and developing human resources**

Expected contributions in the field of quantum technology

Fundamental understanding of quantum dynamics

- Elucidation of the mechanism by which protons are made of quarks and gluons by quantum dynamics and **can maintain a stable quantum spin state over a wide energy range**

Image courtesy of Brookhaven National Laboratory

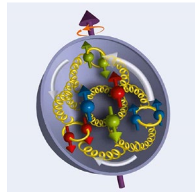


Image showing inside of a proton

➢ Contribution to the **preservation of quantum entanglement*** and the **search for matter with stable quantum properties**

* Situation in which quantum states remain closely related even if they are far apart. Used in quantum computers, etc.

➢ Contribution to the **realization of quantum computers and high-performance devices** (ultra-sensitive sensors, etc.)

Copyright; RIKEN Center for Quantum Computing

Japanese quantum computer "A"

Following contributions are also expected:

✓ Realization of **fault-tolerance**,* essential for the practical application of **quantum computers**, through understanding the fundamental theory of nuclear physics

* Technology for correcting errors that occur in the process of quantum computing

✓ **Resolution of common issues and development of human resources** in both nuclear physics and quantum technology, such as data processing technology

Overview of the Electron Ion Collider (EIC) Project

Reference 2

[Overview]

- The EIC Project is a project for **the world's first high-energy polarized electron–polarized proton/ion collider**, being developed by the U.S. Department of Energy (DOE) at Brookhaven National Laboratory (ring accelerator of approximately 3.8 km in circumference; construction scheduled to begin in 2026, full-scale operation scheduled to begin in 2034).
- **Only large accelerator project** planned for the next 10 years (joint international project).
- In February 2024, **the U.S. requested Japanese collaboration**. **Contributions expected to be made by the Japanese scientific community**, including RIKEN and the University of Tokyo.
- Japan Group in charge of **experimental instruments and data acquisition/analysis systems**, leveraging **Japan's strengths in semiconductor and data acquisition technologies**. Expected to **take lead in creation of research results**, promote **international standardization of Japan's basic technology**, and contribute to **the development of human resources and industry**.
- Of the total EIC construction cost of $1.7–2.8 billion (approximately 270–450 billion yen),* Japan is expected to contribute **a total of approximately 9.2 billion yen (including 4.2 billion yen for the provision of measuring instruments, etc.) during the construction phase (2025–2030)** and **approximately 19.2 billion yen during the operation phase (2031–2050)**.

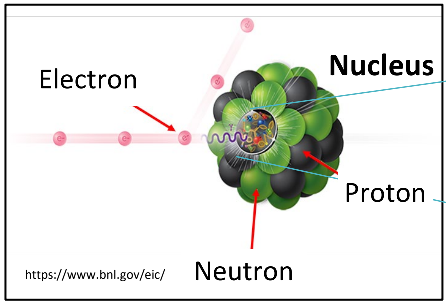
  * Total construction cost at present is a range because the project is still in the conceptual design phase. In addition to the accelerator, includes measuring instruments, personnel costs and other operational costs. Conversion rate: USD 1 = JPY 160.

[Significance]

- Expectations include **scientific results**, such as a new picture of the nucleus and elucidation of the origin of proton mass/spin, as well as **a wide range of applications, such as the development of new energy sources and the realization of quantum computers**.

Image of the experiment

- Use electrons to explore the structure of a nucleus
- So-called **"ultra-precise electron microscope"**



Size of nucleus: Approx. $\mathbf{10^{-14}}$ **m**

Image showing inside of a proton

- Precise measurement of 3D structure inside protons, neutrons, and nuclei

→ **Elucidation of the origin of proton mass and spin**

Size of proton: Approx. $\mathbf{10^{-15}}$ **m**

Image showing EIC

Total circumference: Approx 3.8 km

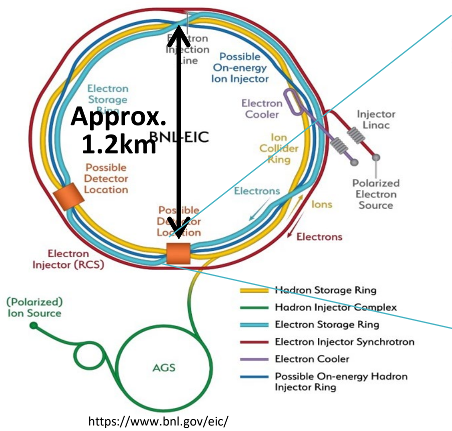


Image of experimental instruments