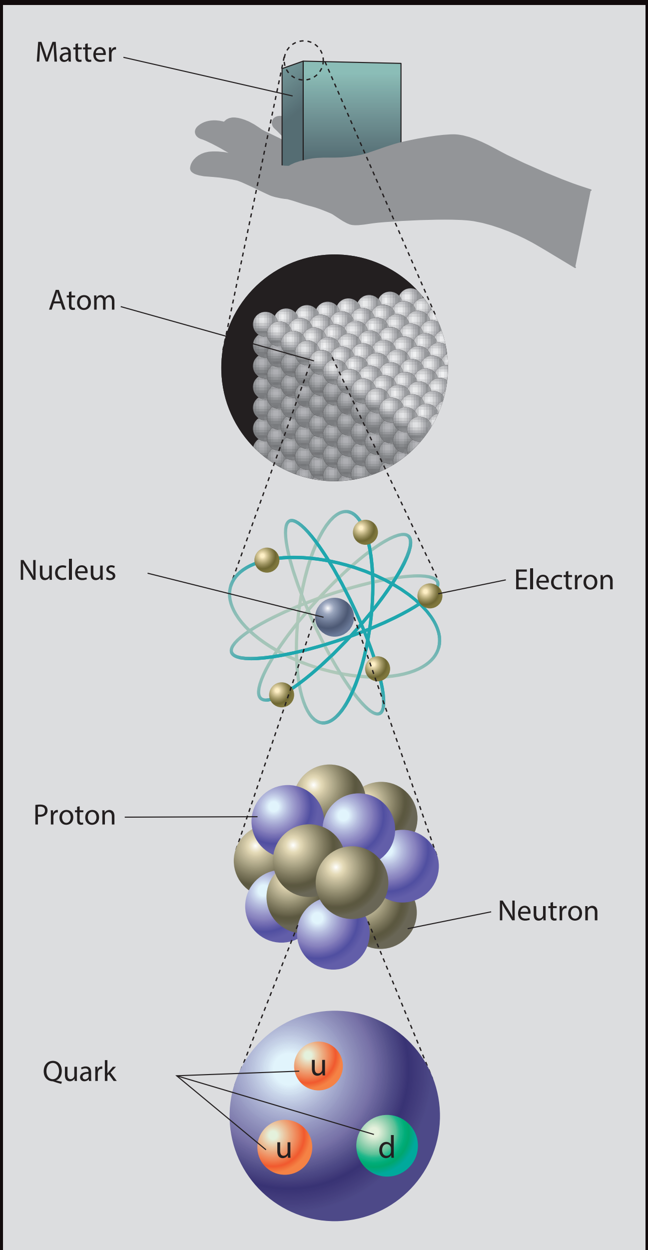
J-PARC HADRON EXPERIMENTAL FACILITY

Advanced Research on Particle & Nuclear Physics with High Intensity Hadron Beams

Welcome to Hadron Experimental Facility

At the J-PARC Hadron Experimental Facility (HEF), fundamental research on particle and nuclear physics is conducted experimentally using hadron beams. What are hadrons, nuclei, and elementary particles? This brochure provides an overview of those and the research activities at HEF as clearly as possible.

History of the Universe *and* the origin of matter



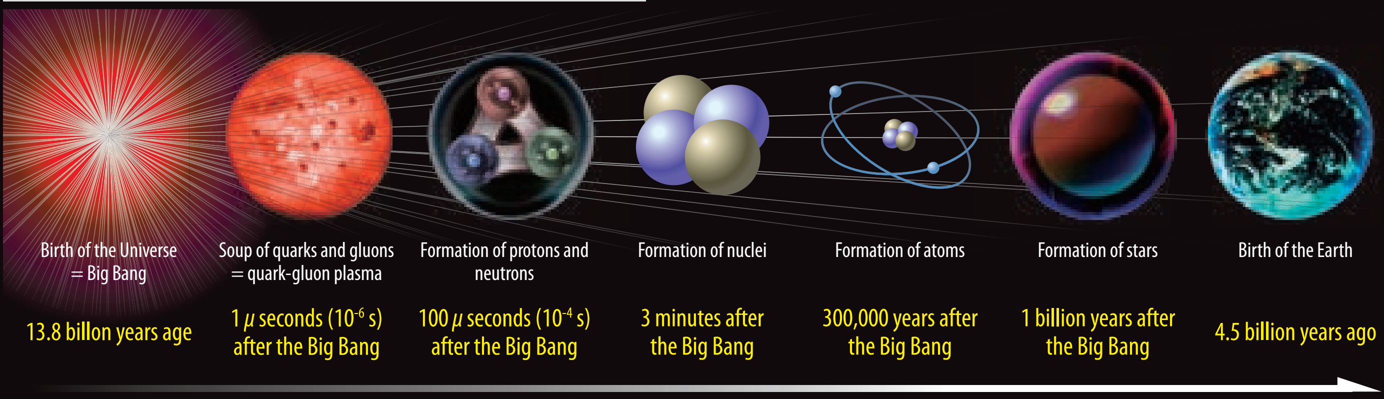
Onion structure of material world

Ordinary materials around us are composed of atoms when viewed in detail. For example, a lump of aluminum, the raw material of a 1-yen coin, is made by connecting aluminum atoms by a metallic bond. When the atom is viewed in detail, we notice its structure is a positively charged **nucleus** at the center and negatively charged **electrons** around the nucleus. An electron is an "elementary" particle, since it cannot be divided into smaller constituents. However, the nucleus is not since it is composed of **protons** and **neutrons**. Furthermore, a proton or neutron is composed of **quarks**. In modern physics, the quark is thought to be a true "elementary" particle. As shown above, the material world has a hierarchical structure like an onion. At the Hadron Experimental Facility (HEF), we investigate elementary particles which lay deep inside the hierarchical structure, protons and neutrons, and the nuclei composed of protons and neutrons.

Tracing the history of the Universe through the study of nuclei and elementary particles

The history of the Universe began at the Big Bang 13.8 billion years ago. Just after the Big Bang, the Universe was very hot. Elementary particles such as quarks and gluons were moving in a state similar to a soup. After that, as the Universe cooled down, protons and neutrons were formed, followed by nuclei and atoms. The great variety of materials around us was finally created.

The study of nuclei and elementary particles is a path to investigate the hierarchical structure of matter, and in other words, a path to investigate the history of the Universe.



What are nuclei and elementary particles?

Quarks and leptons

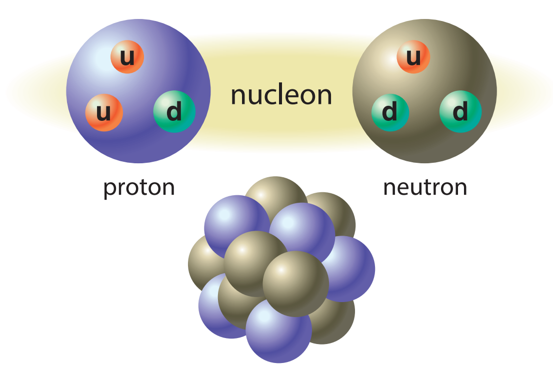
Modern physics has created the "Standard Model" of elementary particles and forces. Elementary particles in the Standard Model, which are not divisible, and are the smallest units of the matter, are thought to be composed of 6 types of quarks, 6 types of leptons, gauge particles which mediate four kinds of force, and the Higgs. There exist anti-particles in quarks and leptons; for example, the anti-particle of the u quark is an anti-u quark. The four kinds of force are gravity, the electromagnetic force, and the weak and strong forces. The weak force acts during nuclear disintegration where one nucleus changes to a different nucleus. The strong force binds quarks to a proton or neutron and makes a nucleus.

quarks			leptons	
up u	down d	the 1st generation	electron e	electron-neutrino ν_e
charm c	strange s	the 2nd generation	muon μ	muon-neutrino ν_μ
top t	bottom b	the 3rd generation	tau τ	tau-neutrino ν_τ

particles which mediate force.				particle which generates elementary particles' masses.
gluon g strong force	photon γ electromagnetic force	weak boson W^+ W^- Z weak force	graviton gravity	Higgs H

Nucleons and nuclei

Protons and neutrons are collectively called nucleons. The nucleon is composed of three quarks. A proton is composed of two up quarks and one down quark, while a neutron is composed of one up quark and two down quarks. Protons and neutrons are bound by the strong force forming an ordinary nucleus.

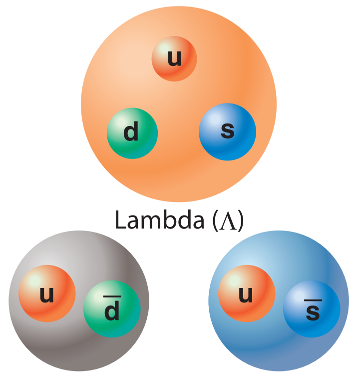


Ordinary and non-ordinary materials

Materials around us are made of ordinary nuclei which are composed of only protons and neutrons. This ordinary material is composed of the 1st generation elementary particles, up and down quarks and electrons. There are non-ordinary particles (matter) which are composed of the elementary particles other than the 1st generation in the particles, and can be produced by cosmic-rays or accelerators.

A Lambda (Λ) particle is composed of one up quark, one down quark, and one strange quark as shown in a right figure.

Pion (π meson) was theoretically predicted by Dr. Hideki Yukawa and later experimentally discovered. For example, a positively charged pion (π^+) is composed of one up quark and one anti-down quark. There are a lot of mesons which are composed of other than up and down (anti-up and anti-down) quarks. A positively charged kaon (K^+ meson), for example, is composed of one up quark and one anti-strange quark.

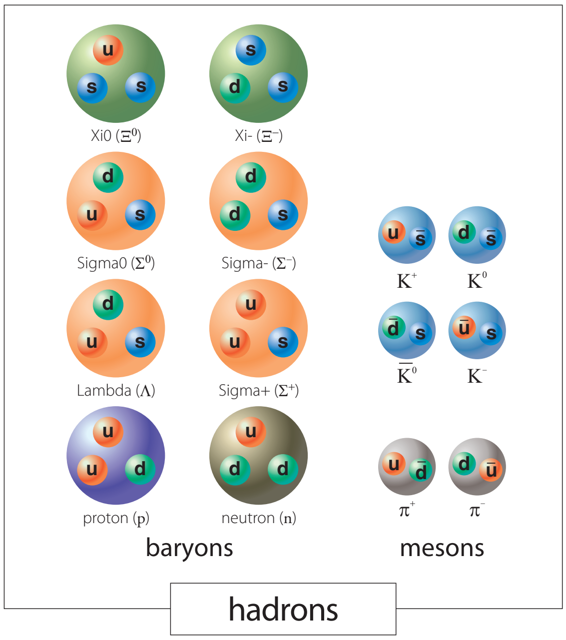


What are hadrons?

Hadrons, Baryons, and Mesons

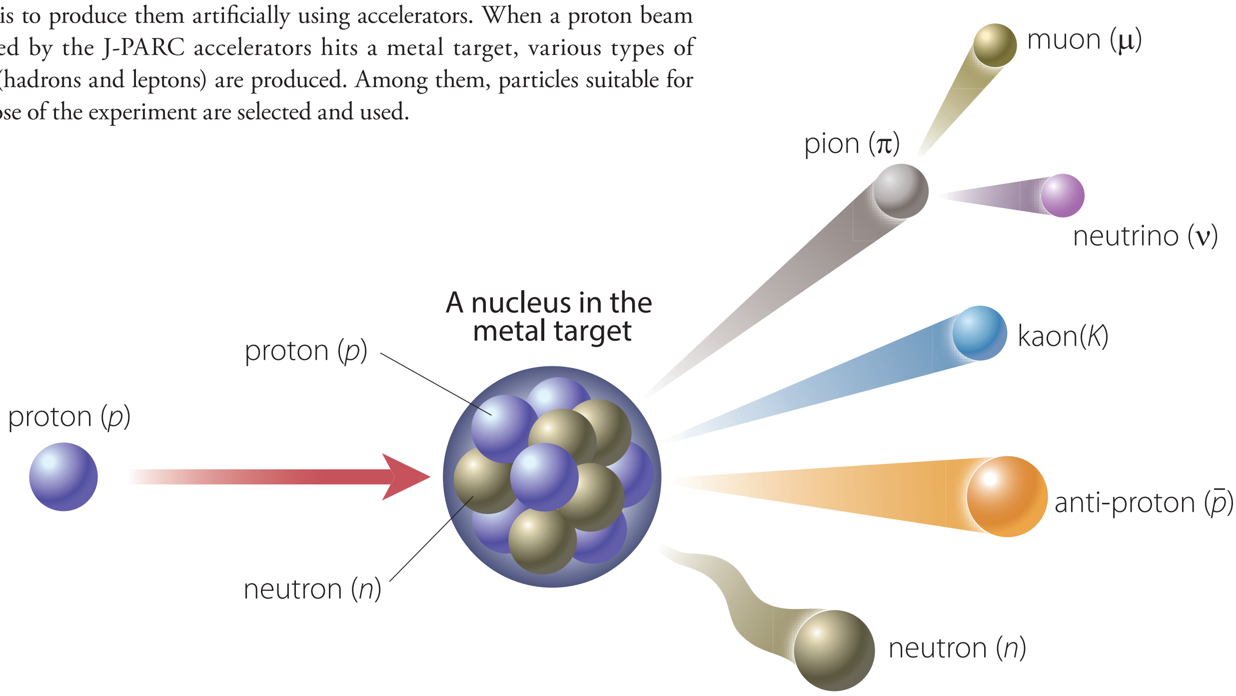
Nucleons, a Λ particle, and mesons, as already mentioned, are particles formed by quarks via the strong force. They are collectively called "hadrons".

A particle composed of three quarks, such as a proton or a neutron, is called a "baryon". Whereas a particle composed of only one quark and one anti-quark is called a "meson".



How to produce hadrons

A lot of protons and neutrons exist around us, as components of nuclei. Other hadrons are found in the cosmic-rays raining down from space. But the number of the hadrons in cosmic-rays is very small and they are not easy-controlled for use in experiments. The only way to obtain a large amount of specific hadrons to study, is to produce them artificially using accelerators. When a proton beam accelerated by the J-PARC accelerators hits a metal target, various types of particles (hadrons and leptons) are produced. Among them, particles suitable for the purpose of the experiment are selected and used.

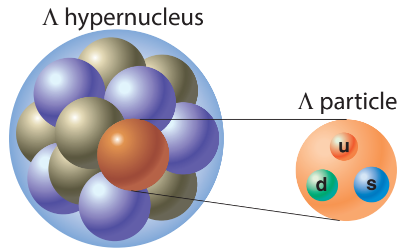


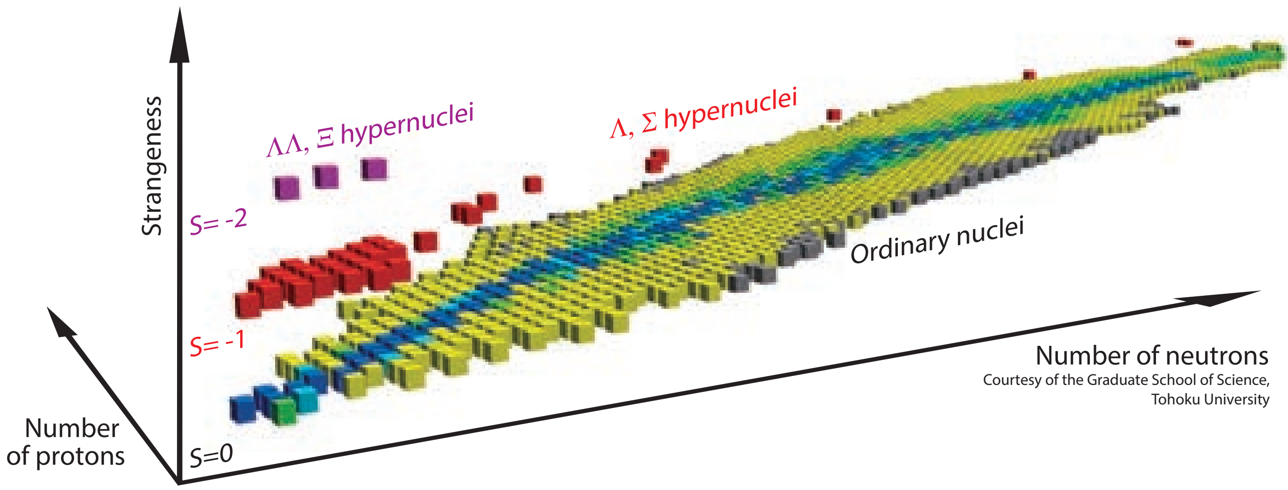
Research using hadrons

What kind of research is conducted at the HEF using hadrons? The HEF is not a research facility for industrial application but a playground for basic science, where we consider the origin and evolution of our universe through the study of nuclei, elementary particles, and the force between them. Properties of the strong force, which works between hadrons and also forms them, is one of main research subjects at the HEF. Dr. Yoichiro Nambu, who is one of the Nobel Prize winners in 2008, proposed a mechanism by which mass is generated in matter. Experimental confirmation of the mass-generation mechanism in the strong force is also another one of main subjects. The experiment to confirm the model by Dr. Kobayashi and Dr. Maskawa, who also won the Nobel Prize in 2008, is also being conducted. At the HEF, research on nuclei and elementary particles is being conducted from various aspects. Let's take a look at some of them starting on the next page.

What is a hypernucleus?

There are a lot of nuclear species (nuclides) in ordinary nuclei that are composed of protons and neutrons. Non-ordinary nuclei which contain not only up and down quarks but also strange quark(s), called hypernuclei, can be produced by the experiments on the Earth. At the HEF, hypernuclei are intensively studied.

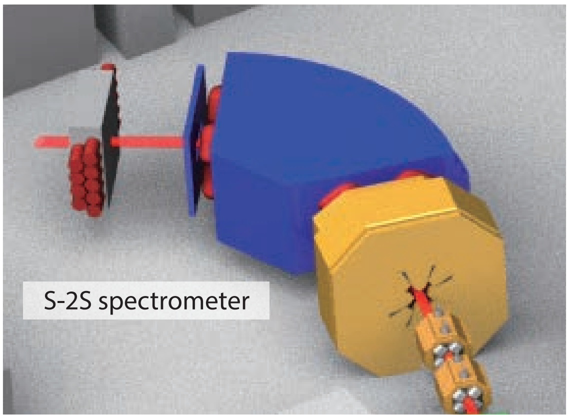




Courtesy of the Graduate School of Science, Tohoku University

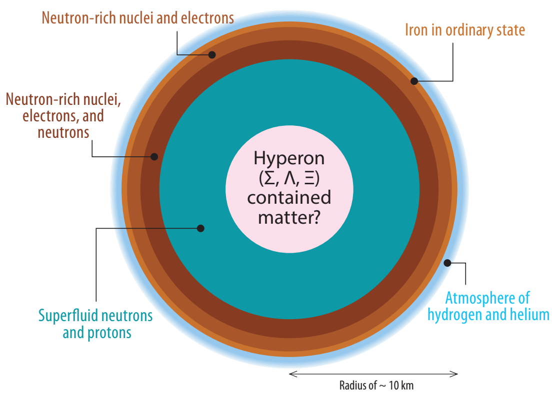
What can we know?

Dr. Hideki Yukawa won the Nobel Prize for showing that attractive nuclear force which binds nucleons together and forms a nucleus can be explained by pion exchange. However, it is known that when nucleons are brought closer, there is a strong repulsive force. The origin of nuclear force and the reason for the strong repulsion at short distances, is expected to be clarified through the study of hypernuclei.



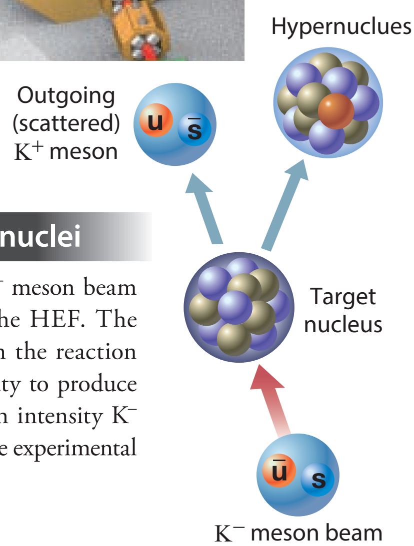
What are the contents of neutron stars?

Neutron stars are extremely dense matter in the Universe; the density is more than 10^{14} times that of the Sun. Baryons which contain strange quark(s), called hyperons, such as Λ and Ξ particles are thought to appear in the core of neutron stars as shown in the figure below. The contents and properties of the matter inside neutron stars can be clarified through the study of hyperon force and hypernuclei.



How to produce hypernuclei

Hypernuclei are produced by K^- meson beam hitting the target nucleus at the HEF. The emitted K^+ meson or pion from the reaction is measured. Since the probability to produce hypernuclei is very small, a high intensity K^- meson beam at J-PARC makes the experimental study of hypernuclei feasible.

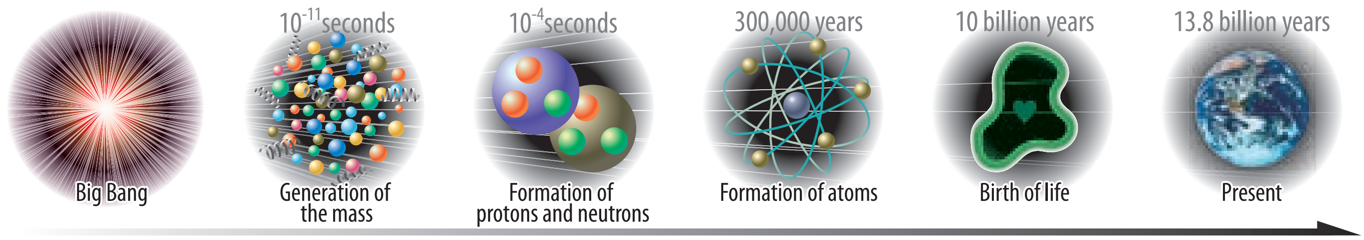


The origin of hadron mass

— Experimental confirmation of the mass-generation model by Dr. Nambu —

How was mass of the matter generated?

We take it for granted that we have mass in ourselves and in the materials around us. However, it is believed that when the Universe was born, the mass of all particles was zero. So how was the mass generated from massless particles? The model proposed by Dr. Yoichiro Nambu explains its mechanism.

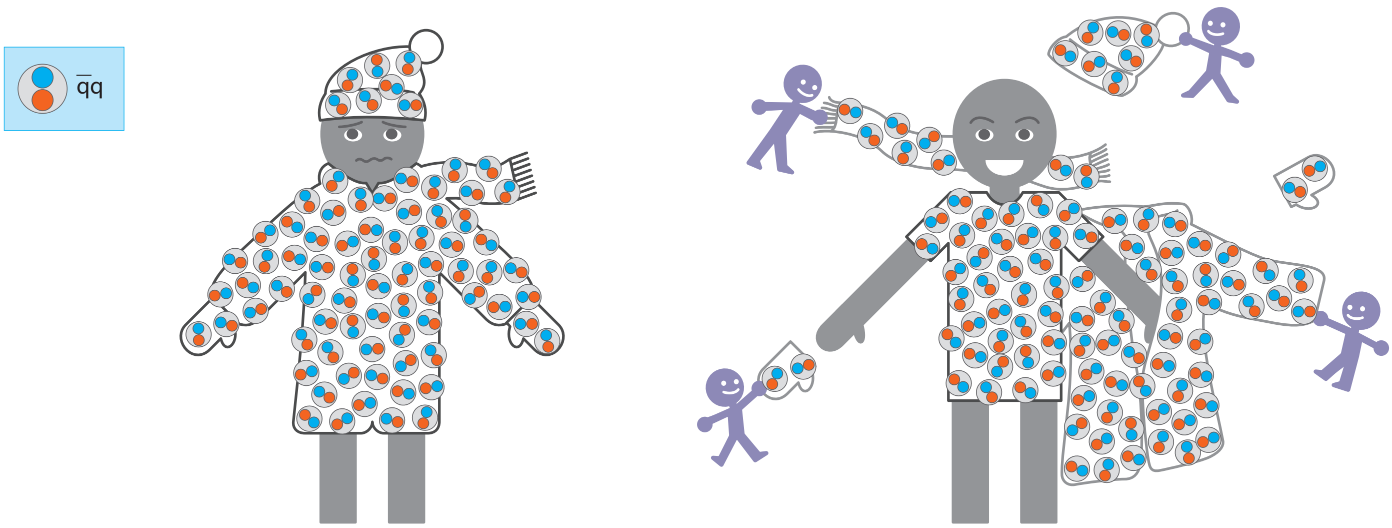


The model by Dr. Nambu

The smallest component of matter is a quark. The quark cannot be found in isolation. Instead, if it is pulled out from a composite particle, then it immediately pairs with the anti-quark ($\bar{q}q$). Consequently $\bar{q}$-q pairs are thought to be condensed in vacuum. The mechanism that causes the $\bar{q}q$ condensation is the spontaneous chiral symmetry breaking proposed by Dr. Nambu. In this mechanism, hadrons are considered to obtain their large mass by interacting with the condensed $\bar{q}q$.

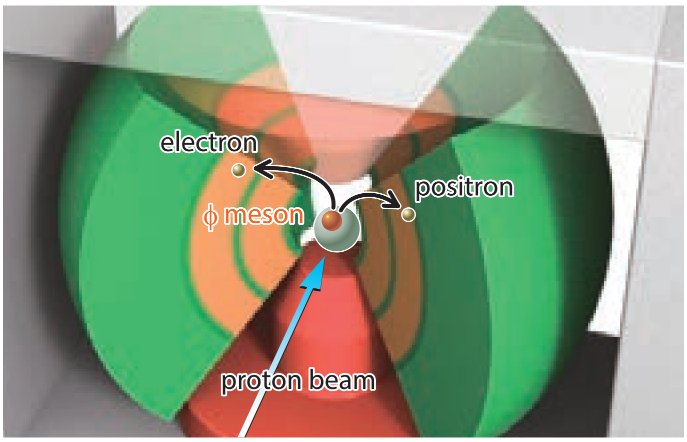
How to confirm?

So how do we confirm this model? The hadron mass is predicted to become lighter when it is put in a high density environment since the condensed $\bar{q}q$ pairs, which generate hadron mass, becomes fewer in a high density environment. At the HEF, we will confirm the model by producing a ϕ meson inside a nucleus and measuring how its mass changes within the nucleus, a high density environment.



In vacuum

At high density



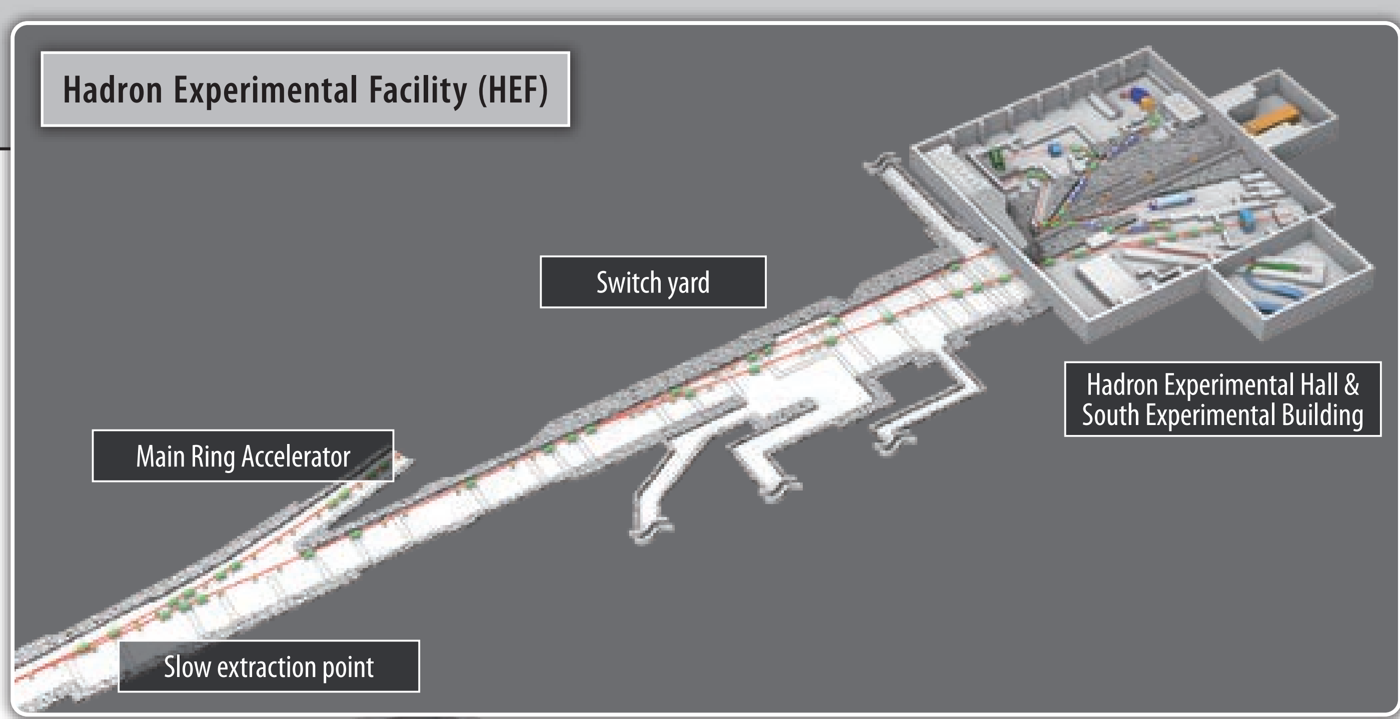
Hadrons will become lighter !

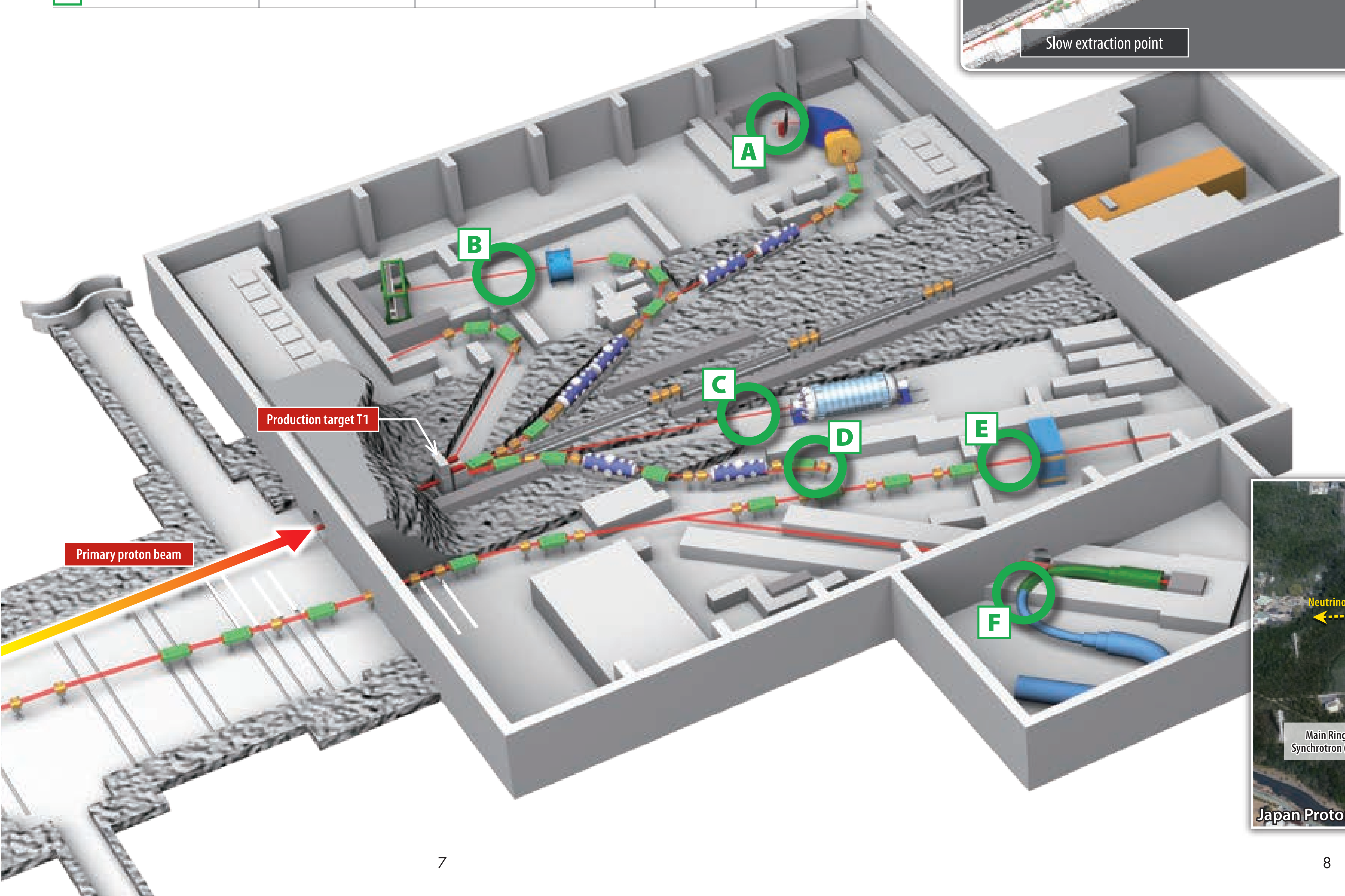
In the experiment, ϕ mesons are produced by the primary proton beam from the accelerator hitting on the target nucleus. The mass of the ϕ meson is measured by detecting an electron and positron pair from the ϕ meson decay inside the nucleus using the spectrometer shown in the figure. If the model is correct, a lighter ϕ meson mass would be measured. This makes it possible to experimentally clarify whether chiral symmetry breaking really generates a hadron mass.

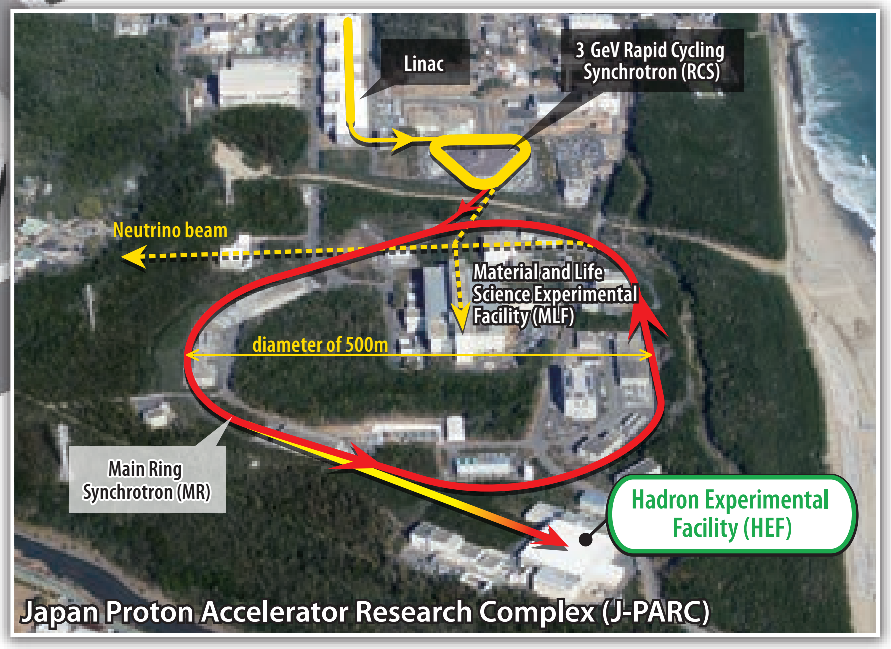
Hadron Experimental Facility

— The origin of matter investigated by various particles beams —

Beamline & main subject		Beam particles	Beam momentum	Beam intensity
A K1.8	hypernuclei (S=−2)	▶(charged) pion, (charged) kaon, anti-proton, etc.	▶≤ 2 GeV/c	▶~ 10^6 K^-/s
B K1.8BR	strangeness & hadron physics	▶(charged) pion, (charged) kaon, anti-proton, etc.	▶≤ 1.2 GeV/c	▶~ 10^6 K^-/s
C KL	CP violation	▶neutral kaon	▶~ 2 GeV/c	▶~ 10^7 K^0/s
D K1.1	hypernuclei (S=−1)	▶(charged) pion, (charged) kaon, anti-proton, etc.	▶≤ 1.1 GeV/c	▶~ 10^6 K^-/s
E high-p	hadron mass, hadron physics	▶primary proton, (charged) pion	▶≤ 31 GeV/c	▶< 10^{12}/s
F COMET	muon to electron transition	▶muon	▶≤ 77 MeV/c	▶~ 10^{11}/s





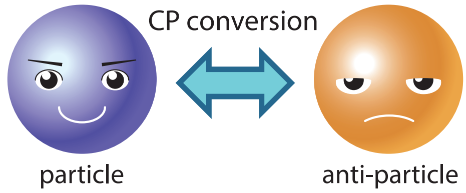


Asymmetry of matter and anti-matter in the Universe

— from confirmation of Kobayashi-Maskawa model to search for new phenomenon —

Why doesn't anti-matter exist?

Anti-matter, composed of anti-particles, is almost non-existent in nature, unlike matter. The asymmetry of matter and anti-matter is called "CP symmetry violation". Why did this asymmetry occur in the Universe?



Kobayashi-Maskawa model

Dr. Makoto Kobayashi and Dr. Toshihide Maskawa predicted three generations of quark pairs; each pair has two quarks. They also showed that CP symmetry violation is naturally explained in this case.

We can investigate how much CP symmetry is broken by measuring particle decay phenomena or decay probabilities. A rare kaon decay measurement at the HEF is one of the experiments to clarify whether the Kobayashi-Maskawa model is correct or if there is a new phenomenon which cannot be explained by the Standard Model (SM).

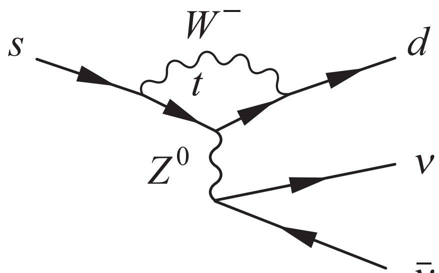
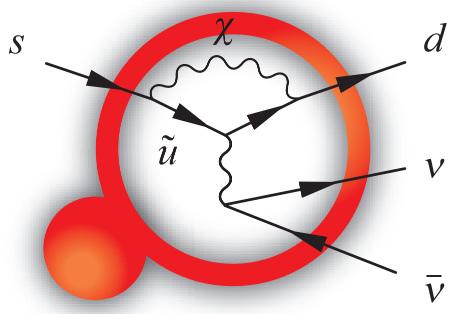


Diagram in the Standard Model

Experiment to search for a rare decay of neutral kaons

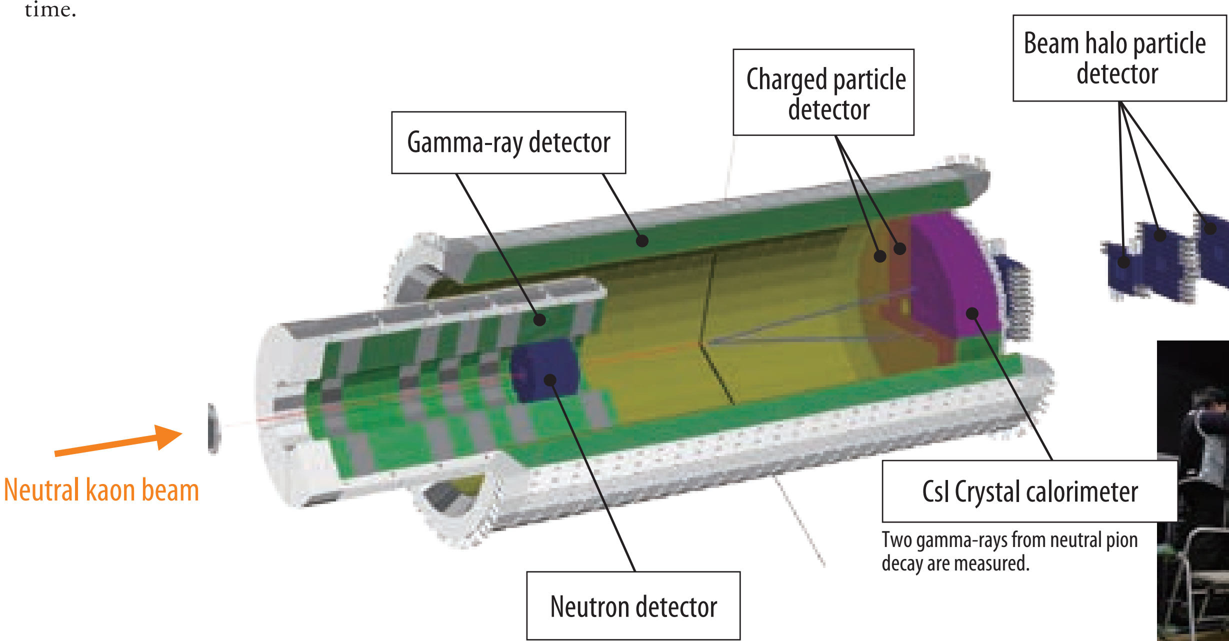
In this experiment, a very rare decay in the SM, where a long-lived neutral kaon (K_L^0) decays to a neutral pion (π^0), neutrino (ν), and anti-neutrino ($\bar{\nu}$), will be observed. If a supersymmetric particle which is not included in the SM exists, the probability of this rare decay would be enhanced.



New diagram for CP violation beyond the SM

Detection of rare decay events

The probability of this rare decay is predicted to be one in several billion by the SM. A huge number of neutral kaons can be produced at J-PARC using the world highest intensity proton beam. The past experiment at the 12 GeV proton synchrotron in KEK Tsukuba Campus achieved the detection sensitivity of one in tens of millions. In the KOTO (K0 at Tokai) experiment at J-PARC, the achieved sensitivity is expected more than a thousand times that of the past experiment. Therefore, the rare decay event is expected to be detected for the first time.



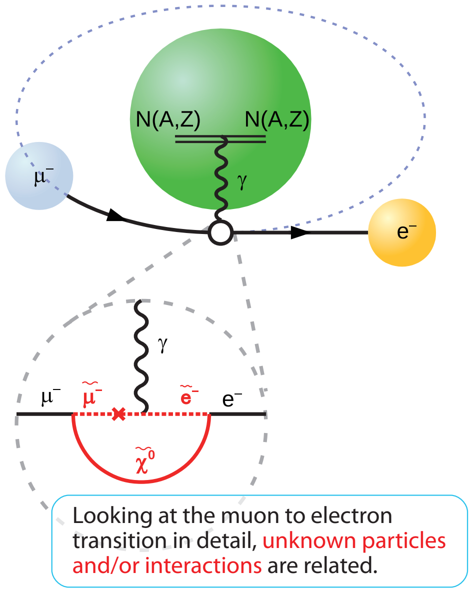
Search for muon to electron transition phenomenon

— Direct evidence of the fraying of the Standard Model —

Feature of muons

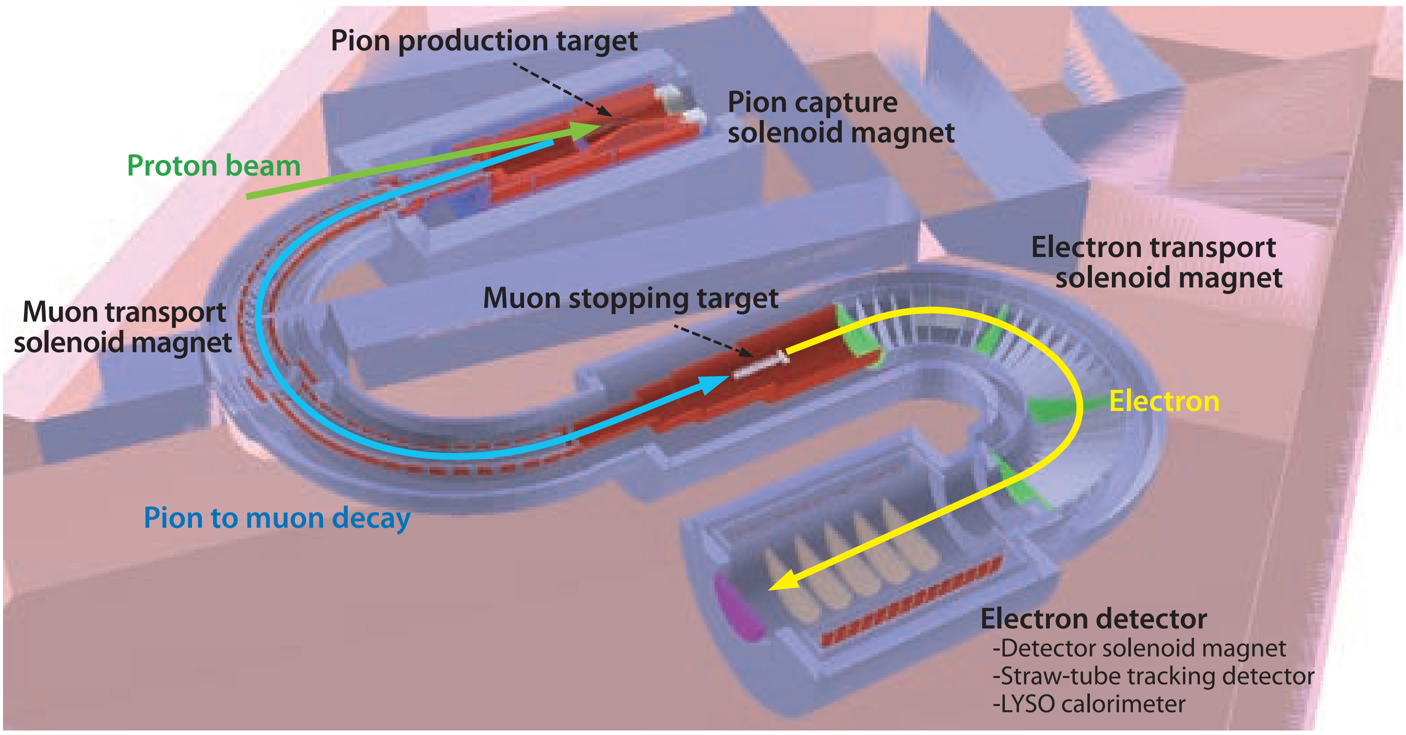
The Standard Model (SM) is the basis of modern particle physics. However, it is thought to be only an approximate model at low energy, of a more fundamental and unknown theory of the elementary particles. A muon is one of the leptons in the SM, and about 200 times more massive than an electron of the same lepton family. Charged leptons (electron, muon, and tau) can not change into other leptons without accompanying neutrinos[*1]. However, the muon to electron transition is suggested to occur in theories beyond the SM. The experimental observation of the muon to electron transition would be evidence for the existence of an unknown theory beyond the SM.

*1 The transition may occur with a quite low probability through the neutrino oscillation phenomenon discovered and established recently.



COMET Experiment

In the COMET (Coherent Muon to Electron Transition) experiment, muon to electron transition (reaction that a muon changes into an electron) event is searched for using a pulsed muon beam obtained at the HEF. Since this transition is a very rare event, huge numbers of muons are required. The events should be measured during the timing between the beam pulses to avoid huge background events (noise) which originate from the beam. The key to success for the experiment is to form a muon beam of very high intensity in a clean pulse shape. In order to identify the "muon to electron transition" event, electrons with a characteristic momentum are selected. The momentum of the electron is measured with a high momentum-resolution detector in order to discriminate the signal electrons from background electrons from known reactions. In the COMET experiment, we aim to achieve the sensitivity of 10^{-16}, one in ten thousand of that in the past experiments, by using state-of-art technology both in the beam and detectors.



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