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FEATURE STORY

The K1.8 experimental group gathers for a group photo after the successful first beam run in October 2009. Prof. Toshiyuki Takahashi of KEK, the third from right in the front row, leads the K1.8 beamline at the J-PARC Hadron Facility.

Hadron spectroscopy: the search for exotic particles

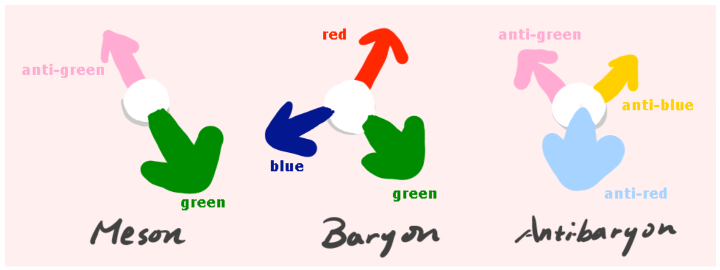
[Strange Hadron Spectroscopy, Xi Particles, Pentaquark]

One of the five beamlines constructed in the Hadron Facility at the Japan Proton Accelerator Complex (J-PARC) is preparing for the fall run where they plan to explore the physics of exotic hadrons. J-PARC will use a high intensity proton beam to produce the world's only kaon beam for use in spectroscopic studies of hadrons with heavy quarks.

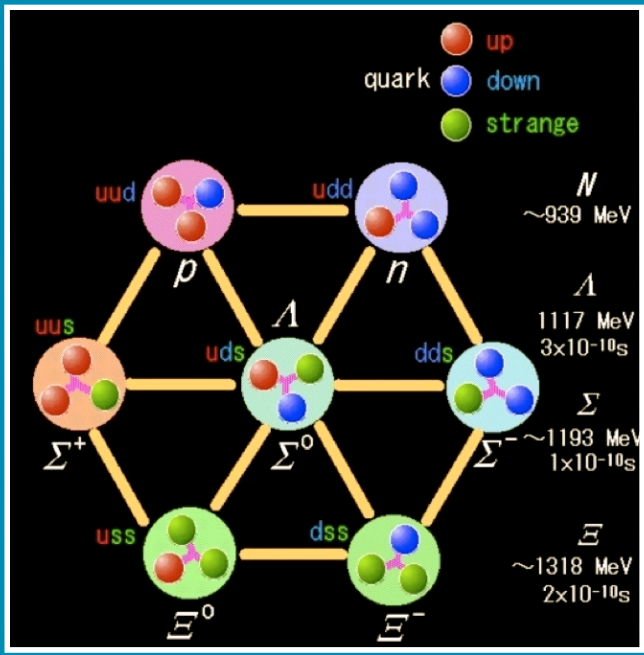
The nucleus of an ordinary atom consists of protons and neutrons. These, in turn, consist of elementary particles called quarks. In fact, they are composed of two types of quarks: *up* quarks and *down* quarks. We know that quarks have six flavors, or types. In order of increasing mass, they are: *up*, *down*, *strange*, *charm*, *bottom*, and *top* (denoted *u*,*d*, *s*, *c*, *b*, and *t* respectively for simplicity). So there are many different particles one can create from these quarks, and these particles are called hadrons.

The quark model describes the combinations of quarks that can bind together to create hadrons. In the quark model, quarks have a property called color charge. These charges are analogous to those in electromagnetism, but with three values instead of two. These three values are: red, blue, and green. The quark model says that hadrons can be formed if the total color charge of the all quarks vanishes to zero. A two-quark hadron is called a meson, and a three-quark hadron is called a baryon. Mesons and baryons that consist of *u* and *d* quarks are abundant in our universe. For example, protons and neutrons—generally

↓Quarks have three color charges: red, blue, and green. Quarks of various color charges bind to produce colorless (color-neutral) hadrons.



→This image shows the baryon octet, the set of three-quark particles which can be constructed using only *up*, *down*, and *strange* quarks. Baryons are composed of three quarks. Baryons with no strange quarks are shown in the top row—proton and neutron. Baryons with one strange quark are called Sigma and Lambda particles (middle row). Baryons with two strange quarks are called Xi particles (bottom row).



called nucleons—are baryons. Normal matter, the atoms that make up all the stuff in everyday life, is made up almost entirely of those nucleons.

Some baryons can only be produced in a laboratory. For example, baryons that include *s*quarks, such as the Lambda, Sigma, and Xi particles, quickly decay into lighter particles containing *u* and *d* quarks, and so are not found in nature. Some hadrons are harder to find even in high energy particle experiments. These are called exotic particles. There are exotic hadrons whose existence is proven recently. KEK's Belle experiment has found four-quark hadrons. The existences of five-quark hadron called pentaquark and the six-quark hadron called dibaryon are still controversial.

Measuring nuclear force in hypernucleus

Baryons that include s quarks are called hyperons. Some common examples of hyperons are the Sigma and Lambda particles, which each have one *s* quark, and the Xi particle, which has two *s* quarks. Since ordinary nuclei are made of nucleons, one naturally wonders whether one could have a nucleus in which one or more nucleons are replaced by hyperons. Indeed, it is possible. Those nuclei are called hypernuclei.

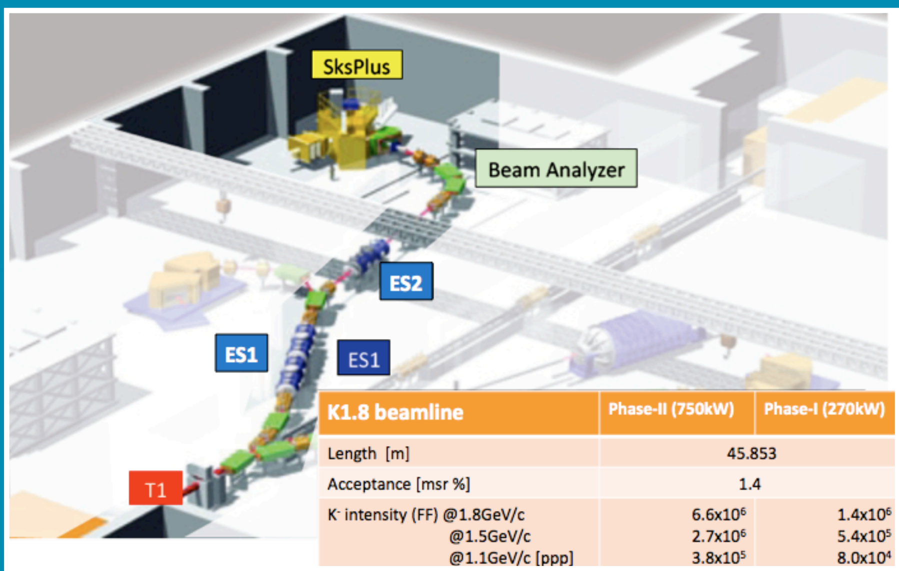
In hadron experiments, one of the many aspects of hadron physics that physicists can explore is the nuclear force, which is an indirect effect of the strong force. Quarks are bound together into hadrons by the strong interaction, which is due to color charge. Because hadrons are color neutral, the strong force does not act directly to bind hadrons together. However, the second order effects of the strong force remains significant, even outside the hadron. These second order effects do act to bind hadrons together, and constitute the nuclear force. Because of this, the nuclear force is also called the residual strong force.

"While the theory of quantum chromodynamics (QCD), describes the mechanism of the strong nuclear interaction, the complexity of QCD makes it hard to derive the nuclear force from QCD by first principles," explains Prof. Toshiyuki Takahashi of KEK, the leader of the K1.8 hadron experimental group. "The nuclear force is still not well understood. Hopefully, our experiments will help us to find some clues to understand the nuclear force."

The Xi hyperon potential

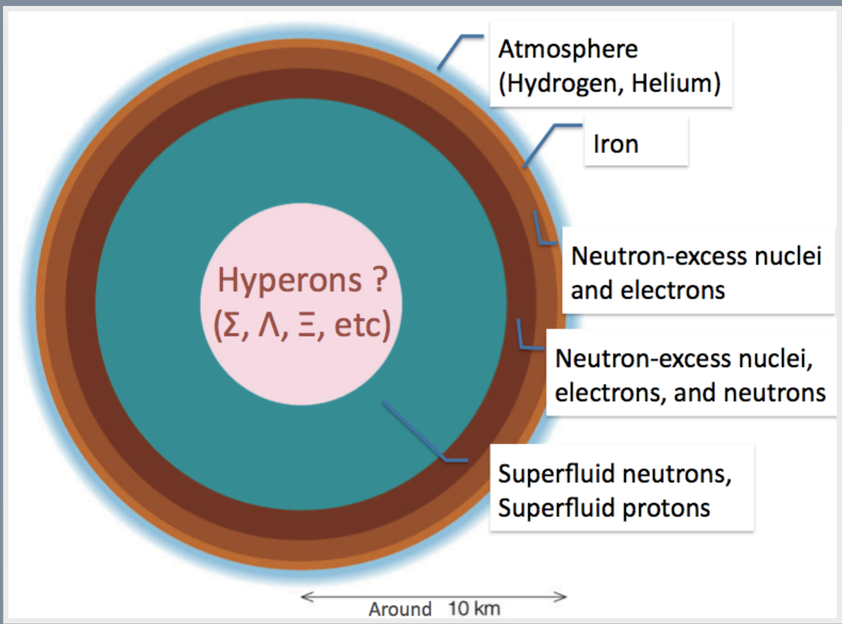
There are two main models that describe the nuclear force. One is called the Yukawa model, and was proposed by Hideki Yukawa in 1935. He theorized that nucleons interact strongly via exchanges of virtual mesons. The other model explains nuclear force in terms of the exchange quarks. One specific objective of many hadron experiments is to measure the strength of the nuclear force, called the nuclear potential, to determine the correct model.

So far, experiments have measured nuclear potentials for nucleons very precisely. KEK and the Brookheaven National Laboratory (BNL) have also studied the nuclear potential of the Lambda hypernucleus. Now, the K1.8 experimental group at the Japan Proton Accelerator Complex (J-PARC) is preparing to start the search for a hypernucleus that include a two-*s* quark hyperon, the Xi particle. Their goal is to study the properties of the Xi particle, and in particular, the nuclear potential of the Xi hypernucleus.



K1.8 beamline	Phase-II (750kW)	Phase-I (270kW)
Length [m]	45.853	
Acceptance [msr %]	1.4	
K⁻ intensity (FF) @1.8GeV/c	6.6x10⁶	1.4x10⁶
@1.5GeV/c	2.7x10⁶	5.4x10⁵
@1.1GeV/c [ppp]	3.8x10⁵	8.0x10⁴

At the J-PARC Hadron Facility, an intense proton beam produces kaons, which are analyzed at the beam analyzer. The kaon beam then hits the nucleus target sitting before the superconducting kaon spectrometer (SKS) to produce hypernuclei.



The internal structure of neutron star is still a mystery.

The main objective of the high-resolution hypernuclear spectroscopy at J-PARC is to make the first clean observation of the energy states of a Xi hypernucleus. The team will shoot kaons—mesons with an *s* quark—into atoms of carbon-12 to create a Beryllium-Xi hypernucleus, and then study the Xi-nucleon interactions. “We don’t know if the Xi-nucleon interaction will be repulsive or attractive,” says Takahashi. “From the results of this experiment, we will be able to infer some interesting information about the physics of neutron stars.”

Could there be Xi hyperons inside neutron stars?

A neutron star is a dense star composed almost entirely of neutrons. However, the Fermi exclusion principle of quantum mechanics states that no two fermions with the same quantum state can occupy the same space at the same time. Since neutrons are fermions, the exclusion principle applies to the neutrons within neutron stars, and means that neutrons cannot be packed more densely than a threshold value. Then, it becomes hard to explain the high density of the star. Neutron stars generally are 10^{14} times more dense than our Sun. Neutrons alone cannot explain the density.

One explanation for the observed density of neutron stars is that a small amount of particles other than neutrons—protons, in particular—may also be present in the neutron star because the exclusion principle on neutron does not apply to protons. Protons have positive charge, so neutron stars also need as many negatively charged particles to neutralize the proton charges.

“If the interaction between a negatively charged Xi particle and a nucleon is found to be attractive rather than repulsive, the Xi would be an ideal candidate for the negatively charged particles inside neutron stars,” says Takahashi. Another negative hyperon, Sigma, is already known to interact with nucleons repulsively. Thus, among the possible set of negatively charged hyperons, the negatively charged Xi is the last possible explanation for the properties of neutron stars.

Creating a neutron-rich environment

In nature, stable atomic nuclei are generally composed of similar numbers of protons and neutrons. If the number of neutrons is increased by one, it is more natural to have one more proton in the same nucleus. Therefore, it is hard to produce nuclei with vastly different numbers of nucleons.

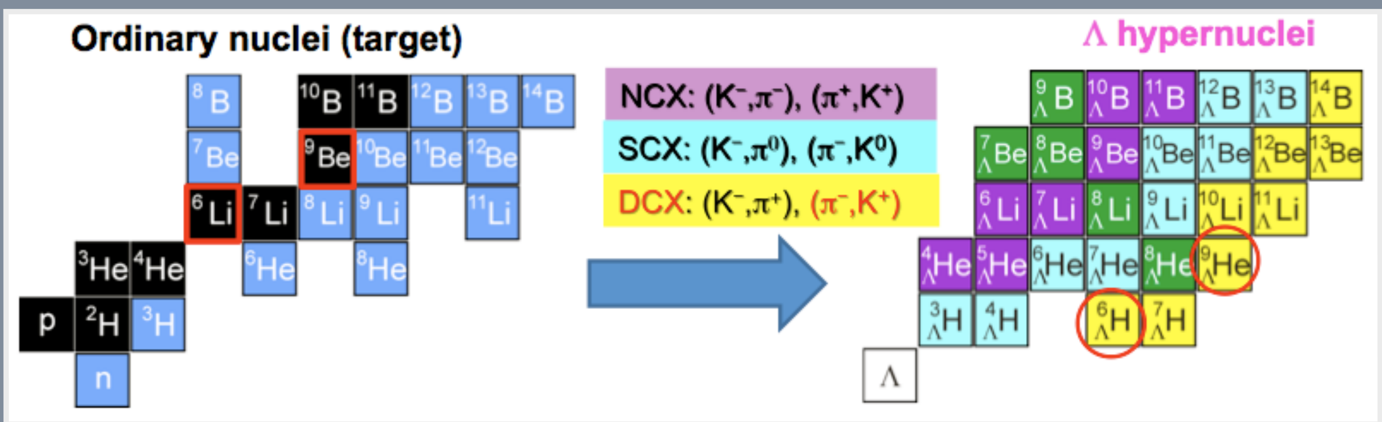
“Thus far, we have looked at the characteristics of hyperons in nuclei where the number of protons is similar to the number of neutrons. However, the physical properties of hyperons might be different in nuclei where, for example, neutrons exist more abundantly than protons,” says Takahashi. “To study systems like neutron stars, it may be necessary to study hyperons in neutron-rich environments.”

Most of the experimental proposals for J-PARC's hadron spectroscopy beamline involve the high-intensity kaon beam. Right now, the beam power at J-PARC is only about one to two kilowatts, a tenth of the designed full power. At this power, a sufficient amount of kaons cannot be produced. However, the number of pions that are produced at the same time is sufficient to conduct experiments, because pions are much lighter and a thousand times more probable to be produced than kaons. Physicists could use the many pions to study Lambda hyperons in a neutron-rich environment.

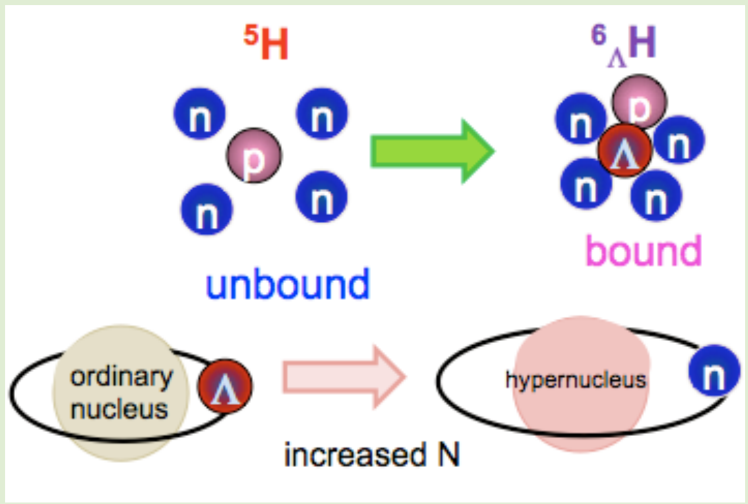
For example, bombarding boron atoms with pions will produce a lithium-Lambda hypernucleus with six neutrons and three protons. “We already know that a Lambda hyperon can act as glue when placed in a neutron-rich environment, bringing unbound nucleons closer to each other,” explains Takahashi. “This experiment could also have important implications for the physics of neutron stars.”

The search for the pentaquark

The pentaquark is a hypothetical hadron containing four quarks and one antiquark. Its existence is still controversial, due to the large amount of error in the analyses which predict the particle. At the J-PARC Hadron Facility,



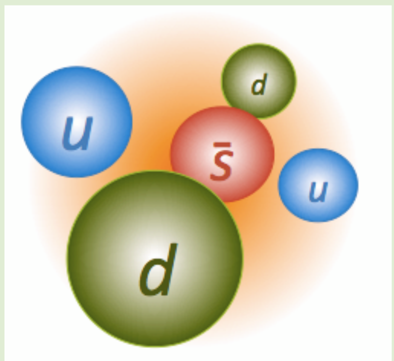
With an intense pion beam, neutron-rich Lambda hypernuclei can be produced from the collision between pions and the nuclei of ordinary atoms.



Top: Lambda particles exhibit a glue-like characteristic, binding nucleons close together. An added Lambda particle binds the unbound 5-H nucleus to become a 6-Lambda-H. Bottom: The structure of hypernuclei may be different when the number of neutrons is increased. In an ordinary hypernucleus, where the number of neutrons is similar to the number of protons, the structure is well described as a system in which a Lambda particle orbiting around ordinary nucleus. In neutron-rich hypernuclei, the picture may change. In such case, neutrons may appear orbiting around a hypernucleus.

however, the search for the pentaquark will be one of the most promising experiments. Physicists believe that a collision between protons and negative pions could produce negative kaons and pentaquarks.

The key to the experiment is the high-resolution detector at the K1.8 beamline. “In the past, we used a detector with poor resolution, and CH_2



A pentaquark, the existence of which is still controversial.

as the target. Unfortunately, the carbon atom contributed as background in the resulting spectrum. This time, we will use a hydrogen only target to get an improved spectrum,” says Takahashi. “With the improved detector resolution, we might be able to find the pentaquark if it exists.”

The world’s highest resolution meson beam detector

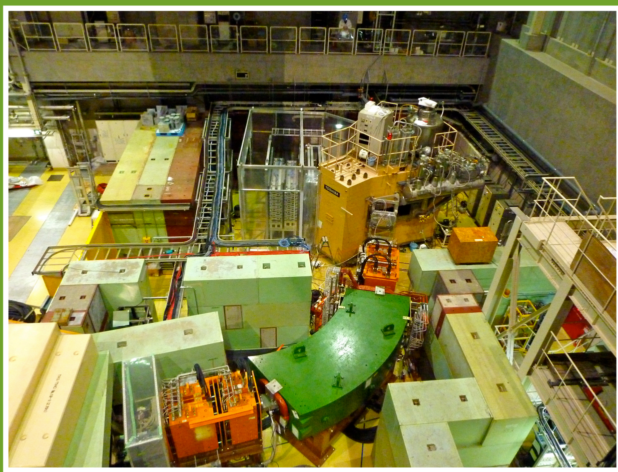
Superconducting kaon spectrometer (SKS) has a trapezoidal superconducting magnet, sandwiched between two sets of two wire chambers. The upstream wire chambers measures the initial trajectory of particles travelling along the beamline. One measures particle positions, and the other measures particle directions. The trajectories of charged particles are then bent in a strong magnetic field of 2.5 Tesla, before being measured again in the downstream wire chambers. From the difference in the upstream and downstream measurements, users can calculate energy of the particles in the beamline. The SKS detector can measure a wide range of trajectory angles from minus 20 degrees to plus 20 degrees from the beam center.

The combination of the high intensity beam, the superconducting magnet, and the finely spaced wire chambers produces an energy spectrum with high-resolution (just 2-3 MeV). The high intensity beam produces particles at the rate of 10^6 to 10^7 particles per second. The superconducting magnet creates the strong magnetic field in a relatively large volume, a gap as wide as 50 centimeters, which allows for the large solid angle required by the system.

The best place to search for exotic particles

The K1.8 experimental group of 10 staff and 20 students from 6 Japanese universities and 2 Japanese research organizations is getting ready for the fall run this October. They are currently analyzing the data from the first beam last year and using this to readjust the detector system. They are also preparing for the analysis of this year's data, improving the detector resolution and completing analysis methods for the high rate signals.

“We are planning for many experiments this year, making the beamline schedule very tight,” says Takahashi. Current proposals come from Italy, Japan, Korea, Russia, and the US. “J-PARC is currently the only hadron facility that can produce a kaon beam, and is the world’s best place to explore the physics of the two-s quark hadron, Xi.” The team’s hope is to construct a complete high-resolution hadron spectroscopy system, and to use it to make new discoveries in the field of exotic hadrons.



The K1.8 beamline and the superconducting kaon spectrometer (SKS) are getting ready for the fall run this year.

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