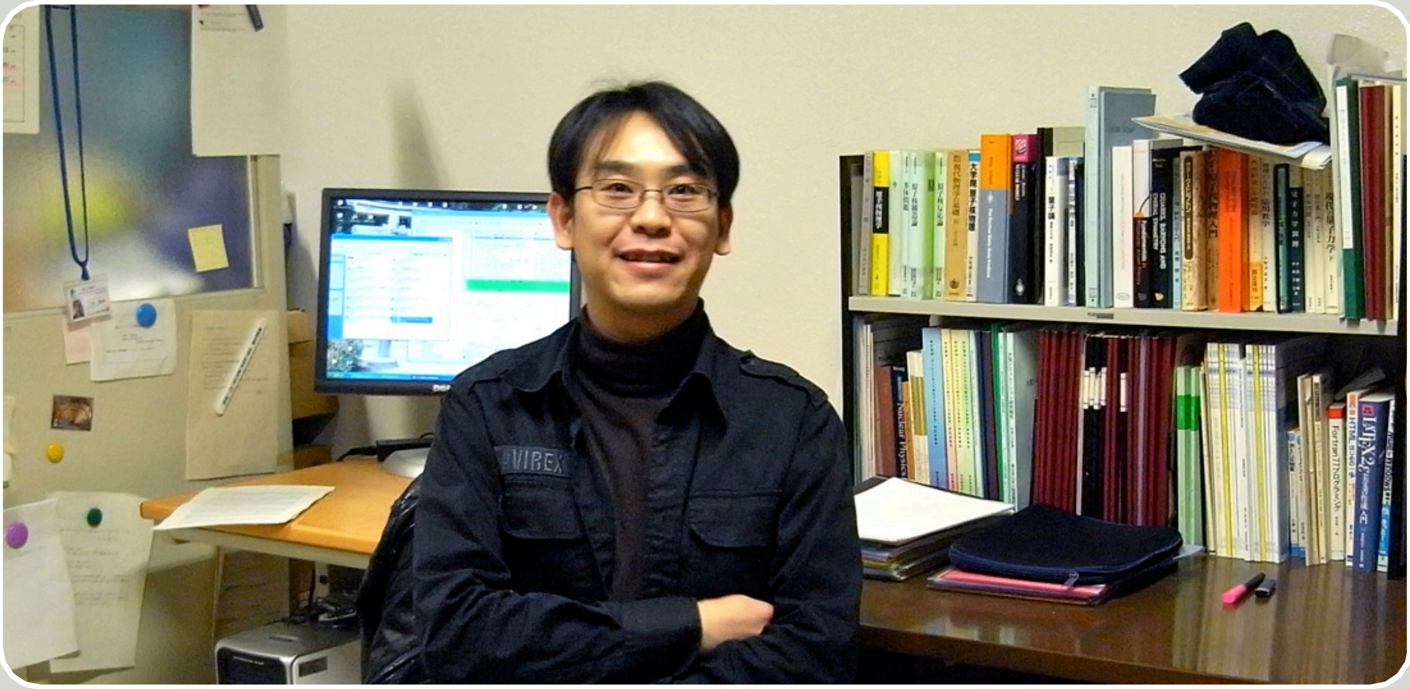
February 2, 2010

FEATURE STORY



Dr. Akinobu Dote, a member of the Hadron Nucleus Group at the KEK Theory Center. Dote studies hadrons that contain strange quarks.

A spice of strangeness

[Hadron Theory, Strangeness, Kaonic Nuclei]

Understanding hadrons is key to understanding the evolution of our universe and the nature of many of the exotic objects it contains. A theoretical hadron physicist from KEK's Theory Center has been pursuing the physics of nuclei that include quarks called 'strange'.

Our universe is filled with exotic objects that we don't currently understand. For example, a supernova remnant called neutron star is believed to have a very dense core from their gravitational compression. The density exceeds the maximum density thought possible inside nucleus, and the mechanism of such dense core offers theoretical hadron physicists interesting topics to explore. Rather unusual nuclei, called kaonic nuclei, have stirred up a decade long debate over dense nuclei.

An atom is composed of a dense central nucleus and a diffuse cloud of electrons that orbit around it. Inside of a normal nucleus are protons and neutrons, collectively called nucleons. Different combinations of those two nucleons create the many different types of atoms and isotopes, which form the matter of everyday life. However, there is more to this story, as physicists have found that the nucleons are themselves composed of even smaller elementary particles, called quarks.

The two nucleons are both composed of three quarks. A proton contains two up quarks and one down quark, while a neutron contains one up quark and two down quarks. In short, the atoms of ordinary matter that we see around us are all composed of up quarks and down quarks. In the Standard Model of particle physics, however, physicists have found six types of quark: up and down, charm and strange, and top and bottom. Each of these six types also has an antiparticle: anti-up, anti-down, anti-charm etc.

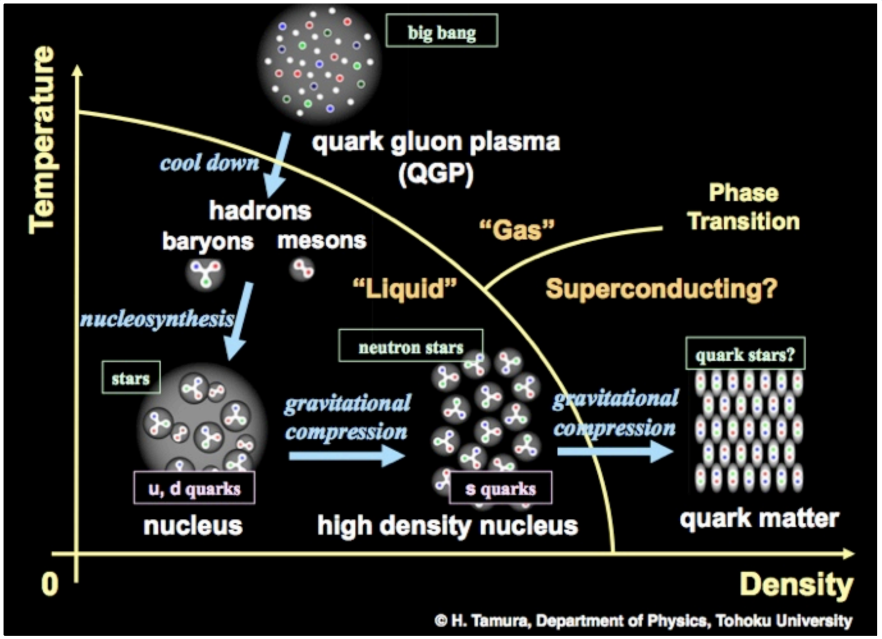
Since the heavier quarks decay quickly into lighter ones, our universe currently consists of only the lighter ones, the up and down quarks. Yet other quarks can exist in dense, high temperature environments, such as those produced in the high energy accelerators at KEK.

Hadrons are those particles that are composed of quarks. quark-antiquark hadrons are called mesons, while three-quark hadrons are called baryons (so nucleons are baryons).

Hadrogenesis

When our universe started out with the big bang, it was a hot, dense fireball. Quarks and gluons were unbound, and could race through the rapidly expanding space. This state of matter is called a quark-gluon plasma. As the universe expanded, it underwent rapid cooling process, accompanied by a phase transition called Chiral symmetry breaking. The symmetry breaking is the reason why matter has mass. Just 10^{-6} seconds after the big bang, the universe had cooled enough that quarks and gluons began to stick together, forming baryons and mesons and their antiparticles: antibaryons and antimesons.

One second later, the temperature and density had decreased enough that hadrons and electrons could meet their antiparticle counterparts and annihilate, giving out energy. The cancellation of particles and antiparticles occurred at an enormous scale, because there were exactly equal numbers of each. However, some diminutive differences in their properties between particles and antiparticles—the complete picture of the differences is still a mystery for us—left just enough matter behind to eventually form stars and galaxies, and us human beings.



The quark-gluon plasma in the early universe underwent a phase transition from gas to liquid to produce hadrons. These hadrons, made of up and down quarks, are the building blocks of matter in our present universe. When gravitationally compressed, heavier quarks, particularly strange quarks, might play a crucial role in the neutron stars and even denser objects. (Image credit: Prof. Hirokazu Tamura, Tohoku University)

A few minutes into its existence, the universe had quieted to relatively calm state, with a temperature of a mere one billion Kelvin and a density of atmosphere. At this time, nucleons began to stick together to form nuclei. (FYI, the current temperature of the universe is 2.7 Kelvin and the density is 10^{-26} of atmospheric density). This phase of the universe is called neucleosynthesis.

In the present universe, neutron stars that have a very dense core are also a topic hadron physics might answer. The core density is expected to be much greater than the nuclear saturation density (the density of nucleons in stable nuclei: normal nuclear density) of 0.17 nucleon per cubic femtometer. Hadron physics can explain the mechanism which allows such dense cores, and the internal structure of neutron stars is currently a hot debate.

Hadron physicists are currently probing such questions about the universe. Dr. Akinobu Dote of KEK is one such physicist, who is fascinated by unexpected phenomena and unconventional physics. He works on theoretical studies of rather unusual nuclei, called kaonic nuclei.

Kaonic nuclei

The most pronounced difference between particle physics and hadron physics is that particle physics studies interactions, between just one or two individual particles, while hadron physics deals with interacting many-body systems.

"Just because we know what would be discussed between two people does not imply we know what will happen when we bring many into a group. New ideas might pop up that might not have otherwise," says Dote. "The same thing happens in physics. We might see entirely new phenomena in many-body systems that we would not have expected by simply looking at few-particle interactions." The basic particle interactions are well understood, but it is extremely difficult to solve many-body systems. That does not stop Dote from exploring the strangeness of physics.

Dote's main interest has been in nuclei that contain a strange quark. One way of creating such nuclei is by bombarding ordinary nuclei with anti-kaons (K^- mesons): mesons composed of one anti-up quark and one strange quark. Nuclei that contain kaons are called kaonic nuclei.

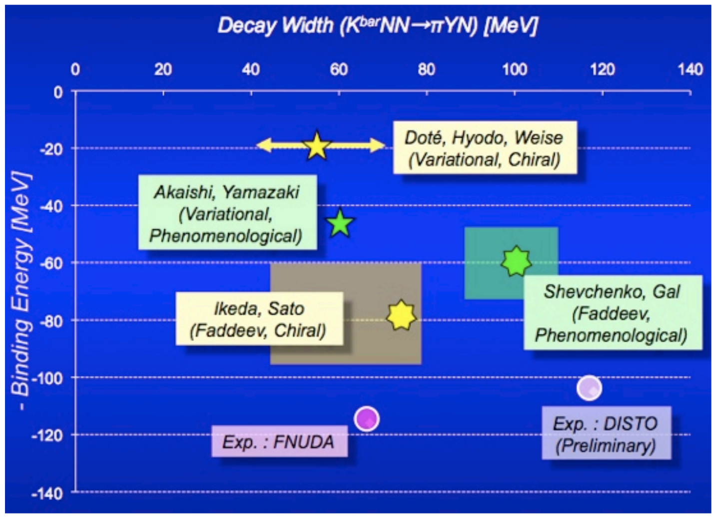
As a meson that contains a strange quark is called kaon, a baryon that contains one or more strange quarks is called hyperon. Nuclei that contain hyperon are called hypernucleus.

Bound to be exotic

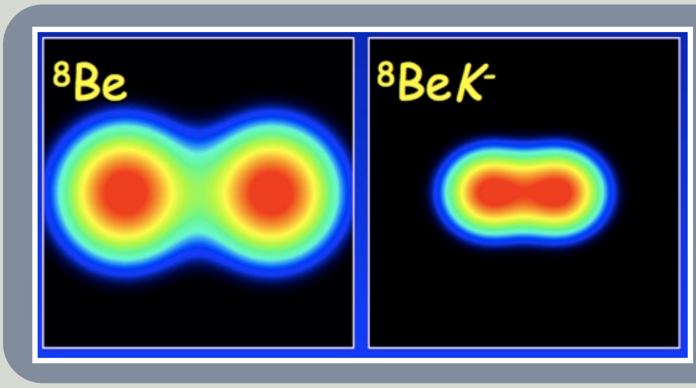
The story of kaonic nuclei starts out with an empirical study of kaonic nuclei published by Prof. Yoshinori Akaishi (then at KEK) and Prof. Toshimitsu Yamazaki (then at University of Tokyo) in 2002.

To model a kaonic nucleus, the two turned to previously obtained experimental results from three systems that contained K^- mesons; a kaonic hydrogen atom (an atom of hydrogen where the electron had been replaced with a K^- meson), scattering of K^- mesons off nucleons, and an excited hyperon called Lambda(1405) interpreted as a bound state of K^- meson and a proton. The combined results had pointed to the conclusion that K^- mesons and protons attracted one another via the strong force. From these empirical results, they have constructed an effective potential in the kaonic nucleus.

Akaishi and Yamazaki first applied their theory to a nucleus called $^3HeK^-$, which is composed of two protons, one neutron, and one K^- meson. A ^3He nucleus and a K^- meson which are not bound to each other are unstable. The



The theoretical calculations of *K^-pp* by various groups show a broad range of predictions in the binding energy and the decay width. None has met the experimental results.



Beryllium-8 has a two helium-4 cluster structure. When a kaon (K$^-$meson) is thrown in, empirical studies predict it will attract the nucleons in the two clusters, bringing them closer together and forming a smaller, higher-density cluster.

system quickly decays into a proton, a neutron, and a pair of hadrons (one pion and one Sigma particle), a state 100 MeV lower level.

A ^{3}HeK$^-$ nucleus, the bound state of a K$^-$ meson and a ^{3}He, should also decay into a proton, a neutron, a pion and a Sigma particle. However, when they are bound, binding energy takes up some amount of energy of the system, bringing the energy level down.

The peculiar thing they found was that, when bound to the ^{3}He nucleus, the K$^-$meson attracts the three nucleons of ^{3}He nucleus so strongly that the binding energy could be greater than 100 MeV. This means that the ^{3}HeK$^-$ system resides in an energy level below the energy of the decay particles and so cannot immediately decay. Therefore, Akaishi and Yamazaki concluded that ^{3}HeK$^-$ should be long-lived. In addition, the decay width—quantum mechanical uncertainty of decaying energy due to the finite lifetime of the system—is at around 20 MeV, narrow enough that the decay peak should be experimentally measurable in 100 MeV sea of decay spectrum.

The deeply bound kaonic nucleus intrigued other hadron physicists including Dote. Dote and his colleagues launched into a systematic study of various other light kaonic nuclei with Akaishi and Yamazaki, using the empirical potential as well as some additional techniques which could be used to calculate nuclear structure.

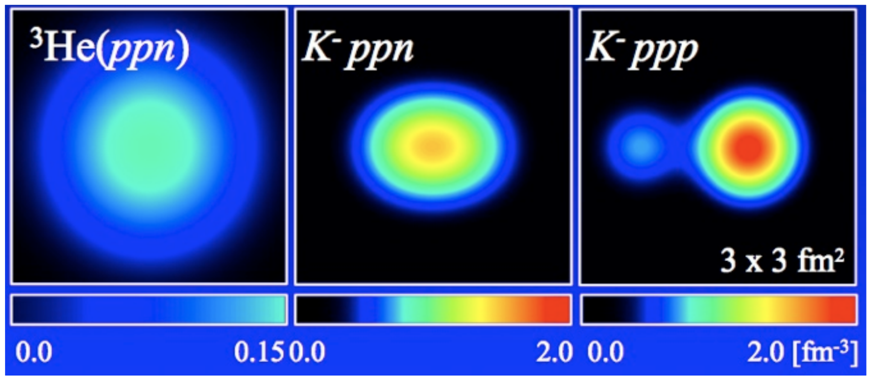
The first interesting result involved beryllium. The nucleus of beryllium-8 contains 4 protons and 4 neutrons which are split into two distinct clusters, each with 2 protons and 2 neutrons (namely ^{4}He, or an alpha particle). When a K$^-$ meson was injected into the system, their calculations predicted a change in the structure. The kaon attracts other nucleons so strongly that two clusters merge together to form a single oval shaped cluster. Binding energy was calculated to be 104 MeV, and the decay width 40 MeV. The deeply bound nuclei should be distinguishable in experiments.

This result had deeper implications; with the nucleons so close together, the density of the nucleus grew. The average density of the kaonic beryllium-8 was calculated to be twice the saturation density for a nucleus, and the maximum density of this nucleus was even larger than four times the saturation density.

Another interesting finding was in a three-proton system. The strong force between a K$^-$ meson and the three-protons work so strongly, pulling them close together. However, the Pauli exclusion principle in quantum mechanics states that two protons cannot occupy the same state at the same time and space. Proton has a quantum state called spin which has two possible states, up and down. So two of the three protons can have two different quantum states and are able to coexist simultaneously. Because of this, the two protons were pulled close by the K$^-$ meson, and the third proton orbited around them.

Binding speculations

These results brought great excitement to the hadron physics community. Could this be the mechanism that explains the dense core of the neutron stars? Accelerators around the world launched experiments to look for the binding energy spectrum in kaonic nuclei. KEK in Japan, LNF-INFN in Italy, GSI in Germany, and BNL in the US all found interesting results but few were to be definitive. Some results were not reproducible, and others had large statistical uncertainty.



A two-proton, one-neutron system and a three-proton system behave differently when a K$^-$ meson is thrown in. This is because of the Pauli exclusion principle in quantum mechanics, which says no two fermions (such as protons) can be in the same state at the same space and time. For spin up and down protons, two protons are attracted strongly by the presence of a K$^-$ meson, and the third proton orbits around the *K$^-$pp* system (left).

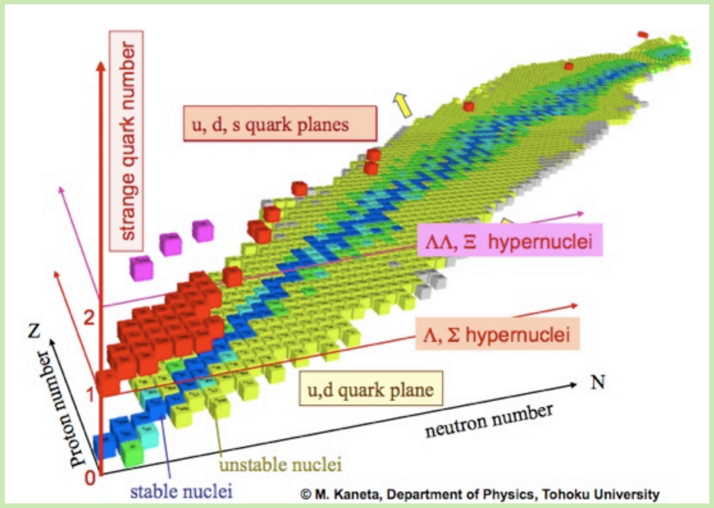
In the midst of these experimental uncertainties, strange hadronists decided to go back to the basics. They thought it more important to understand the simplest kaonic nucleus than to explore complex ones. In particular, the experimental result on two protons and a kaon system, *K$^-$pp*, produced at LNF-INFN was the one reliable data that it was worthwhile to explore.

There were many techniques available to model a kaonic nucleus system. There were also controversies over the way interactions in the nuclei were modeled. “It had been pointed out on various occasions that the empirical potential which we used was not consistent with the theoretically-driven potential,” says Dote.

In hadron theory, calculations need to take into account every possible contribution from participating bodies, and these contributions are many. For example, in a two particle system of a K$^-$meson and a nucleon, researchers needed to consider the odd-seeming possibility of those particles changing themselves into a pion and Sigma particle, and then reverting back to the original K$^-$ meson and nucleon pair. In the empirical potential, the self-interaction of the pion-Sigma particle pair, a possibly significant contribution, was ignored.

An issue with the approximation technique was also pointed out. As nucleons come very close to each other, they start experiencing a strong repulsive force. Conventional models smoothed this short-range repulsive potential, using a method called G-matrix. This would not have affected the calculation if the nucleons were at a normal distance, but it seemed likely to be important if the nucleons were brought unusually close together by the K$^-$ meson.

Dote decided to work on the problem with a physicist from the Technical University of Munich, Prof. Wolfram Weise. Weise proposed to utilize a theoretically based potential called the Chiral unitary model. They also avoided the small distance approximation by changing their technique to something called the variational method. This is a technique to find



Nuclei with various neutron numbers and proton numbers have been explored throughout last century (yellow, blue, and green). Now exploration of another dimension, strange quark number, is beginning. (Image credit: Dr. Masshi Kaneta, Tohoku University)

Experiments on kaonic nuclei are planned at the Japan Proton Accelerator Complex (J-PARC).

the minimum energy state of a system by varying the parameters of a trial wave function that can handle the short-range repulsive potential between nucleons properly.

Their findings were less sensational. With the binding energy of 20 MeV and a decay width of 40 to 70 MeV, the nuclei with two protons and a kaon would be unstable if ever observable. The nucleon's distance was at around 2.2 femtometers (10^{-15} meters), as would be in ordinary nucleus, meaning that the saturation density of nucleons would be unaffected.

"However, the variational technique with the empirical potential still gives a large binding energy," says Dote. Including Dote's result (the lowest) the range of predicted binding energies runs from 20 MeV to 100 MeV, none of them really in agreement with experimental results. "None of the results of our theoretical studies are final yet. There are multitudes of uncertainties, but that is why it is interesting."

The Lambda(1405) debate

One particularly interesting result of Dote's study was that using the variational method, they were able to model the distribution of a K^- meson-proton pair inside a K^-pp, which came out to be very close to that of a Lambda(1405) particle.

"The discrepancies between the empirical potential and the Chiral potential had been an issue with us," says Dote. "Now we know the discrepancies stem from different ways of interpreting the Lambda(1405) particle."

In the empirical potential, the Lambda(1405) particle is considered a bound state of a proton and a K^- meson with a binding energy of 27 MeV. However, the theoretically based Chiral potential has a different interpretation. In experiments, the energy of 27 MeV actually is obtained by measuring the energy of a pion and a Sigma particle, the decay products of Lambda(1405). In hadron theory, physicists can use this known contribution of the pion and Sigma pair to compute the contributions of a kaon and a nucleon interaction. Then, they can look for the theoretical binding energy of Lambda(1405)—a bound state of a K^- meson and a nucleon. The calculation found that the theoretical binding energy was 15 MeV, a little more than half that predicted by the empirical model.

Black or white

The resolution of this discrepancy will come from a pair of experiments planned at the Japan Proton Accelerator Research Complex, J-PARC. The two experiments, E17 and E15, will look at kaons' behavior in kaonic atom and in kaonic nuclei, respectively.

The E17 experiment will produce kaonic ^{3}He atoms—a K^-meson replacing one of the electrons in a ^{3}He atom. Because the well-understood and simple force, electromagnetic force binds the K^- meson in the system, observation of a slight deviation from the expected force potential can induce strong force between the K^- meson and nucleons. The experiment will be already starting this year.

The other experiment, E15, will produce and directly look at kaonic nuclei. The experiment will create a system of two protons and one K^- meson, K^-pp, by bombarding ^{3}He (2 protons and 1 neutron) with K^- mesons. The idea is to knockout the neutron and replace it with a K^- meson. The kaonic nuclei will immediately decay, but the details of the decay will provide important information. Specifically, researchers will not only measure the energies of the decay products, but also of the neutrons knocked out. "This will be a 'perfect' experiment, meaning that we will be making a complete observation of every participating particle," says Dote. "The experiment will hopefully provide us with critical data for the kaonic nuclei systems."

Dote is currently working on some possible improvements to his theoretical method for modeling kaonic nuclei. He is also studying physics of hypernucleus with his colleagues from Hokkaido University by throwing hyperons, instead of kaons, in a nucleus. "Hypernucleus is a comparatively well-established branch of physics, while the physics of kaonic nuclei is still new," says Dote. "We are excited by the possibility that the density of kaonic nuclei can really exceed the nuclear saturation density. This would have broad implications." He says that the high density and high temperature can restore the broken Chiral symmetry to explore the extremely early universe. Technologically, the high temperature condition is achievable, but the high-density condition required for such extreme physics had been thought not feasible.

"With strangeness, we might see things we don't expect from the conventional hadron and nuclear physics," says Dote. "Strangeness is now another dimension for us to explore in nuclear science, adding a new third dimension to the previous two dimensions of proton number and neutron number."

Related Link:
Hadron, Nuclear, and Quantum Field Theory Group

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