【Grant-in-Aid for Scientific Research (S)】

New Developments Toward Elucidation of Kaonic Nuclei

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Project Information	Project Number : 24H00029 — Project Period (FY) : 2024-2028 Keywords : accelerator experiment, anti-K meson, new form of nuclei, quantum chromodynamics (QCD), quantum many-body system

Purpose and Background of the Research

●Outline of the Research

Our ultimate goal is to understand "the origin and evolution of matter," *i.e.,* how the matter around us is created from elementary particles, quarks, and how it leads to the final form of matter, the neutron star, which is considered to be a "giant nucleus." To unravel these mysteries of matter produced by quantum chromodynamics (QCD), a wide variety of research is being conducted on different scales of time, space, and energy.

In this research, we will use completely new atomic nuclei, "kaonic nuclei," that are made up of protons and neutrons (called nucleons) and embedded with an anti-K meson made up of a quark and an antiquark - essentially a particle that can only be created by accelerators. Using kaonic nuclei, we will take a new approach to solving the mysteries of the origin and evolution of matter. In kaonic nuclei, new physical properties such as changes in meson mass and increases in nuclear density are expected to emarge due to the extremely strong interaction between an anti-K meson and a nucleon. By systematically and quantitatively understanding these phenomena, we will attempt to unravel the quantum many-body system governed by QCD (Figure 1).

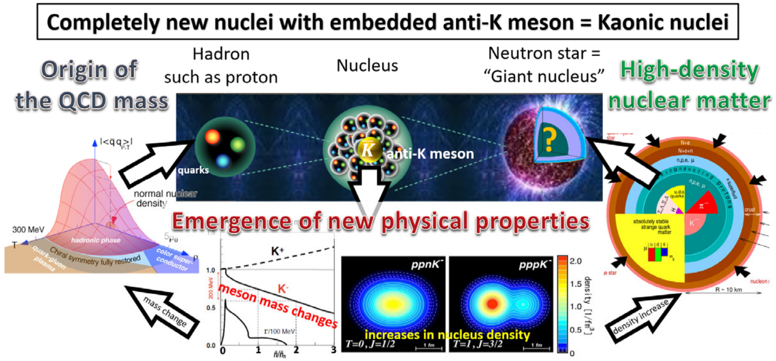

Figure 1. Image of the entire research

●Aim of systematic research on kaonic nuclei

We have discovered the "K-pp" bound state, in which two protons (p) and one anti-K meson (K^-) are bound, at J-PARC. The obtained result suggests that the "K^-pp" bound state may be a compact and dense state, and more detailed and systematic results are awaited.

In this research, we will further investigate kaonic nuclei. Specifically, we will increase the number of protons and neutrons in kaonic nuclei and extract in detail the properties that depend on the number of nucleons. In this way, we will clarify the fundamental properties of kaonic nuclei. We aim to establish a completely new picture of nuclei containing an anti-K meson and to explore various unknown physical properties produced by interactions between hadrons, a complex of quarks.

●High-intensity anti-K meson beam + Large detector + Detailed theoretical calculation

Comprehensive measurements of kaonic nuclei will be conducted using the world's most intense K^- beam at J-PARC and a large superconducting solenoid spectrometer (Figure 2) to be newly constructed at the Hadron Experimental Facility. The spectrometer is currently under construction, and the experiment is scheduled to start in FY2026.

In addition, we will systematically compare the nucleon number dependence of mass spectra, binding energies, decay branching ratios, etc., obtained from experiments with detailed theoretical calculations to elucidate the internal structure of kaonic nuclei.

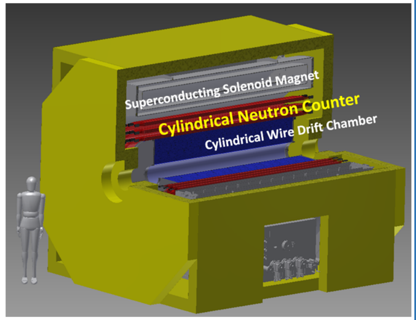

Figure 2. Large superconducting solenoid spectrometer

Expected Research Achievements

● Establishment of the "K^-ppn" and "K^-ppnn" bound states of kaonic nuclei

As shown in Figure 3, a K^- beam, an anti-K meson, is irradiated onto a helium-4 target, and a neutron in the target is knocked forward like a billiard. The "K^-ppn" bound state is then produced. The "K^-ppn" bound state is identified by measuring and reconstructing the decay to a lambda particle and a deuteron. Decays involving three or more particles, such as a lambda, proton, and neutron, are also measured. In addition, we irradiate a lithium-6 target with a K^- beam and produce the "K^-ppnn" bound state by knocking out a deuteron.

In this way, we will establish the existence of the "K^-ppn" and "K^-ppnn" bound states. By integrating the results of this research with those of our previous studies, we will derive experimentally for the first time the nucleon number dependence of kaonic nuclei with nucleon numbers from 2 to 4 (Figure 4).

● Elucidation of the internal structure of kaonic nuclei

Based on the experimental results, we theoretically clarify the details of kaonic nuclei.

① Construct precise optical potentials in systems consisting of an anti-K meson and nuclei based on chiral dynamics and predict these internal structures.

② Derive the theoretical mass spectra to be measured in the experiments by reaction calculations with the actual experimental setups.

③ Systematically compare the experimental and theoretical results.

Thus, we will elucidate the internal structure of the kaonic nuclei, such as spatial size and density.

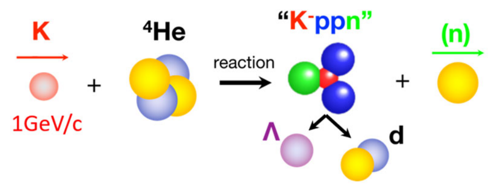

Figure 3. Conceptual diagram of "K^-ppn" bound state formation and decay reaction

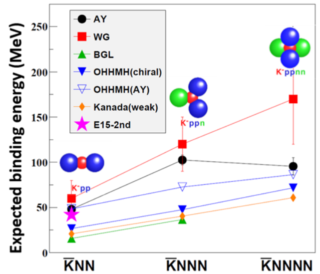

Figure 4. Theoretically predicted dependence of binding energy on the number of nucleons

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