Letter of Intent for the Systematic Study of the Kaonic Nuclear Bound States at K1.8BR in J-PARC Hadron Hall

M. Iwasaki[a], H. Ohnishi[b], H. Noumi[c], K. Ozawa[d], T. Hashimoto[e], C. Curceanu[f], J. Zmeskal[g], E. Widmann[g], F. Sakuma[a] and T. Yamaga[a]

(a) *RIKEN Nishina Center, RIKEN, Saitama, 351-0198, Japan*

(b) *Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai, 982-0826, Japan*

(c) *Research Center for Nuclear Physics (RCNP), Osaka University, Osaka, 567-0047, Japan*

(d) *High Energy Accelerator Research Organization (KEK), Ibaraki, 305-0801, Japan*

(e) *ASRC, Japan Atomic Energy Agency, Ibaraki, 319-1195, Japan*

(f) *Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy*

(g) *Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria*

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Abstract

We observed a nucleus consisting of K^- meson and two protons, "K^-pp", at the J-PARC. The binding energy is as large as ~ 50 MeV, which is much deeper than the standard nuclear binding energy, and the width is ~ 100 MeV. Simple momentum transfer analysis based on PWIA is indicating that the size of "K^-pp" could be as small as ~ 0.5 fm. Thus, based on the scientific case raised by E15 data and its impact in understanding the K-meson mediated quasi-stable systems tightly bound by strong interaction, we propose to perform dedicated and systematic experimental studies of Kaonic Nuclear Bound States, for which a new spectrometer system is required.

1 Introduction

As it is well known, the matter around us is composed of leptons and quarks (fermions). Gauge-bosons, photon and gluons, form fields around those fermions due to fermion's charge and color-charge. The virtual-photon exchanging field is called Coulomb field, and by this field, electrons and nuclei form atomic systems. In the case of gluon exchange, it forms gluon field around color-charge, and "quark composite particles", hadrons, are formed by exchanging gluons, but the situation is more complicated.

Every quark has three different "color-charges", and only the "color-less" quark combination is allowed. It is called the "color-confinement" in the quantum chromodynamics (QCD). Hadron is categorized into two sub-groups: Baryons (consist of three-quarks qqq) such as proton and neutron, and mesons (consist of an anti-quark and a quark $\bar{q}q$) such as pions and kaons. In a baryon, the color-less combination is realized by three different color charges ("color-singlet" state), while in a meson, the color-less state is formed between a color-charges of q and a complementary color-charges of $\bar{q}$.

There is a clear hierarchy between quark-hadrons and nuclei. There is no need to describe nuclei directly using quark degrees-of-freedom. This is realized, since the spatial size of the color-confinement of the nucleon (the size of the quark distribution with color charge) is smaller than the inter-nucleon distance in the nucleus, which secures the nucleon can behave as a particle also in nucleus. In general, quark and gluon degrees-of-freedom is hidden in a nucleon by the color-confinement.

However, the particle-like nature of these nucleon is not so strong. If one can increase the nuclear density sufficiently, in which the inter-nucleon distance falls below the color-confinement size, then the quark is released from the color-confinement, where a phase transition to an entirely new "quark matter phase (color superconducting phase)" is expected to be realized. The nucleons are bound in nuclei primary by exchanging "color-less" virtual meson, because the nucleons in nuclei are "color-less". In this sense, the gluon-field is confined in a nucleon (or in a meson) where color-charge is confined. The virtual mesons, which forms a Yukawa-potential around nucleons, behave as a field-particle in nuclei instead of globalized gluon-field.

Then a question arises: Can meson be a real particle even in a nuclear media? In other words, could it be possible to form a meson bound state in a nucleus, whose total mass is below the mass of the meson and the nucleus? Since the mesons are bosons, the Pauli exclusion principle does not work with nucleons, so the wave function of meson and that of nucleon can overlap. A meson has anti-quark as a constituent, so if such a quantum state exist, the spatial distributions of anti-quark and quark should overlap and coexist. Furthermore, as a meson attracts surrounding nucleons, the "colored-quark distributions" in each nucleon could be partially overlapped in between two nucleons. Therefore, mesonic bound states in nuclei are very "weird" quantum states, and the study will give us insight on "how the color is confined in nucleon / nucleus" and "how hierarchical structure is formed in nuclei where hadrons (nucleons and mesons) behave as $\sim$ isolated / independent particles", although all those particles are composed by quarks (and gluons).

There is a more sophisticated and challenging problem in the color-confinement mechanism. It is well known that the mass of the matter can be represented by the sum of the mass of elements, except for the very slight mass shift caused by the binding energy of the elements. Astonishingly, this rather trivial rule does not hold at all for hadrons, *i.e.,* quark-composite particles. For example, the so-called *current quark mass* provided by the Higgs mechanism gives us only ~ 1 % of the proton mass.

The standard scenario to explain the missing hadron mass is the "spontaneous chiral symmetry breaking and resulting scalar boson $\bar{q}q$ condensation in vacuum". In this scenario, the missing hadron mass is dynamically generated by the interaction between hadron and the $\bar{q}q$ condensation, *i.e.,* $\bar{q}q$ bares a role of higgs in QCD. It is believed that the density of the $\bar{q}q$ condensation depends on energy and matter density, so the hadron mass should vary depending on media in which it locates. In order to understand this mechanism specifically and in detail, it is very important to examine the hadrons mass-modification in various media by accumulating observational facts.

If this standard scenario is true, meson in vacuum is already in a media which is consist of quarks and gluons forming $\bar{q}q$ condensation. Thus the existence of a meson bound state in nuclei, where nucleons and virtual mesons exist as a media, is not outrageous, and its property modification in different media must be examined experimentally.

2 Grand Objectives of the Study

One of the most interesting meson, which may form nuclear bound state is $\bar{K}$. The S-wave $\bar{K}N$ interaction has been studied by the atomic level shift of kaonic hydrogen. It is known that the atomic ground state has repulsive shift due to the strongly attractive interaction between K^- and p in $I = 0$ channel, and that is the strong evidence of the nuclear bound state formation further below the atomic levels [1].

Another supporting fact of the existence of kaon bound state in nuclei is the presence of $\Lambda(1405)$ resonance, whose energy locates at ~ 27 MeV below the mass of K^- and proton. Thus, the $\Lambda(1405)$ resonance can be a K^-- p bound state[1] having binding energy of ~ 27 MeV, instead of the conventional three-quark state (excited state of Λ baryon), as illustrated in Fig. 1.

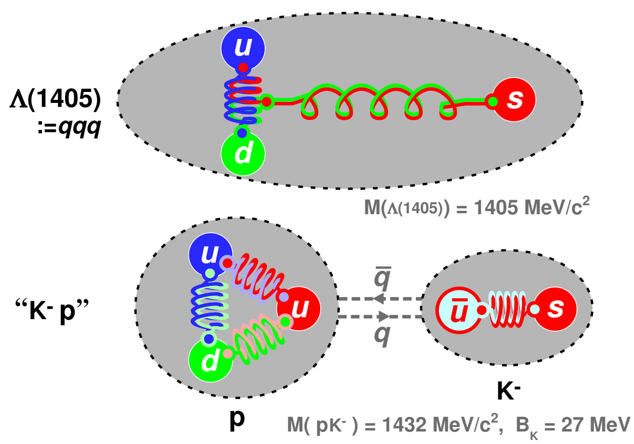

Figure 1: Schematic diagram of $\Lambda(1405)$ as for baryon: qqq (top) and that of nucleon-$\bar{K}$ bound state: "K^-p" (bottom).

The two pictures are inherently different. In the three-quark picture, qqq are bound by exchanging gluons, while in the K^-- p bound state picture, two color-singlet particles, *e.g.* K^- and p, are bound by virtual meson $\bar{q}q$ exchange. However, the two pictures are seamless in a sense, because one can interpret that the stretched s-quark in $\Lambda(1405)$ baryon is "*hadronized*" by

[1]For more exact, it is $\bar{K}$-N bound state in isospin 0 channel. We take charge-representation instead of isospin-representation, for simplicity.

capturing $\bar{u}u$ (in the case of illustrated figure) from $\bar{q}q$ condensation of vacuum, and can convert to K^-- p bound state. A recent lattice QCD calculation is suggesting that the $\Lambda(1405)$ is admixture between qqq and mason-nucleon bound state, but more than 90 % is K^-- p while qqq component stays about few % [2]. Thus, the $\Lambda(1405)$ is *on site of the "hadronization"* of the stretched quark complex.

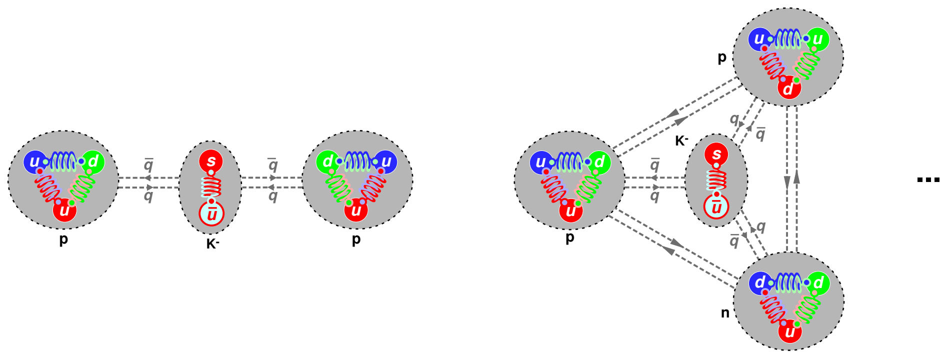

Figure 2: Schematic diagrams of possible kaonic bound states.

If the "K^-- p bound state picture" is more close to the actual object, then one can expect that there are many other kaon bound states in nuclei as shown in Fig. 2. Therefore, we conducted J-PARC E15 experiment to search for "K^-pp" bound state (the simplest kaonic nuclear bound system), and successfully observed the nuclear bound state at $B_K \sim 50$ MeV [3]. The binding energy is about twice bigger than that of "K^-- p bound state", and it seems to be quite consistent with present picture of $\Lambda(1405)$ as it is illustrated in figures 1 and 2, that the kaon bound two protons in "K^-pp".

The binding energy, however, is about 10 times bigger than that of nucleon binding energy in normal nuclei. This fact implies that the large binding energy could be a precursor phenomenon due to the mass modification of hadron in nuclear medium. To approach the standard scenario of the hadron mass generation, we need to study the kaonic nuclear bound states systematically in light nuclear system, to check whether large binding energy could be attributed to *the hadron mass modification in nuclear media*.

There is another extremely interesting experimental observable, that is the momentum transfer to the bound states, because the form factor of the bound state depends on that. If one can approximate the wave function of the kaonic nuclear bound states by a harmonic oscillator model, then the formation yield can be simply proportional to the Gaussian form factor, whose width is inversely proportional to the spatial size of the wave function of the harmonic oscillator.

J-PARC E15 results indicate that the spatial size of "K^-pp" could be as small as $\sim$ 0.5 fm (in radius), if one ignores the angular dependence of the $\bar{K}N \to \bar{K}N$ reaction[2] in the formation process. This is astonishingly small in view of the standard nuclear scale, although we shall admit that the present possible interpretation of the size is based on extremely simplified model, ignoring the reaction dynamics of the formation process. On the other hand, preliminary results of J-PARC E31 is indicating that the spatial size of $\Lambda(1405)$ (or "K^-- p") could be about the half of "K^-pp" in the simple harmonic oscillator model, which is consistent with our picture of these system illustrated in the figures 1 and 2. This means that the inter-nucleon distance of the kaonic nuclear bound states could be below 1 fm, *cf.* Fig. 2. In such a distance, "color-confinement regions" in two nucleons are already partially (but substantially) overlapping in the standard picture of "color-confinement size" of $\sim$ 0.7 fm for a nucleon.

Thus, it is quite important to examine the momentum transfer dependence of the formation yields in other kaonic nuclear bound states to study the dynamics of the color-confinement, although we definitely need to wait for the theoretical development to reach more reliable spatial size (distribution scale) analysis at the same time. By this study, one can have important information on the *"color-confinement regions" of the nucleon.*

3 Systematic Study at J-PARC K1.8BR

We intend to conduct a systematic study of the kaonic bound state on light nuclei, to know the basic properties of the $\bar{K}$ in the nuclear media. For that purpose, J-PARC K1.8BR having the beam-line-spectrometer [4] is the unique place to conduct study of the kaonic nuclear bound states, also it is the only place in the world where intense 1 GeV/c K^- DC beam is available.

The reason, why J-PARC K1.8BR is the unique facility for this study, is rather simple. To generate the kaonic nuclear bound states and to measure those properties, an ideal reaction channel is the exchange reaction between

[2] To evaluate the angular dependence of the reaction dynamics, one need to know the angular distribution of the recoiled virtual-$\bar{K}$, where it is not experimentally accessible.

kaon and nucleon at K^- momentum 1 GeV/c, as it was successfully applied in E15. The elastic $\bar{K}N \to \bar{K}N$ reaction channel, which is the source of low momentum virtual-$\bar{K}$ to form kaonic nuclear bound states, has the maximum cross section at 1 GeV/c [5]. The signal of kaonic nuclear bound states can be kinematically separated from spurious spectroscopic structure caused by multi-nucleon absorption processes at this incident momentum. On the other hand, kaon absorption at-rest produces very large backgrounds caused by multi-nucleon absorption processes, which are severely overlapping with the signal, in contrast to the in-flight reaction.

Moreover, it is obvious that the K^- is involved in the reaction, if we use K^- as the incident particle. In the other reaction channels using different incident particles, K^+Y/K^0Y reactions (energetically more easy to be formed than K^+K^- in nuclear reaction) become serious background because the hyperon Y can be misinterpreted as a decay particle of kaonic nuclear bound states, although $\bar{K}$ is not involved in the reaction.

3.1 Necessity of the Major upgrade of the CDS

For the systematic study, we definitely need a major upgrade of the cylindrical detector system (CDS) for the further study of the kaonic nuclear bound states, although we succeeded in observing "K^-pp" with present CDS of E15 experiment [4]. The reason is again simple. We wish to study the basic properties of kaonic nuclear bound states, moreover, the mass number A dependence of these properties to realize the global objectives. In this study, as the number of nucleons increases, the number of particles emitted from the decay increases, and the detection efficiency, covering all decayed particles, is the repeated multiplication of the normalized solid-angle. Thus a 4π-detector system with neutron detection capability is a must. In table 1, we summarized the reaction channels of interest and the possible decay channels.

The 4π-detector system is essential for two other reasons. One is to cover the whole kinematically-allowed momentum-transfer region, because the momentum-transfer dependence of the formation yield is sensitive to the spatial size of the bound state. In the case of the E15 experiment, the E15-CDS coverage is limited to $\sim 2\pi$, which covers relatively small momentum-transfer region. This momentum-transfer region is sufficient only to search for "K^-pp" in E15, and insufficient for other kaonic nuclear states. For example, in the case of "K^-p", the preliminary analysis on E31 data is already

Table 1: Reaction channels of interest and the possible decay channels

system	charge state	reaction	decay channels
$\bar{K}N$	K^-p ($\Lambda(1405)$)	$d(K^-,n)$	$(\pi\Sigma)^0$
$\bar{K}NN$	K^-pp K^-pn ($\bar{K}^0nn$)	$^3\mathrm{He}(K^-,n)$ $^3\mathrm{He}(K^-,p)$	YN / $\pi\Sigma N$
$\bar{K}NNN$	K^-ppn K^-pnn ($\bar{K}^0nnn$)	$^4\mathrm{He}(K^-,n)$ $^4\mathrm{He}(K^-,p)$	YNN / Yd / $\pi\Sigma NN$ / $\pi\Sigma d$
$\bar{K}NNNN$	K^-ppnn	$^6\mathrm{Li}(K^-,d)$	$YNNN$ / $\pi\Sigma NNN$ / ...

showing that the E15-CDS do not cover whole region-of-interest range of the momentum-transfer. The "K^-p" signal is extended to the larger momentum-transfer side, where one shall detect $K^- + d \to$ "K^-p" (*forward*) + n (*backward*) events. In the case of "$\bar{K}^0nn$", – isospin partner of "K^-pp" –, the situation is opposite. The proton in the formation reaction $^3\mathrm{He}(K^-,p)$ will be emitted to the forward direction, where E15-CDS do not have efficiency also. It is same for the "$\bar{K}^0nnn$", – isospin partner of "K^-ppp".

The 4π-detector system is also very powerful to suppress the unfavored background contamination substantially. In E15, they primary analyzed "K^-pp"$\to \Lambda p$ decay followed by $\Lambda \to p\pi^-$, because the kinematics can be reconstructed only from charged particles. In that analysis, the final state was identified by the reaction kinematics without observing particle emitted from the formation stage, *i.e.*, N' of $K^-N \to \bar{K}N'$ reaction. By observing the N', one can utilize the redundancy in the reaction kinematics to improve the purity of the event selection of the final state.

It is also very important to have γ-ray detection capability. As shown in the table 1, there are many γ-rays emitted from the decay of kaonic nuclear bound states. If one can detect both neutron and gamma at the same time, one can conduct a detailed study on the decay branch and its dependence on the mass number A.

In fact, the selection of the final state in charge mode is not sufficient in many cases to know the isospin dependence of the reaction / decay. For example, $\Sigma\pi$ pair can be produced from $I = 0, 1$ and 2. Even if we ignore $I = 2$ channel, it is not easy to separate $I = 0$ and 1 channels, while one can naturally assign $I = 0$ for $\Sigma^0\pi^0$ mode.

The γ-ray detection capability also provide a method to discriminate the final state in more convincing manner. For example, Σ^0 is one of the difficult particle to specify. Σ^0 decays 100% to $\gamma\Lambda$ (74 MeV/c), and the γ gives only small kick to Λ. Thus, it is rather difficult to separate from Λ. Therefore, Λpn final state selected in E15 is contaminated by the $\Sigma^0 pn$ final state.

3.2 Conceptual design of the new CDS

As described above, a large acceptance detector system having neutral particle detection capability are strongly desired for the experiment. The conceptual design of the new CDS is as follows.

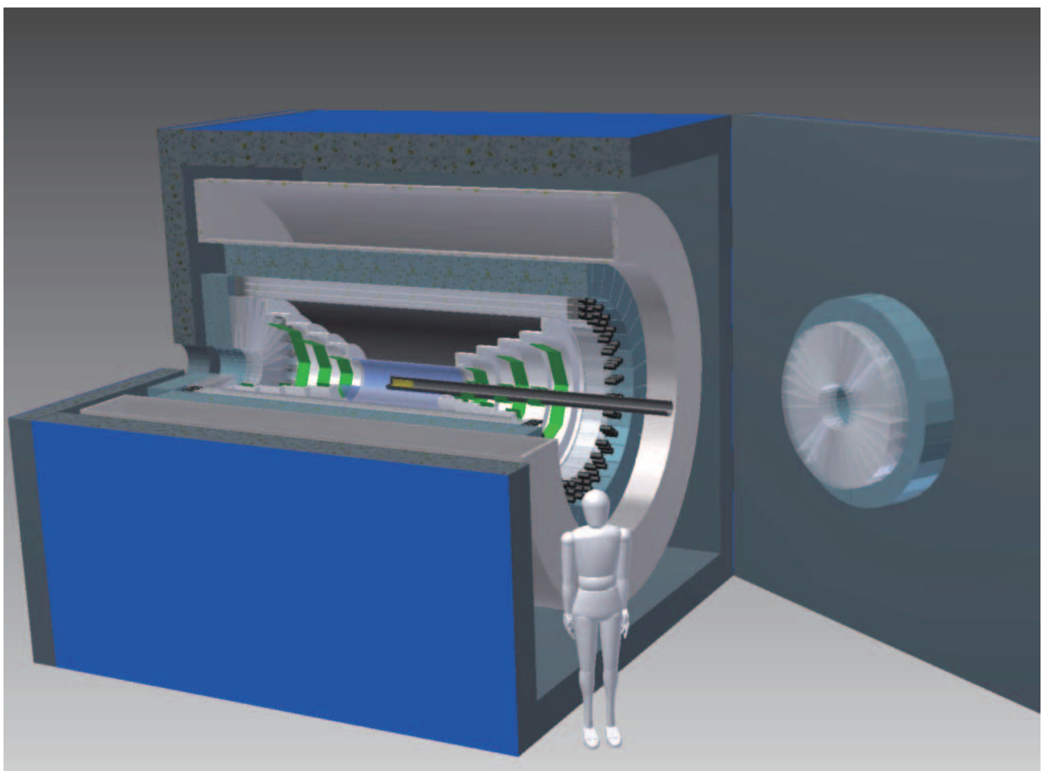

Figure 3: Conceptual design of the new CDS.

Superconducting Solenoid Magnet

The solenoid magnetic field up to 1.0 T is provided by new constructed superconducting solenoid magnet. All of the detectors are installed into the magnet. The design work of the magnet has been already finished by the KEK Cryogenic Science Center.

Cylindrical Drift Chamber
Charged particle from the reaction is traced by the cylindrical drift chamber (CDC). The momentum of a charged particle is calculated from the curvature of its track in the solenoid magnetic field.

Backward and Forward Drift Chambers
A charged particle going to the entrance and the exit of the solenoid magnet is detected by the BDC and FDC which consist of planar drift chambers.

Charged-particle Counter
For the particle identification, a charged particle is detected with thin detector to measure the velocity by means of TOF. The detector is located next to CDC, BDC and FDC.

Neutron Counter
Behind the Charged-particle counter, the neutron counter is installed to detect neutron. The momentum of neutron is measured by TOF. Therefore, the NC is constructed by plastic scintillation counter to achieve both of high detection efficiency and good TOF resolution.

Electromagnetic Calorimeter
The most outside part is a sampling-type electromagnetic calorimeter to detect γ-ray and to measure its energy.

4 Concluding Remarks

As it is described above, we intend to study kaonic nuclear bound states on light nuclei at J-PARC K1.8BR with a new-CDS system. To optimize the detector performance, we are conducting a detailed simulation. We are also preparing several physics papers based on the accumulated data in E15 and E31 experiments, to go forward to the detailed design of the new-CDC. By compiling those efforts, we are going to submit a new proposal in the near future.

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