Letter of Intent
for

Study of Dense $\overline{K}$ Nuclear Systems

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Contents

Abstract

We propose to create $\overline{K}$ nuclear systems at the 50-GeV PS of J-PARC. Very recently, possible existence of discrete nuclear bound states of $\overline{K}$ has been predicted based on the experimental information on the $\overline{K}N$ scattering lengths, kaonic hydrogen atom and the $\Lambda(1405)$ resonance. Due to the strong attraction of the $I = 0$ $\overline{K}N$ interaction, the surrounding nucleons are contracted to $\overline{K}$, forming high-density nuclear systems, where deeply-bound $\overline{K}$ states are accommodated. They are expected to lie below the thereshold for the main decay channel ($\Sigma\pi$), and thus can be studied as discrete states. The nuclear densities thus formed are expected to be 3-5 times as much as the normal nuclear density, which have never been reached without the aid of gravity.

Various deeply-bound $\overline{K}$ states, from few-body systems such as ppK^-, $ppnK^-$, $pppK^-$ to heavier systems, can be populated by (K^-, π^-), (π^+, K^+) and (K^-, N) reactions at $p_K \sim 1$ GeV/c. We also note that double-$\overline{K}$ nuclei can be studied by (K^-, K^+) and (K^-, K^0_S) reactions at $p_K \sim 2 - 3$ GeV/c. If discrete $\overline{K}$ bound states are found experimentally, it will open a new paradigm with enormous impacts on fundamental physics: i) In-medium $\overline{K}N$ interactions can be deduced, and the problem of chiral symmetry restoration at high nuclear density will be addressed experimentally, ii) the structure of dense nuclear systems will be studied, possibly in terms of quark-gluon phase and colour superconductivity at $T = 0$, iii) direct information on kaon condensation and strange matter formation will be obtained, and an equation-of-state for neutron stars and strange stars will be derived on laboratory based infortmation on their building blocks, iv) very exotic nuclear dynamics and structure under extreme conditions will be revealed.

In this letter of intent, we propose several experimental approaches to investigate deeply-bound kaonic states. Intense K^- meson beams are indispensable. Thus, the 50-GeV PS of J-PARC will provide a unique playground for this entirely new type of particle-nuclear spectroscopy.

1 Introduction

To investigate the behavior of hadrons in nuclear media it is essentially important to form and study hadron-nucleus bound states, because their binding energies and widths provide clear information on the hadron-nucleus interaction (mass shift, in-medium modification, etc.) in well-defined quantum states, in contrast to so-called invariant mass spectroscopy for investigating "in-medium" hadron masses in unbound nuclear media [1]. However, no discrete states are normally expected for bound hadrons because of their strong absorption by nuclei. A narrow bound state, if any, would require an unusual suppression mechanism. Recently, a new spectroscopy for deeply-bound pionic states has evolved [2, 3], which are halo-like Coulomb-assisted bound states [4, 5]. An important information on the partial restoration of chiral symmetry and reduced quark condensate in the nuclear medium has been obtained [6, 7].

In the strange sector, however, the subject on K-meson nuclear bound states is untouched. The first argument on this subject was given by Wycech in 1985, in which discussed the possibility of the existence of deeply-bound kaonic states based on kaonic atom data [8]. At this stage, however, the experimental data on the $\overline{K}N$ interaction was rather poor. The biggest problem, called *kaonic hydrogen puzzle*, was that the kaonic hydrogen atom data is inconsistent with the $\overline{K}N$ scattering data and the existence of the sub-threshold $\Lambda(1405)$ resonance. This inconsistency was solved by the KpX experiment at KEK [9], indicated that the $\Lambda(1405)$ can be treated as a strong-interaction bound state of K^-p. Akaishi and Yamazaki constructed the $\overline{K}N$ interaction based on the new experimental information [10] and applied this to light nuclear systems. In their calculation, the strong attraction in the isospin-zero ($I = 0$) channel plays an important role in accommodating extremely high nucleon densities so that the states formed have narrow widths because they lie deeper than the $\Sigma\pi$ emission threshold. The theoretical development with predicted $\overline{K}$ bound states will be described in the next section.

It will be extremely interesting in many aspects, if such a state is really found. The study of those states will shed a new light on physics of extremely dense nuclei. The predicted density is comparable to, or even higher than, the estimated central neutron star density. If $\overline{K}$ is indeed found to contract the surrounding nucleon density without the aid of gravity, it will help to form even a denser strange star under gravity. A recent Chandra satellite data [11] suggested the existence of a dense strange star. How hadrons behave in such a dense nuclear medium (chiral symmetry restoration, quark-gluon phase, etc.), is an extremely interesting question, which we can address experimentally from bound-hadron nuclear systems. These interesting problems will be studied in laboratory-based experiments.

In section 2 we describe theoretical predictions as a guide to design future experiments, and in sections 3 - 5 possible experimetal procedures and instrumentations will be proposed.

2 Predicted structure of $\overline{K}$ nuclear bound states

2.1 $\overline{K}N$ interactions

Very recently, possible presence of discrete nuclear bound states of $\overline{K}$ in light nuclear systems was predicted [1, 10, 12]. The $\overline{K}$-nucleus interaction was derived from $\overline{K}N$ interactions, which were constructed so as to account for i) the $\overline{K}N$ scattering lengths, ii) the K^--p atomic shift and iii) the energy and width of $\Lambda(1405)$. This phenomenological interaction is consistent with that obtained from chiral perturbation theory [13]. In these systems the strong attraction of the $I = 0$ $\overline{K}N$ interaction ($\overline{K}N^{I=0}$) plays an important role.

The strong attractive interaction of $I = 0$ $\overline{K}N$ helps accommodate a deeply-bound state, while contracting the surrounding nucleus, thus producing an unusually dense nuclear system. Since the binding energies are so large that the main decay channel of the $I = 0$ $\overline{K}N$ to $\Sigma + \pi$ is closed energetically (and additionally, the channel to $\Lambda + \pi$ is forbidden by the isospin selection rule), these deeply bound states are expected to have small widths. Such $\overline{K}N$ bound states constitute a new family of strange nuclei, which lie above the Λ and Σ hypernuclear families, as shown in Fig. 1.

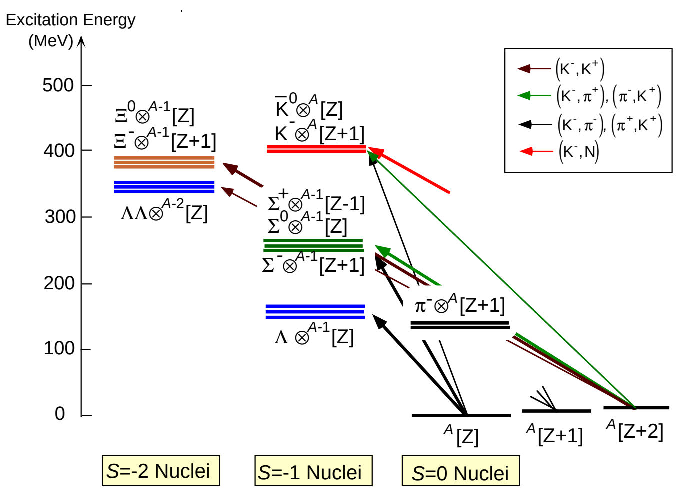


Figure 1: Schematic diagram of nuclear systems of various hyperionic and mesonic constituents. The kaonic family is located much higher than the Σ family.

It was recently shown [12] that the "traditional" (K^-, π^-) reaction (or equivalently (π^+, K^+) reaction) can be used to produce deeply-bound $\overline{K}$ systems on proton-rich exotic nuclei, if their final state is tuned to the kaonic bound state region (far above the Σ formation). The role of $\Lambda(1405)$ and $\Lambda(1520)$ as door ways was also discussed in [12].

There are various reactions to populate kaonic nuclei, as shown in Table 1. The momentum transfer is generally high compared with the normal Fermi momentum. Since the kaonic bound states are strongly bound, the internal momentum of the bound kaon is large so that the formation of kaonic bound states may be favoured.

Table 1: Light target nuclei and $\overline{K}$ nuclei to be produced by (K^-,π^-) (and (π^+,K^+)), (K^-,n) and $(e,e'K^+)$ reactions.

Target	Reaction		
	(K^-,π^-) (π^+,K^+)	(K^-,n)	$(e,e'K^+)$
	Momentum Transfer (MeV/c)		
	∼500	∼400	∼600
p			pK^-
d	ppK^-	pK^-	
^{3}He	$pppK^-$	ppK^-	$ppnK^-$
^{4}He	$pppnK^-$	$ppnK^-$	$ppnnK^-$
^{6}Li	$ppppnnK^-$	$pppnnK^-$	$pppnnnK^-$
^{7}Li	$ppppnnnK^-$	$pppnnnK^-$	
^{9}Be	$pppppnnnnK^-$	$ppppnnnnK^-$	
^{A}[Z]	$^A[Z+1]K^-$	$^{A-1}[Z]K^-$	$^A[Z]K^-$

2.2 pK^-, ppK^- and $ppnK^-$ systems

The constructed $\overline{K}$-nucleus potentials for the most fundamental cases are shown in Fig. 2. The elementary two-body bound state, pK^-, is asserted to be the $\Lambda(1405)$ resonance. The ppK^- may be called strongly bound *kaonic hydrogen molecule*; the K^- behaves as a glue to combine two protons. The energy level of ppK^- lies above the $\Sigma\pi$ emission threshold, and its width is broad. The $ppnK^-$ is very strongly bound, and its width is suppressed. The nucleus ppn is drastically shrunk by the strong attraction of K^-.

2.3 Further predictions by the AMD method

The exotic structure involving a $\overline{K}$ has also been studied by the Anti-symmetrized Molecular Dynamics method by Dote *et al.* [16]. This method can predict the density distributions of the constituent $\overline{K}$, protons and neutrons, as shown in Fig. 3 for the $ppnK^-$ system. The central nuclear density is several times as much as the normal nuclear density.

Another example is shown in Fig. 4. The two-α cluster structure of ^{8}Be is drastically contracted when a K^- is bound, forming a high-density system. The protons are more contracted than the neutrons.

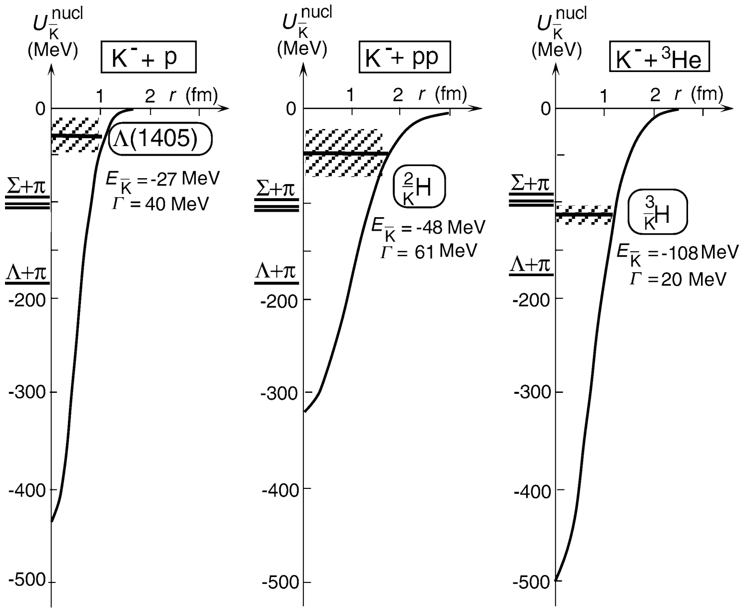


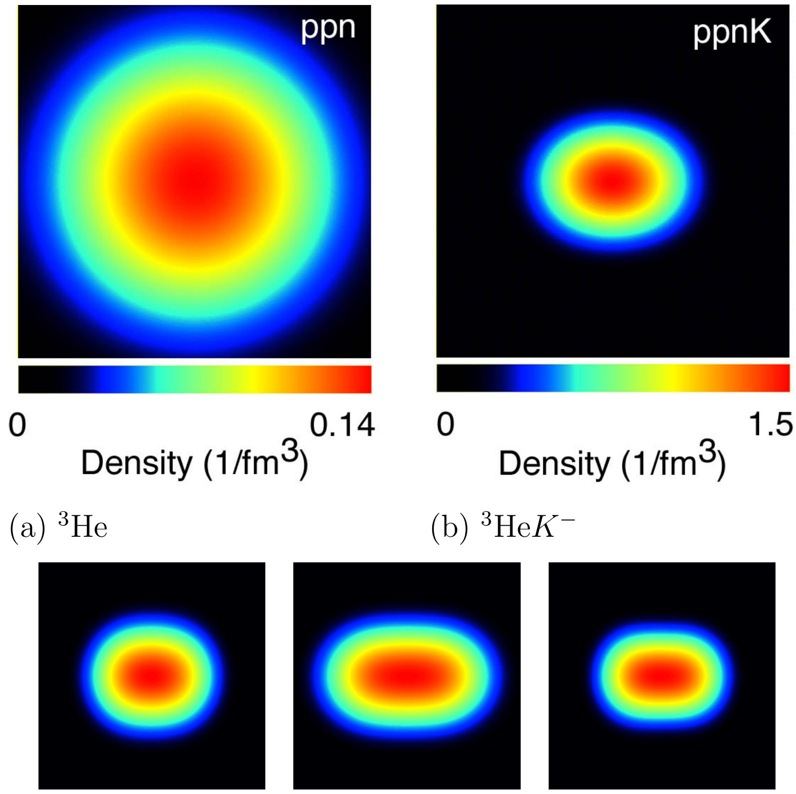
Figure 2: Calculated $\overline{K}N$ and $\overline{K}$-nucleus potentials and bound levels: $\Lambda(1405)$, ${}^{2}_{K}$H and ${}^{3}_{K}$H for K^-p, K^-pp and K^-ppn systems, respectively. The nuclear contraction effect is taken into account. The shaded zones indicate the widths. The $\Sigma\pi$ and $\Lambda\pi$ emission thresholds are also shown.

2.4 (K^-, π^-) reaction spectra for exotic $\overline{K}$ bound states

Following the AMD calculations, Dote *et al.* have produced theoretically (K^-, π^-) spectra to produce exotic deeply bound proton-rich $\overline{K}$ bound systems, as shown in Fig. 5.

2.5 $\overline{K}$ bound states as cold and dense nuclear systems - a gateway to strange nuclear matter

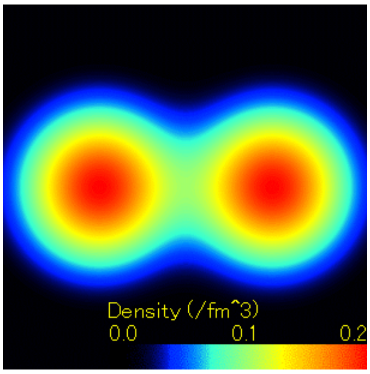
We have emphasized a new domain of physics paradigm. Due to the very strong K^--p attraction, very deep discrete states of $\overline{K}$ are expected. They are predicted to have binding energies, $B_K \sim 100$ MeV. Whether or not the $\overline{K}N$ interactions are modified in nuclear medium can be addressed. Since the predicted high-density systems are likely to be in a quark phase, the $\overline{K}$ bound states must provide a unique play ground for nuclear quark systems in well defined bound systems. It is natural to extend our consideration to multi-$\overline{K}$ systems, where more dense systems are expected to be formed. It has already been predicted that the most fundamental $S = -2$ systems, namely, ppK^-K^- and $ppnK^-K^-$, are strongly bound high-density systems [18] (see Fig. 6). This leads to an exciting possibility that dense strange nuclei can be formed without the aid of gravity. Thus, these systems appear to be extremely important as "precursors" to kaon condensation and strange matter formation.



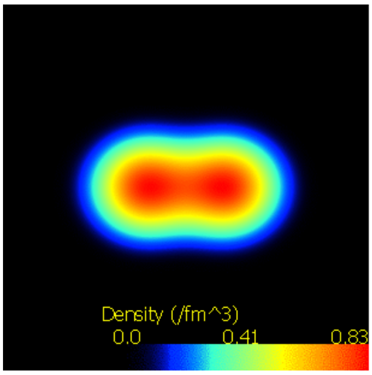
(a) ^{3}He (b) ^{3}HeK^-

(c) Proton (d) Neutron (e) K^-

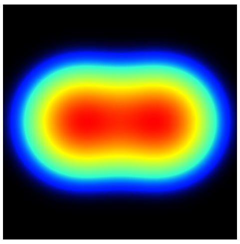
Figure 3: Calculated density contours of $ppnK^-$. Comparison between (a) usual ^{3}He and (b) ^{3}HeK^- is shown in the size of 5 by 5 fm. Individual contributions of (c) proton, (d) neutron and (e) K^- are given in the size of 3 by 3 fm.



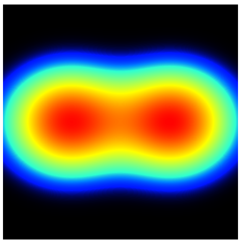
(a) ^{8}Be



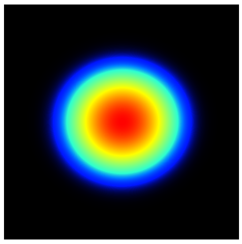
(b) ^{8}BeK$^-$



(c) Proton



(d) Neutron



(e) K$^-$

Figure 4: Calculated density contours of ^{8}BeK^-. Comparison of the density distributions of (a) usual ^{8}Be and (b) ^{8}BeK^- is shown in the size of 7 by 7 fm. Individual contributions of (c) proton, (d) neutron and (e) K^- are given in the size of 4 by 4 fm.

2.6 Current experimental search

The ^{4}He(K$^-_{stopped}$, n) process was considered to produce ${}^3_{\bar{K}}$H($T = 0$), in which the ejected neutron is used as a spectator [10]. Its experimental feasibility has been discussed by Iwasaki *et al.* [14]. An experiment via ($K^-_{stopped}$, n) reaction on ^{4}He nuclei (KEK-PS E471) has just been finished, and the data analysis is in progress.

Another type of reactions, in-flight (K^-, N), was discussed by Kishimoto [15]. A new possibility using (K^-, π^-) to populate exotic systems such as K^-pp, K^-ppp, etc., [12] will be pursued, and its first experimental trial is proposed at BNL-AGS [17].

In the following sections we describe how to study kaonic nuclei in the era of J-PARC. The required momentum range to study using these reactions are similar to that of hypernuclear studies so that we can share the beam line proposed in K-Arena.

On the other hand, there is one area which needs higher energy than that. If the kaon can bound in nuclei, there will be also a possibility to form $S = -2$ system as double-kaon bound states. We can also study also $\overline{K}$- $\overline{K}$ interaction in this system. Actually, the $S = -2$ system has been studied for long time via (K^-, K^+) reaction, to search for H-dibaryon, Ξ and double-Λ hypernuclei [19, 20].

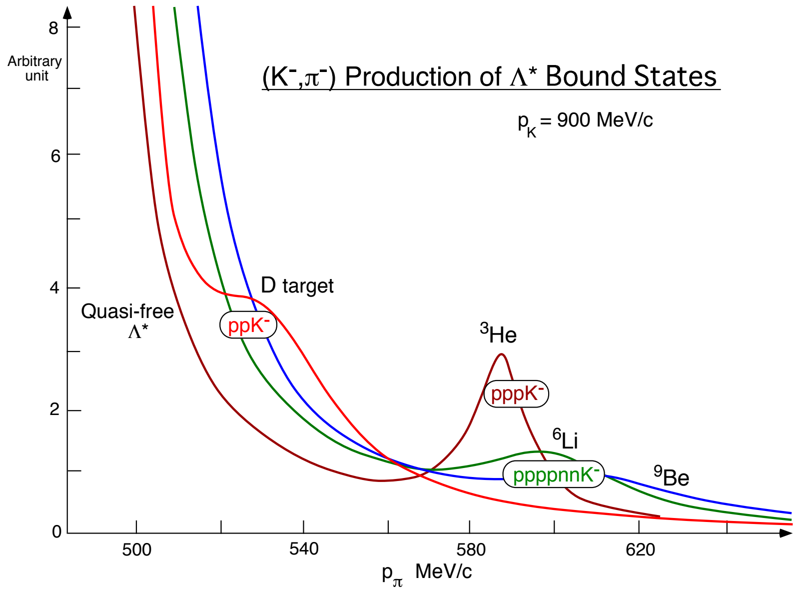


Figure 5: Calculated (K^-, π^-) reaction spectra for the formation of exotic proton-rich $\overline{K}$ bound systems.

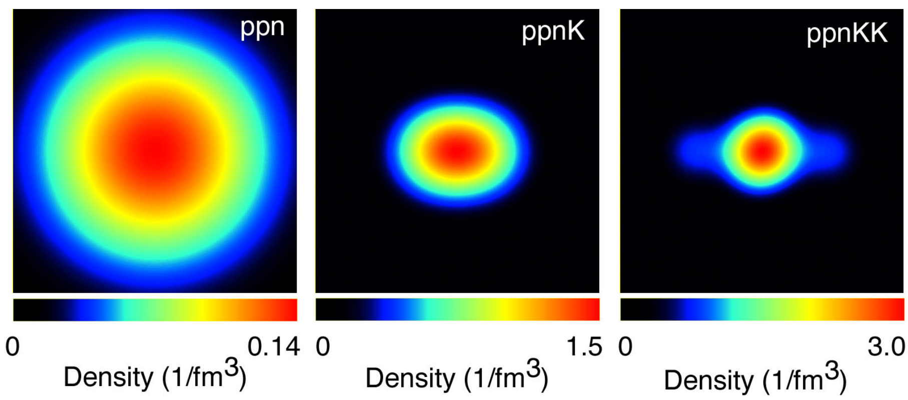


Figure 6: Density distribution of $ppn(={}^3$ He) (left), $ppnK^-$ (center) and $ppnK^-K^-$ (right) obtained by the AMD calculation of Dote [18].

3 Production with the (K^-, N) Reactions

If $\overline{K}$-nuclear potential is as attractive as suggested by studies of kaonic atoms [21], then deeply-bound kaonic nuclei should exist. The observation of kaonic nuclei gives directly the $\overline{K}$ optical potential and gives decisive information on the existence of kaon condensation in neutron stars. Here we present the general properties of the kaonic nuclei and would like to propose an experiment to study them by the (K^-, N) reaction.

Energies of the states are calculated with the potential given by the kaonic atom data. Harmonic oscillator potential gives crude though easy estimate of the energies. If the potential depth is as deep as -200 MeV suggested by kaonic atoms, the deepest energy state of kaonic nuclei is given by $(\frac{3}{2}\hbar\omega_K - 200)$ MeV. The $\hbar\omega_K$ is roughly 40 MeV, for instance, for the kaonic ${}^{28}_{K}$Si nucleus. The $1s$ state thus appears at around -140 MeV bound, which is the deepest bound state ever observed in nuclear physics. If the potential shape is closer to the square-well it appears deeper. In order to observe the state its width has to be reasonably narrow. The width is given by the imaginary part of the potential, which decreases for the deeply bound state and could be around 10 MeV [13, 21]. The narrow width is not unreasonable since dominant conversion channels like $KN \rightarrow \pi\Sigma$ or $KN \rightarrow \pi\Lambda$ have little phase space for such a deeply-bound state. Kaon absorption by two nucleons ($KNN \rightarrow YN$) gives a little width since two nucleons have to participate to the reaction. Estimation of the width may have an error. If the width is twice wider one can still observe the $1s$ state since next $1p$ state appears 40 MeV higher. Even though the width is wide enough to obscure the peak structure, strength of the cross section at deeply bound region is much more prominent than the case where the interaction is not attractive.

3.1 Reaction Kinematics

The (K^-, N) reaction where a nucleon (N) is either a proton or a neutron is shown schematically in Fig. 7. The nucleon is knocked out in the forward direction leaving a kaon scattered backward in the vertex where the $K + N \rightarrow K + N$ takes place. This reaction can thus provide a virtual K^- or $\overline{K}^0$ beam which excites kaonic nuclei. This feature is quite different from other strangeness transfer reactions like (K^-, π), $(\pi^\pm, K^+)$ and (γ, K^+) extensively used so far. They primarily produce hyperons and thus are sensitive to states mostly composed of a hyperon and a nucleus. Thus the reactions have been used to study hypernuclei.

The momentum transfer, which characterizes the reaction, is shown in Fig. 8. It depends on the binding energy of a $\overline{K}$. We are interested in states well bound in a nucleus (BE = 100 ∼150 MeV). The momentum transfer for the states is fairly large ($q = 0.3 \sim 0.4$ GeV/c) and depends little on the incident kaon momentum. Therefore one can choose the incident momentum for the convenience of an experiment. It is a little beyond the Fermi momentum and the reaction has characteristics similar to the (π^+, K^+) reaction for hypernuclear production where so-called stretched states are preferentially excited [22].

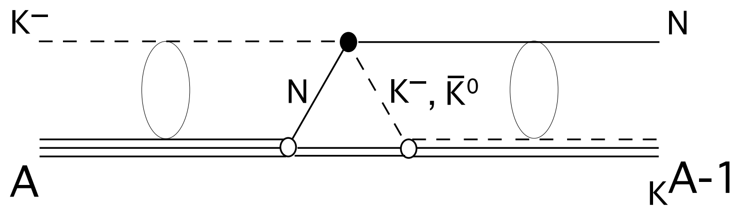


Figure 7: Diagram for the formation of kaonic nuclei via the (K^-, N) reaction. The kaon, the nucleon, and the nucleus are denoted by the dashed, thin solid and multiple lines, respectively. The kaonic nucleus is denoted by the multiple lines with the dashed line. The filled circle is the $KN \to KN$ amplitude while the open circles are the nuclear vertices. The bubbles represent distortion.

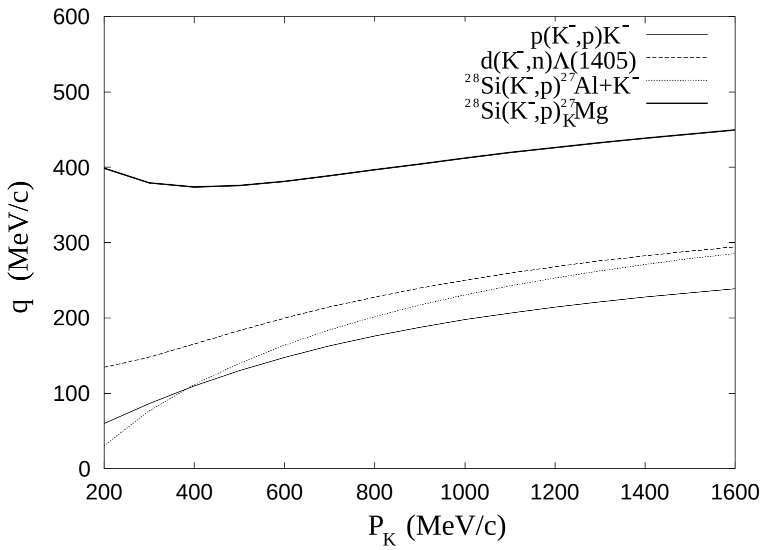


Figure 8: The momentum transfer of the (K^-, N) reaction at 0 degrees is shown for four reactions. Here binding energy of kaonic nucleus ${}^{27}_{K}\mathrm{Mg}$ is taken to be -150 MeV.

Recently deeply bound π^- atoms were observed by the $(d, {}^3\mathrm{He})$ reaction [2]. A small momentum transfer ($\sim$ 60 MeV/c) was essential to excite the atomic states which were typically characterized by the size of the atomic orbits. The large momentum transfer of the (K^-, N) reaction matters little to excite the deeply bound kaonic nuclei with appreciable cross section since the momentum transfer is typically characterized by the Fermi momentum to excite nuclear states.

3.2 Cross sections

The cross section of the reaction has been worked out in the recent paper [15] which uses the distorted wave impulse approximation (DWIA) with harmonic oscillator wave functions.

The differential cross section in the laboratory system for the formation of kaonic nucleus is given by

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)^{K^- N \to N K^-}_{L,0^\circ} N_{eff}. \tag{1}$$

It is given by the two body laboratory cross section multiplied by the effective nucleon number (N_{eff}).

The cross section of the elementary reaction has been available [23]. The CM differential cross section of elastic and charge exchange reactions at 180° are shown in Fig. 9 as a function of incident kaon momentum.

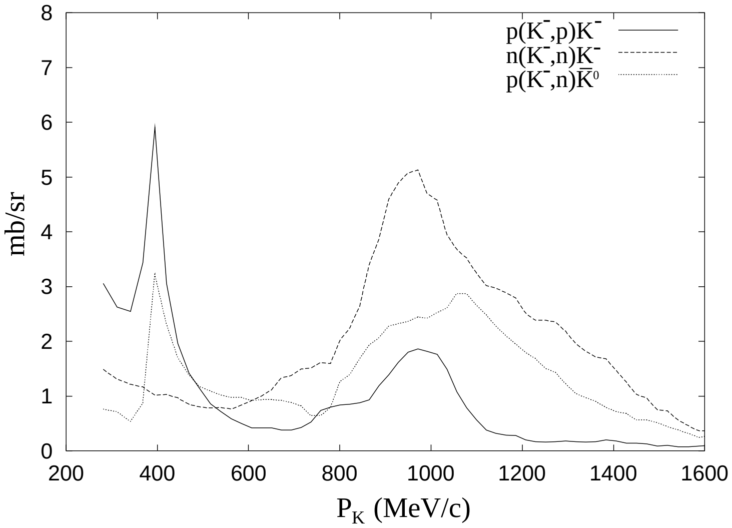


Figure 9: The CM differential cross sections of the three reactions are shown as a function of incident kaon lab momentum.

The elementary cross section has a peak at around 1 GeV/c. The cross section for the $1s$ states are $1 \sim 100\mu b/sr$ for various nuclear targets [15]. The magnitude of the cross section is large enough to have detailed study at the coming J-PARC where we can have intense kaon beam.

3.3 Experimental Procedure

Kaonic nuclear states will be observed by the missing mass spectrum of the (K^-, p) and (K^-, n) reactions. Outgoing protons will be measured by a spectrometer of which construction we would like to have support from J-PARC. Since the state we will study has relatively broad width (10∼40 MeV) no particular request is made for the momentum resolution of the spectrometer. We will use standard detector system (Plastic scintillators, Drift chambers, Cherenkov counters) equipped to the spectrometer system.

We also need to measure neutrons from the target. We would like to construct neutron counters around 10 m downstream of the target. We thus would like to ask J-PARC to keep enough space for this kind of study. Since we would like to have momentum resolution of around 10 MeV/c combination of neutron counters with high time resolution still require flight length of 10 m.

We will install counters surrounding target to observe decay particles from kaonic nuclei.

We would like to study various nuclear targets although in the beginning we will concentrate on light nuclear targets which will give us information on kaon-nucleon and kaon-nucleus interaction. Another reason is that the cross section of production of specific states like 1s state becomes small for heavy nuclear targets. We would like to study deuterium, ^{3}He, ^{4}He, ^{12}C and Si in the beginning and would like to extend to various nuclear targets later.

The (K^-, N) reaction on deuteron has special meaning. It can excite the $\overline{K}N$ component of hyperons. The $d(K^-, p)$ reaction excites a K^-n system which can only have $I = 1$ component. On the other hand $d(K^-, n)$ reaction excites both $I = 1$ or $I = 0$ components. Cross sections to the hyperons depend on their $\overline{K}N$ component. For instance, the well known Λ(1405 MeV) is abundantly excited by the (K^-, n) reaction if it is a $\overline{K}N$ bound state with $I = 0$ as usually believed. Other hyperons like Λ, Σ and Σ^* are less populated if those have little $\overline{K}N$ component.

3.4 Information currently available

In 2001 we carried out a test experiment as a parasite of the E930 experiment at BNL. The E930 experiment measured hypernuclear γ rays by using Ge detectors surrounding the target region. When E930 was looking for γ rays from the ^{16}O(K^-, π^-) reaction, we measured neutrons from the (K^-, n) reaction. The schematic layout of the test experiment is shown in Fig. 10.

The Hyperball was used to tag the decay products from the kaonic nuclear states. The Hyperball is not optimized for the present experiment although we can use it to reduce background. Figure 11 shows the time-of-flight spectrum which is shown as a function of $1/\beta$. The spectrum in the left is inclusive spectrum and the spectrum in the right is required to have more than one hit in the Hyperball and dE/dX in the neutron counter is consistent with energetic protons. A broad peak corresponding to K_L disappear. This cut is shown to be effective and important since K_L looks like a energetic neutron and could become a serious background at the deeply bound region. We have clear demonstration that K_L is not a serious background anymore.

Figure 12 shows missing mass spectrum of the ^{16}O(K^-, n) reaction obtained from the TOF spectrum (figure 5). Kaon is bound to the ^{15}O nucleus in the negative side of the spectrum. The peak around 50 MeV above the threshold is due to the quasi-free

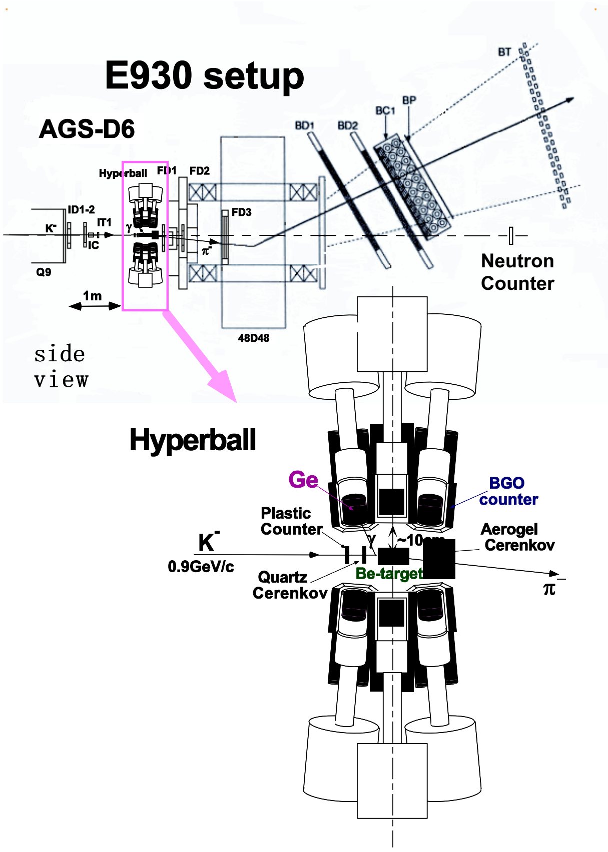


Figure 10: Schematic layout of the test experiment setup is shown. Upper half shows D6 beam line for incident K^- beam and 48D48 spectrometer for the detection of scattered π^-. Lower half shows the Ge detector system (Hyperball) for the detection of hypernuclear γ rays. A neutron counters which was a array of plastic scintillators was set 7 m downstream of the target. It covers $20 \times 100cm^2$ area. It consists of 4 layers of 5 cm thick plastic scintillators with 1 cm thick plastic scintillator for charged particle veto.

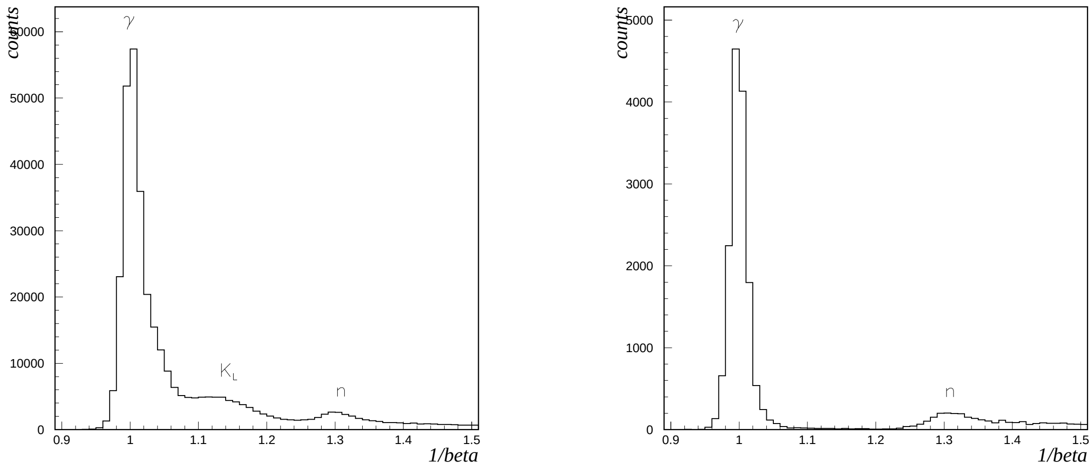


Figure 11: Time-of-flight ($1/\beta$) spectrum of the neutrons from the K^- bombardment on the water target is shown (left). Spectrum in the right shows the same spectrum with cuts on hits in the Hyperball and dE/dX (see text). Here incident kaon momentum was 0.93 GeV/c.

production of kaon by the ^{16}O(K^-, n) reaction which also corresponds to the $p(K^-, n)\overline{K}^0$ reaction.

The spectrum shows that we have appreciable amount of events in the bound region. It cannot be explained if there is no attractive interaction between kaon and nucleus. We show spectrum that include backgrounds from hyperon production and quasi-free knockout of the neutron from the nucleus by the $n(K^-, n)K^-$ reaction.

Backgrounds from accidental coincidence of Hyperball is almost flat in the missing mass spectrum. The spectrum shows excess down to around 130 MeV bound region. Events below 150 MeV bound region is mostly from the accidental coincidence of the Hyperball which can be reduced with detector that have better time resolution. This region should still have physics background since highly exited hypernuclear states exist. We have around $\sim 1\mu b$/sr/MeV below 150 MeV which is very small. This spectrum clearly indicates that kaon-nucleus potential is strongly attractive. If that is quantitatively verified at J-PARC we will have rich physics in future experiments.

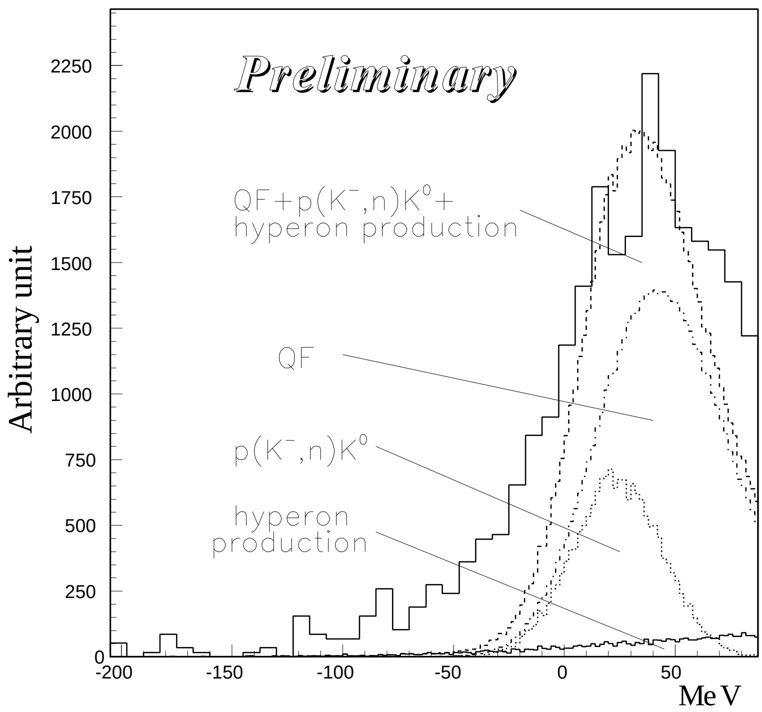


Figure 12: Missing mass spectrum of the $^{16}\mathrm{O}(K^-, n)$ reaction is shown. Zero corresponds to sum of $^{15}\mathrm{O}$ and K^- masses. QF stands for the quasi-free production of neutrons where $N(K^-, n)$ reaction takes place on a proton or neutron in $^{16}\mathrm{O}$. The QF gives expected spectrum where there in no kaon nucleus interaction. Background due to hyperon production by the $N(K^-, \pi^-)Y$ reaction where pions are scattered backwards are very small. We carried out this simulation by using GEANT.

4 Production with the (K^-, π^-) and (π^+, K^+) Reactions

Recently, an experiment was proposed[17] to search for a nuclear $\overline{K}$ bound state K^-pp in the $d(K^-,\ \pi^-)$ reaction at BNL-AGS. It has not been considered by the Program Advisory Committee, yet. It seems quite likely that the program should be extended at the 50-GeV PS even if we could succeed to carry out the first measurement at BNL-AGS in the limited beam time. Here, we summarize the concept of the proposal, P967, and mention about its extension at the 50-GeV PS.

The proposal is based on an idea by Yamazaki and Akaishi (YA02)[12] to produce exotic K^- bound states in proton-rich nuclear systems by (K^-, π^-) and $(\pi^+,\ K^+)$ reactions. Since these reactions have an advantage to leave a K^- in an unbound proton-rich nucleus (say, ^{2}He, ^{3}Li and ^{4}Li), the strong attraction of the $\overline{K}N^{I=0}$ interaction plays a decisive role in forming deeply bound states in which a substantial nuclear shrinkage occurs. The simplest system K^-pp, which can be produced from a d target, is predicted to have a binding energy of 48 MeV and a width of 61 MeV. This system can be compared with $\Lambda(1405)$ with a binding energy of 27 MeV and a width of 40 MeV (see Fig. 2).

In view of the situation that $\Lambda(1405)$ and these $\overline{K}$ nuclei are bound states which are accommodated in K^- potentials, as calculated and shown in Fig. 2, we readily recognize that a nuclear $\overline{K}$ system is nothing but "dissolved" Λ^* states. Therefore, the formation of a Λ^* in a nucleus as a "seed" will lead to the production of $\overline{K}$ bound states. In other words, the Λ^* produced in a nucleus can serve as a "doorway" toward $\overline{K}$ bound states. The problem is how to produce Λ^* in a nucleus and how to identify produced $\overline{K}$ bound states. YA02 pointed out that the "strangeness exchange reactions" (K^-,π^-) (or similarly, (π^+,K^+)) would lead to the production and detection of $\overline{K}$ bound states [12].

Table 2 shows what kinds of exotic species of $\overline{K}$ bound states are formed following (K^-, π^-) reactions. The doorway states are expressed as ${}^{2}_{\Lambda^*}$H and ${}^{4}_{\Lambda^*}$He in the hypernuclear nomenclature, which are converted to $\overline{K}$ bound states, namely, ${}^{2}_{\overline{K}}$H and ${}^{4}_{\overline{K}}$He, respectively. Table 2 shows the calculated binding energies and widths [12, 10, 16].

Although the (K^-, π^-) reaction resembles the ordinary way for Λ and Σ hypernuclear spectroscopy, no attention has ever been paid to the excitation region, which is much higher than the Σ emission threshold, $M_\Sigma = 1180$ MeV. In the proposal we have proposed to investigate the most basic reaction:

$$K^- + d \to (K^-pp) + \pi^-. \tag{2}$$

The (K^-, π^-) experiment on d target is the first step for a series of future experiments on $\overline{K}$ nuclei, which will provide totally new information on the $\overline{K}N$ interaction in the nuclear medium. Such "bound-$\overline{K}$ nuclear spectroscopy" will become a new paradigm in strangeness nuclear physics. Of particular interest is the possibility that a high-density nuclear medium will be created around a K^-. Whether or not the K^- and the surrounding nucleons keep their identities and are subject to the present $\overline{K}N$ interactions even at such a high density ($\rho \sim 5 \times \rho_0$) is an extremely interesting question. Certainly, the bound-$\overline{K}$

Table 2: Light target nuclei and $\overline{K}$ nuclei to be produced by (K^-, π^-) reactions through Λ^* doorways, and calculated binding energies (B in MeV) and widths (Γ in MeV).

Target	Reaction	Λ^* doorway	$\overline{K}$ nucleus	B	Γ
n	(K^-, π^-)	Λ^*	$K^- - p$	27	40
d	(K^-, π^-)	$\Lambda^* p$	${}^2_K\mathrm{H} = K^- pp$	48	61
^{3}He	(K^-, π^-)	$\Lambda^* pp$	${}^3_K\mathrm{He} = K^- ppp$	~ 80	~ 20
^{4}He	(K^-, π^-)	$\Lambda^* ppn$	${}^4_K\mathrm{He} = K^- pppn$	~ 90	~ 20

nuclear systems are far beyond the ordinary nuclear and hadron physics. Our strategy to disentangle all the complicated open problems is to start with the simplest case of K^-pp, which is exotic but still resembles the ordinary nuclear system. From the $d(K^-, \pi^-)K^-pp$ reaction we may be able to examine experimentally the underlying assertions concerning the nature of $\Lambda(1405)$ and its propagation in nuclei. This will provide an important gateway toward more complicated and more exotic systems.

4.1 Production Mechanism

Hepp *et al.* [24, 25] studied the following elementary processes in a deuterium bubble chamber:

$$K^- + \text{“}n\text{”} \quad \rightarrow \quad \text{“}\Lambda(1405)\text{”} + \pi^-, \tag{3}$$

$$K^- + \text{“}n\text{”} \quad \rightarrow \quad \text{“}\Lambda(1520)\text{”} + \pi^-. \tag{4}$$

These processes were deduced from the invariant mass spectrum of $(\Sigma\pi)^0 = \Sigma^\pm\pi^\mp$ in the $K^- + d \rightarrow (\Sigma\pi)^0 + \pi^- + p_s$ reaction channel with p$_s$ being a spectator of the above process (see Fig. 13). The cross section for the $(\Sigma\pi)^0 + \pi^- + p_s$ channel was obtained to be ≈ 0.9 mb in the c.m. excitation E^* around 1660 MeV (corresponding to an incoming K^- momentum of around 630 MeV/c), of which a substantial fraction is due to $\Lambda(1405)$ production (see Fig. 14. The cross section for $\Lambda(1520)$ production at $E^* \sim 1730$ MeV was found to be about 1 mb and that for $\Lambda(1405)$ production at this energy was about 0.3 mb. YA02 considered these elementary production processes to be sources for the production of $\overline{K}$ bound states in the missing mass spectra of (K^-, π^-) reactions on nuclear targets.

YA02 noted that a “K^--coalescence” model for $\Lambda(1405)$ formation in the above reactions, in which an energetic incident K^- fuses with a proton, may not account for the abundant production of $\Lambda(1405)$, as long as $\Lambda(1405)$ is a bound state of $K^- + p$ with an internal momentum of 270 MeV/c. It is also a remarkable fact that the production patterns of $\Lambda/\Sigma/\Lambda(1405)/\Lambda(1520)$ in various different reactions, (K^-, π^-), (π^+, K^+), (γ, K^+), (e, $e'K^+$), etc., are more or less similar. Thus, we may have to admit that $\Lambda(1405)$ partially possesses an “elementary particle” character, like Λ and Σ. Once a $\Lambda(1405)$ or $\Lambda(1520)$ is formed in a nucleus in such a “hard” process, it is subject to be dissolved into $\overline{K}$ bound states because of its “soft” character.

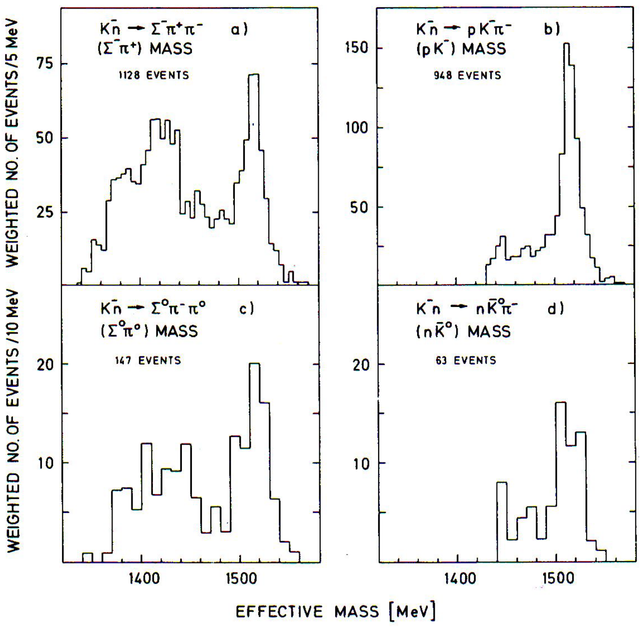


Fig. 11. Distribution of invariant masses: (a) $\Sigma^-\pi^+$ in the reaction $K^-n \to \Sigma^-\pi^+\pi^-$; (b) pK^- in the reaction $K^-n \to pK^-\pi^-$; (c) $\Sigma^0\pi^0$ in the reaction $K^-n \to \Sigma^0\pi^-\pi^0$; (d) $n\bar{K}^0$ in the reaction $K^-n \to n\bar{K}^0\pi^-$.

Figure 13: Observed invariant mass spectra of $\Sigma\pi$ in $K^- + d \to \Lambda^* + \pi^- + p_s$ events [24, 25].

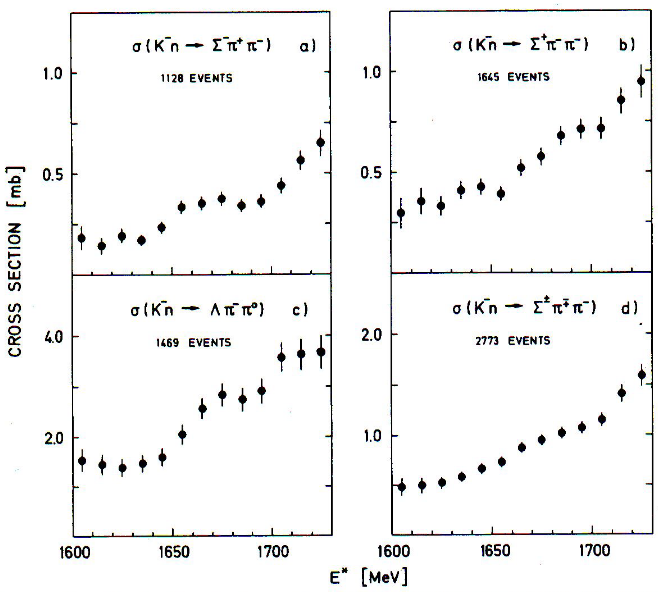


Fig. 8. Cross sections for the three-body reactions (4) to (6). The points in fig. 8d are the sum of the corresponding points in figs. 8a and 8b.

Figure 14: Observed cross sections for the productions of Λ^* in $K^- + d \to \Lambda^* + \pi^- + p_s$ events [24, 25].

YA02 considered two processes responsible for the production of $\overline{K}$.

i) Production via $\Lambda(1405)$ *formation*

The role of $\Lambda(1405)$ as a doorway state is shown in a diagram in Fig. 15a. When a $\Lambda(1405)$ is produced by a reaction (eq.(3)) in a target A:$_Z[A]_N$ (= B + n) and remains in the nucleus B:$_Z[A-1]_{N-1}$, it serves as a "seed" to produce a K^- bound state with the core nucleus C:$_{Z+1}[A]_N$. The $\Lambda(1405)$ propagating in the residual nucleus B either decays, "$\Lambda(1405)$" $\to (\Sigma\pi)^0$, or becomes dissolved as

$$\begin{aligned} K^- + \mathrm{A} &\to \text{“}\Lambda(1405)\text{”} + \mathrm{B} + \pi^- \qquad (5) \\ &\to \mathrm{C} + K^- + \pi^-, \qquad (6) \end{aligned}$$

which ends up as a K^-C nucleus (= $_{\overline{K}}$A).

ii) Production via $\Lambda(1520)$ *formation*

This is, so to speak, the "resonant formation of a compound nucleus". The production cross section for $\Lambda(1405)$ observed in a bubble-chamber experiment [24, 25] shows a resonance-like plateau at a c.m. energy of $E^* \sim 1660$ MeV (see Fig. 14). This indicates

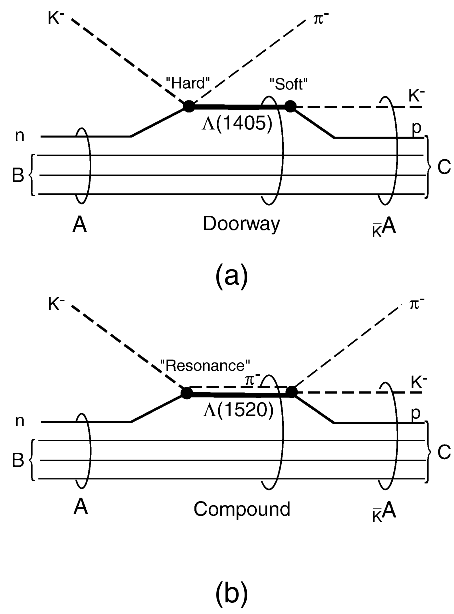


Figure 15: Diagrams for the production of $\overline{K}$ bound states in (K^-, π^-) reactions through Λ^* as a doorway. a) "Hard" production of $\Lambda(1405)$ and its propagation. b) Resonant formation of $\Lambda(1520) + \pi^-$ and their propagations.

the resonant formation of a compound state,

$$K^- + \text{“}n\text{”} \leftrightarrow \Lambda(1520) + \pi^- \leftrightarrow K^- + p + \pi^-, \tag{7}$$

which decays in vacuum as

$$K^- + \text{“}n\text{”} \rightarrow \text{“}\Lambda(1405)\text{”} + \pi^-, \tag{8}$$

as shown in Fig. 16. When this resonant formation of $\Lambda(1520) + \pi^-$ takes place in a nucleus,

$$K^- + \mathrm{A} \;\leftrightarrow\; \mathrm{B} + \Lambda(1520) + \pi^- \tag{9}$$

$$\leftrightarrow\; \mathrm{B} + K^- + p + \pi^-, \tag{10}$$

it leads to the production of not only a $\Lambda(1405)$, but also a $\overline{K}$ bound state as

$$\rightarrow\; \mathrm{B} + \Lambda(1405) + \pi^-, \tag{11}$$

$$\rightarrow\; K^-\mathrm{C}\ (\equiv_{\overline{K}} \mathrm{A}) + \pi^-. \tag{12}$$

Namely, the resonating particles, $\Lambda(1520)+\pi^- \leftrightarrow K^- + p + \pi^-$, together with the nucleus B form a "compound nucleus" which decays to a $\overline{K}$ bound state in C without producing a $\Lambda(1405)$. A diagram for this process is shown in Fig. 15b. In this $\Lambda(1520)$ doorway process, the productions of a free $\Lambda(1405)$ and of a $\overline{K}$ bound state are two competing final channels having the common origin. The branching ratio, $\sigma[\overline{K}\text{−nucleus}]/\sigma[\Lambda(1405)]$, is expected to be large.

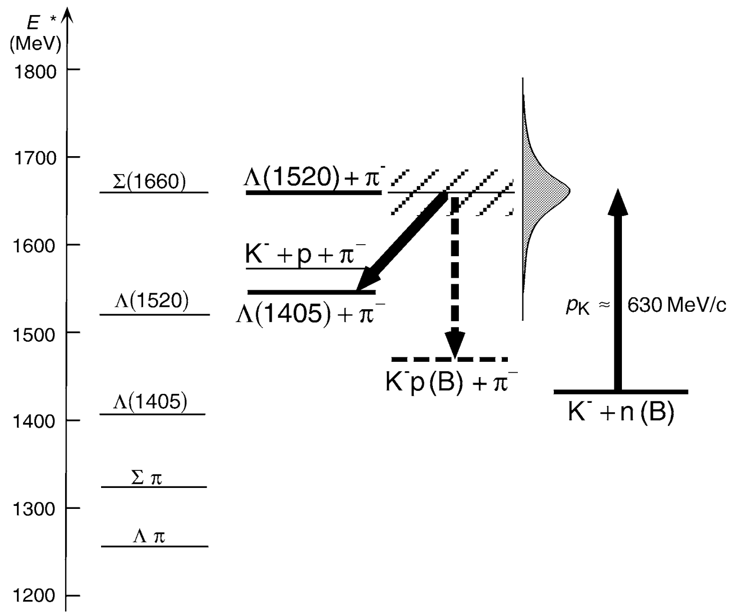


Figure 16: Energy diagram relevant to the formation of $\overline{K}$ bound states in (K^-, π^-) reactions through $\Lambda(1520) + \pi^-$ resonance as a doorway.

4.2 Experimental Procedure

4.2.1 Experimental Setup

We are going to use the spectrometer system at the K1.1 beam line: a beam line spectrometer and the SPES-II spectrometer. For the tagging of decay products from the K^-pp bound state, the Cylindrical Detector System (CDS) constructed for the BNL E906 will be used. The large acceptance of $\sim$60% of 4π realized with the CDS is very useful for this experiment.

We use the K^- beam at 900 MeV/c from the K1.1 beam line. The incident beam momentum was selected as the maximum beam momentum of the past deuterium bubble chamber measurement [24] not to loose the beam intensity because of the K^- decays. From the bubble chamber data, we can estimate the contribution of background processes and the production mechanism for the K^-pp bound state reliably. We expect the intensity of 3×10^6 K^-s/sec.

The outgoing pion momentum from the $d(K^-, \pi^-)^2_K$H reaction is calculated to be 500 – 560 MeV/c in the forward direction of $\theta_\pi \leq 7$ degrees assuming the binding energy of the ^2_KH is 50±20 MeV. The solid angle acceptance of the spectrometer is 20 msr. The missing mass resolution of $\sim$1 MeV$_{fwhm}$ will be achieved in the current design, which is quite enough for this experiment considering the large width of the K^-pp bound state.

The target we use is a CD_2 target of 5.0 cm wide, 1.0 cm high, and 2.0 cm thick. The small beam size in vertical is very helpful to detect protons coming out from the target in the CDS. The target will be installed at around the upstream entrance of the CDS, from which the protons emitted from 20 degrees to 90 degrees are detected in good particle identification with a time-of-flight (TOF) measurement using plastic scintillators. The momentum resolution of the CDS was obtained to be 20 – 30 MeV/c in r.m.s. for the protons at 200 – 300 MeV/c in E906, which is sufficient for the π^+/p separation with the TOF in this measurement.

4.2.2 Yield Estimation

The production cross section via the $\Lambda(1405)$ formation is estimated in YA02 as

$$\frac{d^2\sigma}{dE_\pi d\Omega_\pi} = \frac{d\sigma^{elem}_{\Lambda^*}}{d\Omega^{(0)}_\pi} \times \alpha(k_\pi)\frac{|\langle\Lambda^*|V^{I=0}_{\bar{K}N}|\Lambda^*\rangle|^2}{(\tilde{E}-\bar{E}_{\Lambda^* p})^2+\frac{1}{4}\Gamma^2_{\Lambda^*}}S(E), \tag{13}$$

with

$$S(E) = \left(-\frac{1}{\pi}\right) Im\left[\int d\vec{r}_K d\vec{r}\,'_K \tilde{f}^*(\vec{r}_K)\times\langle\vec{r}_K|\frac{1}{E-H_{K^-pp}+i\epsilon}|\vec{r}\,'_K\rangle\tilde{f}(\vec{r}\,'_K)\right], \tag{14}$$

where $\tilde{E}$ is the energy transfer to the Λ^*-p relative motion in doorway states, $\bar{E}_{\Lambda^* p}$ the average energy of the interacting Λ^* and p, and E the energy transfer to the K^-pp relative motion in the K^-pp system, and $\alpha(k_\pi)$ is a kinematical factor around 0.7. The function $\tilde{f}(r)$ is

$$\tilde{f}(\vec{r}) = 2^3 e^{i2\beta\vec{q}\vec{r}}C(r)\frac{\Phi^*_{pp}\Psi_d(2r)}{|\Phi_{\Lambda^*}(0)|}, \tag{15}$$

with $\vec{q}=\vec{k}_K-\vec{k}_\pi$, $\beta = M_p/(M_{\Lambda^*}+M_p)$ and $C(r) = 1-exp[-(r/1.2fm)^2]$.

The calculated total strength to the K^-pp bound state formation is 2.3% of the total $\Lambda(1405)$ production, which is about 0.3 mb from Ref. [24]. The angular distribution of the $\Lambda(1405)$ production was not obtained in Ref. [24] due to poor statistics. Here we assumed it to be similar to the angular distribution of the $K^-n\rightarrow\Lambda^0\pi^-$ reaction. Then, the average production cross section in our forward spectrometer acceptance is estimated to be 2.83 μb/sr in Lab. Thus, the total yield for the signal in 100 hours of data taking is

$$\begin{aligned} 3 &\times 10^6[/sec.]\times 3600[sec./hour]\times 100[hours] \\ &\times 2.83\times 10^{-30}[cm^2/sr]\times 0.02[sr]\times\frac{N_A}{16}[/g]\times 2\times 2[g/cm^2] \approx 9170 events. \end{aligned} \tag{16}$$

We can expect a rather abundant yield. However, we should take account of the backgrounds.

4.2.3 Background

K^- decay-in-flight

Although the $K_{\mu 2}$ and $K_{\pi 2}$ decays are out of range from the momentum acceptance, the $K_{\pi 3}(K^-\rightarrow\pi^-\pi^0\pi^0\ or\ \pi^-\pi^-\pi^+)$, $K_{\mu 3}(K^-\rightarrow\mu^-\bar{\nu_\mu}\pi^0)$, and $K_{e3}(K^-\rightarrow e^-\bar{\nu_\mu}\pi^0)$ contribute to the momentum acceptance of the spectrometer because of their very wide momentum distributions. The branching ratios are 1.73%, 5.59%, 3.18%, and 4.82%, respectively. Only from the forward particle momentum, we can not distinguish them from the signal (see Fig. 17). However, the coincidence requirement with protons from the targets will suppress them completely.

Quasi-free Productions of Σ and Λ

The Σ and Λ are produced with large production cross sections through quasi-free two-body processes:

$$\begin{aligned} K^- + d &\rightarrow \Sigma^0 + \pi^- + p_s, \\ K^- + d &\rightarrow \Lambda + \pi^- + p_s, \\ K^- + d &\rightarrow \Sigma^+ + \pi^- + n_s, \end{aligned}$$

where the subscript s indicates the spectator nucleon in the quasi-free process. The total production cross sections in these modes are of the order of 1 mb. However, the forward π^- momenta are above 700 MeV/c, and are well separated from the signal pions (see Fig. 17).

The most serious background processes are the quasi-free three-body productions of Σ and Λ:

$$\begin{aligned} K^- + d &\rightarrow \Sigma^- + \pi^+ + \pi^- + p_s, \\ K^- + d &\rightarrow \Sigma^+ + \pi^- + \pi^- + p_s, \\ K^- + d &\rightarrow \Lambda + \pi^0 + \pi^- + p_s, \\ K^- + d &\rightarrow \Sigma^0 + \pi^0 + \pi^- + p_s, \\ K^- + d &\rightarrow \Lambda + \pi^+ + \pi^- + n_s. \end{aligned}$$

The total production cross sections in these modes are of the order of several hundreds μb for each. The forward π^- momenta overlap almost completely with the signal pions (see Fig. 17).

4.2.4 Proton Tagging

The decay mode of the K^-pp bound state, ${}^{2}_{\bar{K}}$H, is not known very well. Considering the binding energy predicted for the ${}^{2}_{\bar{K}}$H is 48 MeV, the main decay modes would be

$$\begin{aligned} {}^{2}_{\mathrm{K}}H &\rightarrow \Sigma^- + \pi^+ + p, \\ &\rightarrow \Sigma^+ + \pi^- + p, \\ &\rightarrow \Sigma^0 + \pi^0 + p. \end{aligned}$$

The Q-values of these decay modes are ~50 MeV in the case of the binding energy of 48 MeV. Thus, we can expect one proton in rather high momentum would be emitted.

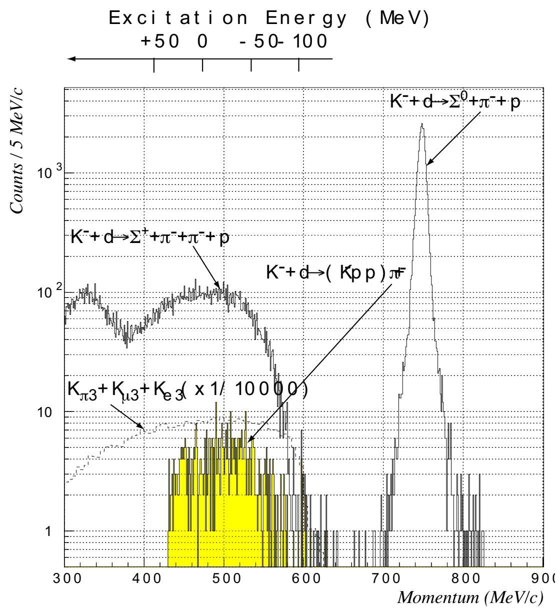


Figure 17: The forward π^- momentum distributions of (a) quasi-free two-body Σ production, (b) K^- decay-in-flights (scaled by 1/10000), and (c) quasi-free three-body Σ production.

In contrast, a spectator proton emitted from the major background process, $K^- + d \to \Sigma^- + \pi^+ + \pi^- + p_s$, has lower momentum because of the small Fermi momentum in deuterium. The calculated momentum distributions in the two processes are shown in Fig. 18. Here, we used the three-Gaussian form of the deuterium Fermi momentum distribution [26].

A problem is that the Σ^+ emits a proton in the decay of $\Sigma^+ \to p+\pi^0$(52% branch) and the Σ^0 also emits a proton in the sequential decay of $\Sigma^0 \to \Lambda+\gamma$(100%), $\Lambda \to p+\pi^-$(64%). Unfortunately, the momentum of these protons overlap with that for the decay proton. Therefore, the requirement of the coincidence of one proton with 300 – 500 MeV/c does not improve the S/N very much(S/N$\sim$1/20).

In this experiment, we propose two-proton tagging to further improve the S/N. Figure 19 shows correlations between two protons' (one from the decay of a Σ and the other from the decay of the K^-pp bound state or the spectator proton) momenta in the case of ${}^{2}_{\bar{\mathrm{K}}}H \to \Sigma^+ + \pi^- + p$ and in the case of $K^- + d \to \Sigma^- + \pi^+ + \pi^- + p_s$. So, if we require the momenta of both protons to be 190 – 490 MeV/c, we could suppress the background contribution, although we loose the detection efficiency for the signal. In addition we further select the proton emission angle in the Lab. frame to be 20 – 80 degrees, because the spectator proton is emitted uniformly while the proton from the K^-pp bound state is emitted in the forward direction. We have found the S/N is greatly improved to be $\sim$3.4; the number of the signal events is $\sim$1200 while that of the background is$\sim$ 340.

In the estimation so far, we have used the formation process through the $\Lambda(1405)$

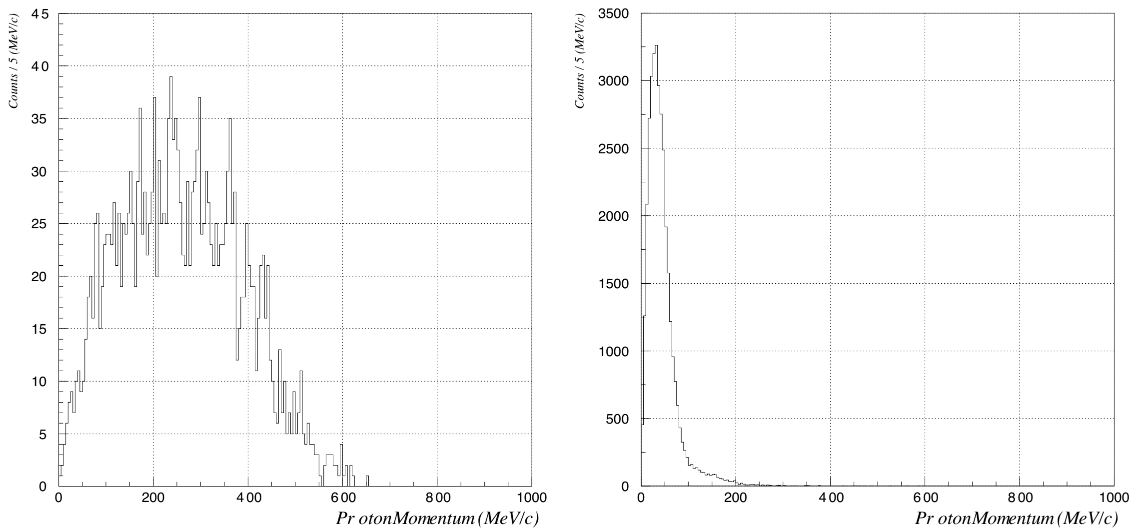


Figure 18: Comparison of the proton momentum distributions from the signal, ${}^{2}_{\bar{K}}H \to \Sigma^- + \pi^+ + p$ (left) and the major background process, $K^- + d \to \Sigma^- + \pi^+ + \pi^- + p_s$ (right).

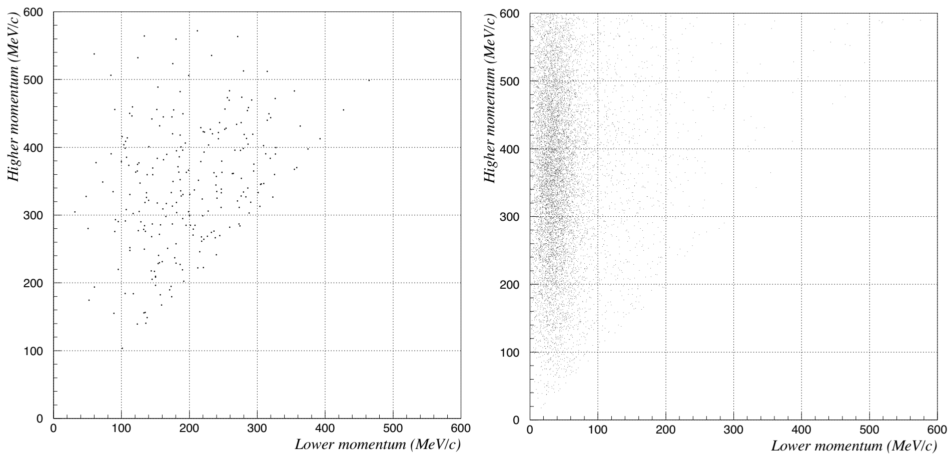


Figure 19: Scatter plots between two protons' momenta for the signal(left) and for the quasi-free Σ process(right).

only. As we discussed, we could expect some more signals through the $\Lambda(1520)$ formation. However, we have no good estimation for this formation mechanism at this moment.

4.3 Future Program

Once the existence of such a K^-pp bound system is confirmed, we can proceed to the ^{4}He(K^-, π^-)K^-pppn reaction, where a very strongly bound K^-pppn system with the binding energy of ~90 MeV will be produced. It is expected to have an enormous nuclear density around the K^-.

4.3.1 Structure of K^-pppn

The ^3_KHe ($T = 1$) system ($= K^-ppp$) is a very exotic nucleus, in which three protons without a neutron (non-existing ^{3}Li) form a bound state with the aid of the strong attraction of K^-. Nuclear contraction counterbalanced by a Pauli blocking effect plays an essential role. Whether the extra proton is attracted to the K^- center to form a shell structure or is repelled to form a cluster structure depends on the inter-nucleon repulsion; this interesting question is under study.

The addition of one neutron to the above system makes a ^4_KHe ($T = 1/2$) system ($= K^-pppn$), in which the nucleus, ^{4}Li, is also non-existing. Here, the pn interaction is found to stabilize the frustrating behavior of the extra proton in ^3_KHe ($T = 1$). The pn interaction produces a stronger binding, as in the case of ^2_KH and ^3_KH. Detailed studies using the Antisymmetrized Molecular Dynamics (AMD) method are in progress [16].

4.3.2 Further Extensions

Doté *et al.* recently investigated the structure of a very exotic system of "^{8}BeK^-" based on the AMD method. They found the K^- is strongly bound (B_{K^-}=104 MeV) and it attracts the surrounding nucleons to an extremely high-density assembly(~several times the normal nuclear density) with iso-vector deformation. In the (K^-, π^-) reactions, we could investigate similar various exotic $\overline{K}$ bound states in non-existing proton-rich nuclei, such as p^4n^2(^{6}Be) and p^5n^4(^{9}B). If confirmed, these will create a new field of "bound-$\overline{K}$ nuclear spectroscopy" to investigate new *dense and cold* hadronic environments, in contrast to *hot and dense* states expected to be realized in relativistic heavy-ion collisions.

5 Double-Kaon bound states

As shown in section 2, one can compress the nucleous even further with double-kaon bound state, as shown in Figure 6. To excite two kaon bound state, there are also several possible processes, namely (K^-, K^+) and $(K^-, \overline{K}^0)$ reaction as shown in Figure 20. The

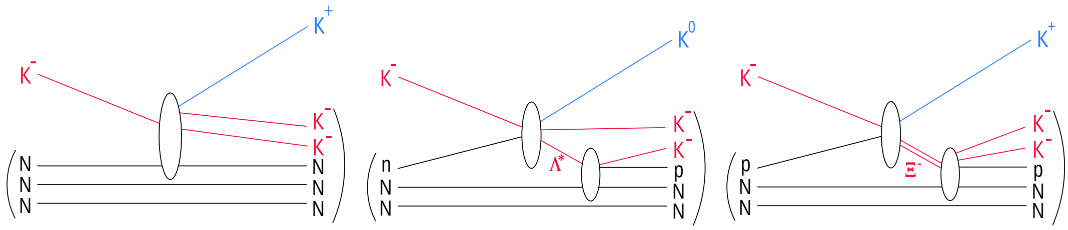


Figure 20: Candidate of production process.

kinematics are similar so that let's discuss the first process as a model case. This process can be formed by single nucleon reaction and more simple than the other.

5.1 Production with the (K^-, K^+) reaction

The (K^-, K^+) reaction is also attractive experimentally by the following two reasons; a) the K^+ identification is easier, and b) required bending magnet to measure the momentum is single arm and easy to achieve better resolution. In the case of $\overline{K}^0$, one needs double arm spectrometer to detect two charged pions from K^0_S. Another point is that it is interesting in relation to the experiment performed at KEK (KEK-PS E471). In this experiment, we are aiming at the production of K^-ppn system. If one apply (K^-, K^+) reaction on ^{3}He target, one may form K^-K^-ppn system.

We can not make detailed feasibility study at present, so that we are going to make very rough evaluation based on simple model. In (K^-, K^+) reaction, the second negative kaon is produced through virtual ϕ production:

$$K^-N \to K^-N\phi.$$

The threshold momentum of kaon to produce ϕ on single nucleon at rest is ~ 2.6 GeV/c. This momentum range is away above than that of the proposed beam line in K-Arena. To have relatively large cross section, one can not be too much away from this momentum. On the other hand, if one consider the direct K^+K^--pair production:

$$K^-N \to K^+K^-K^-N,$$

the required incident kaon momentum is getting smaller.

The threshold energy of $K^-N \to K^+K^-K^-N$ reaction with a nucleon at rest can be easily obtained as:

$$E_K = \frac{(m_N + 3m_K - B_{KK})^2 - {m_K}^2 - {m_N}^2}{2m_N}, \tag{17}$$

where m_N and m_K are the mass of nucleon and kaon, and B_{KK} is the binding energy of two kaons. The obtained incident K^- momentum is shown in Figure 21.

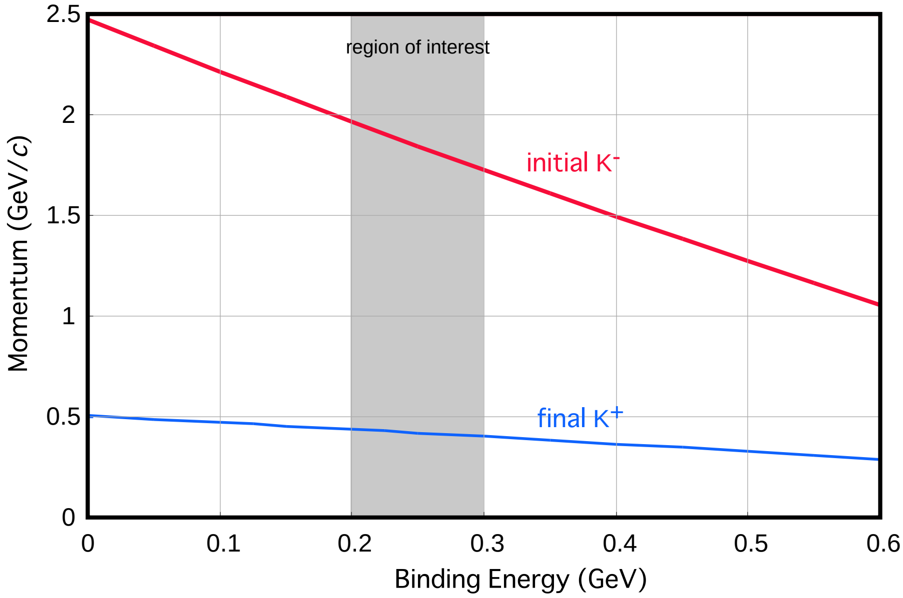


Figure 21: Threshold K^- momentum to produce double-kaon bound state is shown as a function of B_{KK}. The threshold is calculated by the reaction with single nucleon at rest. Therefore, this is roughly the minimum required momentum for the production. The K^+ momentum is also shown.

Here we assume that we have substantial formation cross-section of the two-kaon bound state even in this incident kaon momentum, and apply the kinematics to nuclear targets. Since the kinematics does not change drastically depending on the mass number, we take ^{3}He as a target in the following discussion. The expected K^+ momentum from the formation of double-kaon bound state is shown in Figure 22.

Next question is the binding energy and the background processes. What is the binding energy? In the case of K^-ppn system, it is predicted to be 108 MeV [10]. In the case of K^-K^-ppn system, however, we know nothing about $\overline{K}$-$\overline{K}$ interaction. Lets assume that it will be the double of the single kaon and the further nuclear compression will give additional binding energy of few tenth of MeV, then the binding energy will be about $\sim$ 250 MeV. Actually, Dote's estimation is about $\sim$ 220 MeV.

There are three major background sources, i) K^-"p" $\rightarrow \Xi^- K^+$ (quasi-free Ξ^- production), ii) K^-"p" $\rightarrow \Lambda K^- K^+$ and iii) K^-"p" $\rightarrow \Sigma^0 \overline{K}^0 K^+$. The ordering of the maximum momenta of these reactions are from i) to iii). The K^+ momentum from the reaction iii) is lower than that from double-kaon bound state, so that we plotted the processes i) and ii) in the Figure 22. The momentum distribution due to the Fermi-motion is also plotted for process i), by cutting off the motion at 200 MeV/c.

As shown in Figure 22, K^+ momentum peak from double-kaon bound state formation

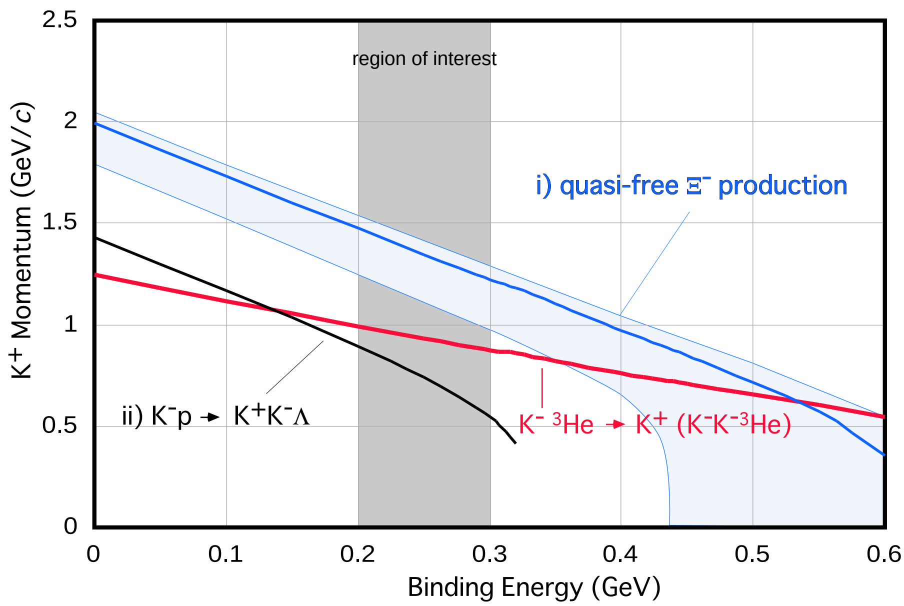


Figure 22: The K^+ momentum from double-kaon bound state formation is shown as a function of B_{KK} at the incident kaon momentum given by Figure 20. The momentum distribution of K^+ from quasi-free Ξ^- production is given with the cut-off Fermi motion of $p_F = 200$ MeV/c. The maximum momentum from K^-"p" $\rightarrow \Lambda K^- K^+$ reaction is also shown.

located in the pocket between the reactions i) and ii) at the region of interest of the binding energy of $B = 200 \sim 300$ MeV. Figure 23 shows the K^+ momentum as a function of incident K^- momentum by assuming the $B_{KK} = 250$ MeV. It should be noted that the

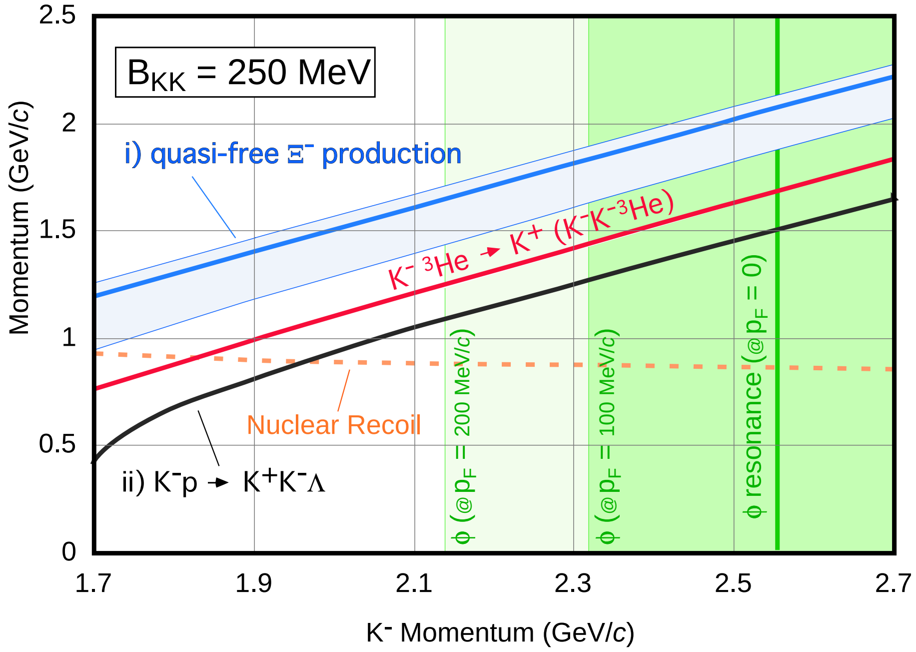


Figure 23: The K^+ momentum from double-kaon bound state formation is shown as a function of incident kaon momentum at $B_{KK} = 250$ MeV. The ϕ resonance region on single nucleon and the nuclear recoil momentum for the double-K formation are also shown.

nuclear recoil is not much different form hypernuclear formation by (π^+, K^+) reaction, and hence the cross-section would not be too small to perform an experiment. The virtual Ξ^- process, shown in Figure 20, would contribute the formation in the lower incident momentum side. Therefore, we have a chance to detect the state by the (K^-, K^+) reaction on ^{3}He target using the initial K^- momentum $2.1 \sim 2.5$ GeV, and the signal is obtained as a monochromatic peak of K^+ in the momentum spectrum at around 0.9 GeV/c.

However, the situation is not that simple. First of all, this area is not totally background-free, because the higher component of the Fermi-motion ($p_N > p_F$(@200 MeV/c)) makes the longer tail towards lower momentum side from the hatched-region of reaction i). Therefore, a reliable estimation of the cross section is indispensable. Another point is that we do not know what is the decay process of this state. If we can tag the formation, we can enhance the signal to noise ratio and be able to identify the state. To perform this, the information of the decay process is also needed.

6 Summary

We have discussed spectroscopic studies of new hadron many-body systems with strangeness degree-of-freedom: Kaon-Nucleus bound systems. So far, baryon many-body systems with strangeness, *i.e.* hypernuclei, have been intensively investigated both experimentally and theoretically. The Kaon-Nucleus bound systems are highly-excited nuclear systems much more than the hypernuclei in energy. Thus, not so much attention has been paid for the spectroscopy of such systems. Although the experimental studies for the kaon nuclear systems are just about to start, there exist various interesting predictions from theorists based on the recent information on the $\overline{K}N$ interactions. One peculiar thing of the kaon nuclear systems is the possibility to form very high nuclear densities in such systems with the help of the large attraction of $\overline{K}$. This is a quite unique opportunity: by injecting kaons into a nucleus we could increase not only strageness but also nuclear density. It is what's assumed to be happening inside a neutron star under gravity. So, it is a great experimental challenge if we could simulate it in a laboratory.

In order to proceed these investigations, we require the K^- beams available at J-PARC. The low momentum K^- beam at 700 – 1000 MeV/c is suitable for initial searches for single-$\overline{K}$ bound states in the (K^-,π^-) and/or (K^-,N) reactions. The proposed K1.1 beam line having a good resolution spectrometer system satisfies the requirement very well. We could start these measurements even with moderate K^- beam intensities.

Once the existence of such deeply-bound $\overline{K}$ states is established, it is a very interesting possibility to look for the double-$\overline{K}$ bound states via the (K^-, K^+) reaction using the K^- beam of 2.1 $\sim$ 2.5 GeV/c. However, the momentum range exceeds that of the presently planned beam line, K1.8. We might need to rebuild some critical magnets, or construct a new beam line. The $(K^-, \overline{K}^0)$ reaction is another possibility to investigate the double-$\overline{K}$ bound states. In this reaction, we could produce proton-rich double-$\overline{K}$ systems such as K^-K^-ppp from a ^{3}He target.

At this moment, we still need more theoretical works on the optimum incident kaon momentum to produce them and the decay property to tag them. However, the experimental feasibility should be pursued.

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