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(K^-, π^-) production of nuclear $\overline{K}$ bound states in proton-rich systems via Λ^* doorways

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Abstract

We propose to use the (K^-, π^-) and (π^+, K^+) reactions to produce deeply bound nuclear $\overline{K}$ states in proton-rich systems, in which an elementary formation of $\Lambda(1405)$ and $\Lambda(1520)$ plays the role of a doorway state. Exotic discrete $\overline{K}$ bound systems on unbound nuclei, such as K^-pp, K^-ppp and K^-pppn, are predicted to be produced, where a high-density nuclear medium is formed as a result of nuclear contraction due to the strong K^-–p attraction.

1. Introduction

Very recently we predicted the possible presence of discrete nuclear bound states of $\overline{K}$ in few-body nuclear systems [1–3]. The $\overline{K}$-nucleus interaction was derived from $\overline{K}N$ interactions which were constructed so as to account for the $\overline{K}N$ scattering lengths, the K^-p atomic shift and the energy and width of $\Lambda(1405)$. In these systems the strong attraction of the $I = 0$ $\overline{K}N$ interaction ($\overline{K}N^{I=0}$) plays an important role. It accommodates 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. Narrow bound states, ${}^{3}_{\overline{K}}H(T = 0) \equiv K^- \otimes {}^3He + \overline{K}^0 \otimes {}^3H(T = 0)$ and ${}^{4}_{\overline{K}}H \equiv K^- \otimes {}^4He$, with $\overline{K}$ binding energies of 108 and 86 MeV, respectively, were predicted. We studied a ${}^4He(\text{stopped } K^-, n)$ process to produce ${}^{3}_{\overline{K}}H(T = 0)$, in which the ejected neutron is used as a spectator. Its experimental feasibility has been discussed by Iwasaki et al. [4]. Another type of reactions, in-flight (K^-, N), was discussed by Kishimoto [5]. In the present Letter we propose an alternative method, namely, (K^-, π^-) and (π^+, K^+) reactions, to produce more exotic $\overline{K}$ bound states.

In view of the situation that $\Lambda(1405)$ is a bound state accommodated in a calculated K^-p potential, as shown in Fig. 1, 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

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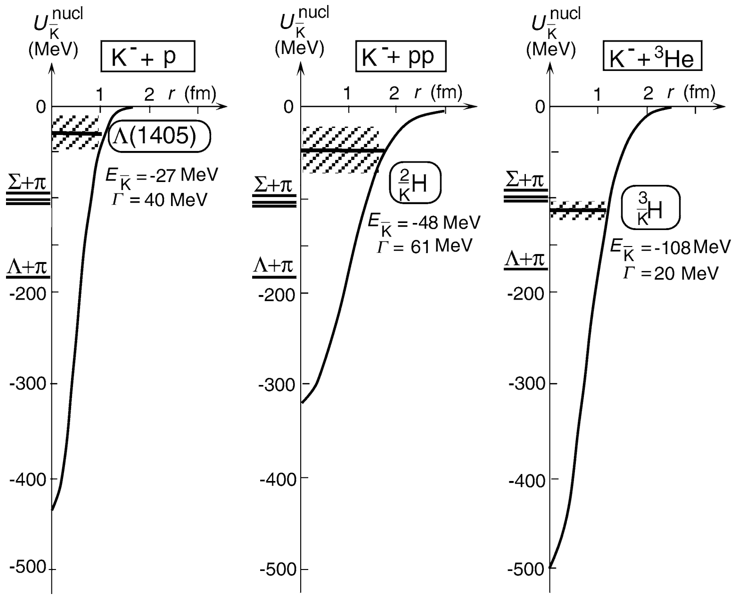

Fig. 1. Calculated $\overline{\rm K}$N and $\overline{\rm K}$-nucleus potentials and bound levels: $\Lambda(1405)$, ${}^2_{\overline{\rm K}}$H and ${}^3_{\overline{\rm K}}$H for $\rm K^-p$, $\rm K^-pp$ and $\rm K^-ppn$ systems, respectively. The nuclear contraction effect is taken into account. The shaded zones indicate the widths. The $\Sigma\pi$ and $\Lambda\pi$ emission thresholds are also shown.

problem is how to produce Λ^* in a nucleus and how to identify produced $\overline{\rm K}$ bound states. Here, we point out that the "strangeness exchange reactions" $(\rm K^-, \pi^-)$ (or similarly, $(\pi^+, \rm K^+)$) would lead to the production and detection of $\overline{\rm K}$ bound states [6]. Although it resembles the ordinary method for Λ and Σ hypernuclear spectroscopy, no attention has ever been paid to the excitation region, which is much higher than $M_\Sigma c^2 = 1190$ MeV. One of the advantages of this reaction is to produce very exotic $\overline{\rm K}$ bound systems on proton-rich "nuclei", such as p–p, that are unbound without the presence of $\rm K^-$. We first discuss the structure of such exotic systems that can be formed only by the $(\rm K^-, \pi^-)$ reaction and then consider their production processes.

2. Structure of proton-rich $\overline{\rm K}$ bound states

Table 1 shows what kinds of exotic species of $\overline{\rm K}$ bound states are formed following $(\rm K^-, \pi^-)$ reactions. The $I = 0$ $\overline{\rm K}$N pair, which possesses a strong attraction, gives an essential clue to lower the energy of a bound system. Thus, $\rm K^-pp$, $\rm K^-ppp$ and $\rm K^-pppn$ systems on non-existing nuclei, which can be produced from $\rm d(K^-, \pi^-)$, $^3\rm He(K^-, \pi^-)$ and $^4\rm He(K^-, \pi^-)$ reactions, respectively, are of particular interest. The doorway states are expressed as ${}^2_{\Lambda^*}$H, ${}^3_{\Lambda^*}$He and ${}^4_{\Lambda^*}$He in the hypernuclear nomenclature, which are converted to $\overline{\rm K}$ bound states, namely, ${}^2_{\overline{\rm K}}$H, ${}^3_{\overline{\rm K}}$He and ${}^4_{\overline{\rm K}}$He, respectively. The two less-exotic $\overline{\rm K}$ bound nuclei, ${}^3_{\overline{\rm K}}$H and ${}^4_{\overline{\rm K}}$H, can be produced by the $(\rm e, e'K^+)$ and $(\rm K^-, n)$ reactions, as shown in Table 1.

We have calculated the binding energies (B) and widths (Γ) of such proton-rich $\overline{\rm K}$ bound states by the G-matrix method, starting from the following elementary $\overline{\rm K}$N interactions, as derived in Refs. [1–3]:

$$v^I_{\overline{\rm K}\rm N}(r) = v^I_{\rm D} \exp\bigl[-(r/0.66\ \text{fm})^2\bigr], \tag{1}$$

$$v^I_{\overline{\rm K}\rm N,\pi\Sigma}(r) = v^I_{\rm C_1} \exp\bigl[-(r/0.66\ \text{fm})^2\bigr], \tag{2}$$

$$v^I_{\overline{\rm K}\rm N,\pi\Lambda}(r) = v^I_{\rm C_2} \exp\bigl[-(r/0.66\ \text{fm})^2\bigr], \tag{3}$$

with $v^{I=0}_{\rm D} = -436$ MeV, $v^{I=0}_{\rm C_1} = -412$ MeV, $v^{I=0}_{\rm C_2} = 0$, $v^{I=1}_{\rm D} = -62$ MeV, $v^{I=1}_{\rm C_1} = -285$ MeV and $v^{I=1}_{\rm C_2} = -285$ MeV, where $v^I_{\pi\Sigma}(r) = v^I_{\pi\Lambda}(r) = 0$ is taken to simply reduce the number of parameters. These interactions, characterized by the strongly attractive $v^{I=0}_{\overline{\rm K}\rm N}$ channel, were shown to lead to a strongly attractive optical potential (see detailed discussions in Ref. [3]), which is consistent with a substantial reduction of the $\rm K^-$ mass in the nuclear medium, predicted

Table 1
Light target nuclei and $\bar{\mathrm{K}}$ nuclei to be produced by (K^-,π^-) (and (π^+,K^+)), $(\mathrm{K}^-,\mathrm{n})$ and $(\mathrm{e},\mathrm{e}'\mathrm{K}^+)$ reactions through Λ^* doorways, and calculated binding energies (B in MeV) and widths (Γ in MeV) with and without nuclear contraction. Numbers of pairs of $I=0$ and $I=1$ $\bar{\mathrm{K}}\mathrm{N}$ are given as guides

Target	Reaction	Λ^* doorway	$\bar{\mathrm{K}}$ nucleus	$\bar{\mathrm{K}}\mathrm{N}^{I=0}$	$\bar{\mathrm{K}}\mathrm{N}^{I=1}$	Uncontracted		Contracted		Ref.
						B	Γ	B	Γ	
n	(K^-,π^-)	Λ^*	$\mathrm{K}^-\mathrm{p}$	1	0	–	–	27	40	
p	$(\mathrm{e},\mathrm{e}'\mathrm{K}^+)$	Λ^*	$\mathrm{K}^-\mathrm{p}$	1	0	–	–	27	40	
d	(K^-,π^-)	$\Lambda^*\mathrm{p}$	${}^{2}_{\bar{\mathrm{K}}}\mathrm{H}=\mathrm{K}^-\mathrm{pp}$	3/2	1/2	unbound		48	61	Present
^{3}He	$(\mathrm{e},\mathrm{e}'\mathrm{K}^+)$	$\Lambda^*\mathrm{pn}$	${}^{3}_{\bar{\mathrm{K}}}\mathrm{H}=\mathrm{K}^-\mathrm{ppn}$	3/2	3/2	76	82	108	20	[3]
^{4}He	$(\mathrm{K}^-,\mathrm{n})$	$\Lambda^*\mathrm{pn}$	${}^{3}_{\bar{\mathrm{K}}}\mathrm{H}=\mathrm{K}^-\mathrm{ppn}$	3/2	3/2	76	82	108	20	[3]
^{4}He	$(\mathrm{e},\mathrm{e}'\mathrm{K}^+)$	$\Lambda^*\mathrm{pnn}$	${}^{4}_{\bar{\mathrm{K}}}\mathrm{H}=\mathrm{K}^-\mathrm{ppnn}$	1	3	69	66	86	34	[3]
^{3}He	(K^-,π^-)	$\Lambda^*\mathrm{pp}$	${}^{3}_{\bar{\mathrm{K}}}\mathrm{He}=\mathrm{K}^-\mathrm{ppp}$	2	1	unbound		97	$\sim$24	[11]
^{4}He	(K^-,π^-)	$\Lambda^*\mathrm{ppn}$	${}^{4}_{\bar{\mathrm{K}}}\mathrm{He}=\mathrm{K}^-\mathrm{pppn}$	2	2	unbound		$\sim$105	$\sim$26	[11]
^{9}Be	(K^-,π^-)	$\Lambda^*(\mathrm{p})^4(\mathrm{n})^4$	${}^{9}_{\bar{\mathrm{K}}}\mathrm{Be}=\mathrm{K}^-(\mathrm{p})^5(\mathrm{n})^4$			unbound				

theoretically [7] and supported experimentally by subthreshold K^- production in heavy-ion reactions [8].

The calculated binding energies and widths in given nuclear systems are shown in Table 1. The general tendency is that the binding energy increases with an increase in the number of $I=0$ pairs and with a decrease in the number of $I=1$ pairs, as given in the table. The calculated optical potentials and bound energy levels in the $\mathrm{K}^-\mathrm{p}$, $\mathrm{K}^-\mathrm{pp}$ and $\mathrm{K}^-\mathrm{ppn}$ systems are shown in Fig. 1.

Because the strong $\bar{\mathrm{K}}\mathrm{N}^{I=0}$ binding force attracts the surrounding nucleons, the calculated binding energies become larger when we allow the freedom of nuclear contraction (shrinkage), which is counterbalanced by large nuclear incompressibility, represented by a hard core part in the nucleon–nucleon interaction [9]. Table 1 shows two cases with and without nuclear contraction. Very recently, an alternative theoretical method, Antisymmetrized Molelecular Dynamics (AMD) [11], has also been employed to calculate the binding energies. The results are in good agreement with the G-matrix calculations. Let us discuss individual cases.

2.1. ${}^{2}_{\bar{\mathrm{K}}}\mathrm{H}$ *and* ${}^{3}_{\bar{\mathrm{K}}}\mathrm{H}$

The $\mathrm{K}^-\mathrm{pp}$ system ($={}^{2}_{\bar{\mathrm{K}}}\mathrm{H}$) is the lightest nuclear system which can be called a *strange dibaryon*. Although the p–p system (^{2}He) is unbound, the presence of a $\bar{\mathrm{K}}$ attracts two protons to form a bound state with $B=48$ MeV and $\Gamma=61$ MeV. This state is lying more deeply than $\Lambda(1405)$, but still above the $\Sigma+\pi$ threshold, as shown in Fig. 1. This situation is intuitively understood in terms of the number of $\bar{\mathrm{K}}\mathrm{N}^{I=0}$ ($=3/2$) and the number of $\bar{\mathrm{K}}\mathrm{N}^{I=1}$ ($=1/2$).

The optical potential obtained for the $\mathrm{K}^-\mathrm{pp}$ system is

$$U^{\mathrm{opt}}(r)=(-300.0-\mathrm{i}\,70.0)\times\exp\bigl[-(r/1.09\ \mathrm{fm})^2\bigr]\ \mathrm{MeV}, \tag{4}$$

whereas the interaction for $\mathrm{K}^-\mathrm{p}$ (namely, for $\Lambda(1405)$) is

$$V^{I=0}_{\bar{\mathrm{K}}\mathrm{N}}(r)=(-595.0-\mathrm{i}\,83.0)\times\exp\bigl[-(r/0.66\ \mathrm{fm})^2\bigr]\ \mathrm{MeV}. \tag{5}$$

The r.m.s. relative momentum of the $\mathrm{K}^-\mathrm{p}$ in $\Lambda(1405)$ is calculated to be 270 MeV$/c$, and the r.m.s. radius of the K^- from the proton is 1.31 fm (0.86 fm from the c.m.). The density distributions of the K^- and the protons in the $\mathrm{K}^-\mathrm{pp}$ system are calculated by the variational (ATMS) method [10] from the above potential, as shown in Fig. 2. The average distances of the K^- from the center of p–p and from the proton are found to be 1.36 and 1.18 fm, respectively. The average distance between the two protons (averaged over the K^- distribution) is 1.90 fm. Namely, in the $\mathrm{K}^-\mathrm{pp}$ system, the inter-nucleon distance is similar to the ordinary one at the normal nuclear density. This is much smaller than the p–n distance in a deuteron (3.90 fm).

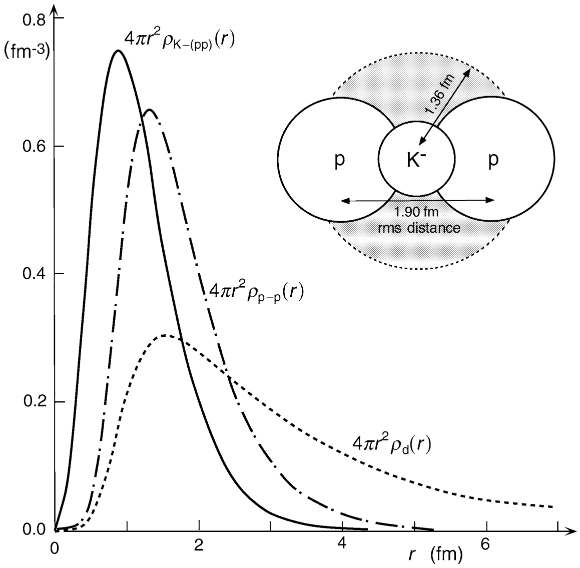

Fig. 2. The K^- and proton density distributions in the K^-pp system. As a reference the p–n density distribution in d is also shown.

When one neutron is added to this system (namely, the nucleus is ^{3}He), the pn interaction helps to increase the binding energy of the K^-ppn system ($= {}^3_{\mathrm{K}}$H) to as much as 108 MeV, as already predicted [1–3]. This value is understood as being consistent with the binding energy of the K^-pp system, which increases from 48 MeV to 98 MeV, if we convert the inter-nucleon interaction from $V_{\mathrm{NN}}(^1\mathrm{S}_0)$ to $V_{\mathrm{NN}}(^3\mathrm{S}_1)$ and the effective nucleon mass from M_{N} to $1.5M_{\mathrm{N}}$. On the other hand, the ${}^4_{\mathrm{K}}$H system has a slightly smaller binding (86 MeV) because of the decrease of the $\overline{\mathrm{K}}\mathrm{N}^{I=0}$ pair.

The other members of the K^-NN strange dibaryon system, namely, K^-nn and K^-d, are found to be unbound or much less bound. This result is understood because the interaction in K^-nn is $2 \times \overline{\mathrm{K}}\mathrm{N}^{I=1}$ on unbound n–n. In K^-d the nucleus is bound, but the interaction is $(1/2)\overline{\mathrm{K}}\mathrm{N}^{I=0} + (3/2)\overline{\mathrm{K}}\mathrm{N}^{I=1}$, too weak to bind K^-d below the $\Lambda(1405) + \mathrm{n}$ threshold. A naive argument in terms of an iso-doublet of Λ^*–N regarding Λ^* as a structureless particle would lead to a totally different result.

2.2. ${}^3_{\mathrm{K}}$He *and* ${}^4_{\mathrm{K}}$He

The ${}^3_{\mathrm{K}}$He($T = 1$) 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 ${}^4_{\mathrm{K}}$He($T = 1/2$) 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 ${}^3_{\mathrm{K}}$He($T = 1$). The pn interaction produces a stronger binding, as in the case of ${}^2_{\mathrm{K}}$H and ${}^3_{\mathrm{K}}$H. Detailed studies using the AMD method are in progress [11].

2.3. ${}^9_{\mathrm{K}}$Be

It has already been shown in Ref. [3] that the ^{8}Be nucleus, which is composed of two well-developed α clusters, is changed to a small-size high-density object when a K^- is bound. With the aid of the strong attraction of a K^- the α-cluster type structure is shrunk and a shell-like structure with a nuclear density 5 times as high as the normal one is developed. How the hard core of the NN interactions at such a high nuclear density behaves is a totally unknown domain of nuclear physics. Assuming various possibilities, the structure of this system is being studied with the AMD method [11]. The (K^-, π^-) reaction on ^{9}Be will produce a ${}^9_{\mathrm{K}}$Be nucleus, the structure of which is similar to that of K^-–^{8}Be.

3. Production of $\overline{\mathrm{K}}$ nuclei via Λ^* formation

Let us now discuss how to produce $\overline{\mathrm{K}}$ nuclei. In the special case for ${}^3_{\mathrm{K}}$H we have proposed to use the ^{4}He(stopped K^-, n) reaction [2–4], which is a nuclear Auger process. The use of in-flight (K^-, N) reactions was proposed by Kishimoto [5], who considered a knock-on type mechanism. In principle, we need a kind of trapping process for an incoming energetic K^- into a nucleus. In this respect the abundant production of Λ^* in K^--induced reactions, which was observed in past bubble-chamber experiments, gives a hint concerning the production of $\overline{\mathrm{K}}$ nuclei.

Of particular interest to us is the study of $\mathrm{K}^- + \mathrm{d}$ reactions in a deuterium bubble chamber by Hepp et al. [12,13], which yielded information on the following elementary processes:

$$\mathrm{K}^- + \text{“n”} \to \text{“}\Lambda(1405)\text{”} + \pi^-, \tag{6}$$

$$\mathrm{K}^- + \text{“n”} \to \text{“}\Lambda(1520)\text{”} + \pi^-. \tag{7}$$

These processes were deduced from invariant mass spectra of $(\Sigma\pi)^0 = \Sigma^\pm\pi^\mp$ in the $\mathrm{K}^- + \mathrm{d} \to (\Sigma\pi)^0 + \pi^- + \mathrm{p}_s$ reaction channel with p_s being a spectator of the above process. The cross section for the $(\Sigma\pi)^0 + \pi^- + \mathrm{p}_s$ 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. 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. We consider these elementary production processes to be sources for the production of $\overline{\mathrm{K}}$ bound states in the missing mass spectra of (K^-, π^-) reactions on nuclear targets.

Historically, $\Lambda(1405)$ was discovered in an invariant mass spectrum of $(\Sigma\pi)^0$ in a $\mathrm{K}^- + \mathrm{p}$ reaction at $p_K = 1.15$ GeV/c in a hydrogen bubble-chamber experiment [14]. Most of the events in the four-body final channel, $(\Sigma\pi)^0 + (\pi\pi)^0$, yielded a total cross section of 0.3 mb for $\Lambda(1405)$. An additional experiment [15] revealed $\Lambda(1405)$ production together with a π^0 with a cross section of 0.1–0.2 mb for $p_K = 0.76, 0.85$ and 1.15 GeV/c. $\Lambda(1405)$ was also identified in the (π^+, K^+) reaction [16] and in a non-pionic reaction, $\mathrm{K}^- + \mathrm{d} \to (\Sigma\pi)^0 + \mathrm{n}$ [17–20]. Recently, abundant production of $\Sigma(1385)$, $\Lambda(1405)$, and $\Lambda(1520)$ has been observed in the missing-mass spectra of $\mathrm{p}(\gamma, \mathrm{K}^+)$ [21,22] and $\mathrm{p}(\mathrm{p}, \mathrm{pK}^+)$ [23].

It is to be noted that a “K^--coalescence” model for $\Lambda(1405)$ formation in the above reactions, in which an incident K^- collides with a proton with a large momentum, may not account for the abundant production of $\Lambda(1405)$, as long as $\Lambda(1405)$ is a bound state of $\mathrm{K}^- + \mathrm{p}$ 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 the above mentioned different reactions 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 $\Lambda(1405)$ is formed in a nucleus in such a “hard” process, it is subject to dissolution into $\overline{\mathrm{K}}$ bound states because of its “soft” character. The key element in the proposed method is the role of $\Lambda(1405)$ as a doorway state, as shown in a diagram in Fig. 3(a). When a $\Lambda(1405)$ is produced by a reaction (Eq. (6)) in a target A: ${}_Z[A]_N$ $(= \mathrm{B} + \mathrm{n})$ 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

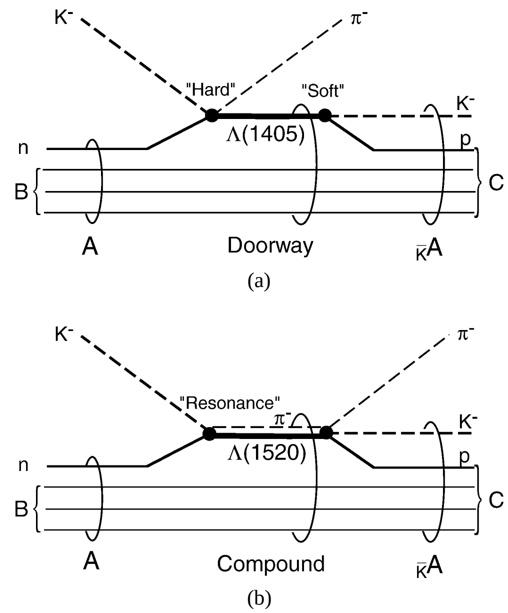

Fig. 3. Diagrams for the production of $\overline{\mathrm{K}}$ bound states in (K^-, π^-) reactions through Λ^* as a doorway. (a) “Hard” production of $\Lambda(1405)$ and its propagation. (b) Resonant formation of $\Lambda(1520) + \pi^-$ and their propagations.

$$\mathrm{K}^- + \mathrm{A} \to \text{“}\Lambda(1405)\text{”} + \mathrm{B} + \pi^- \tag{8}$$

$$\to \mathrm{C} + \mathrm{K}^- + \pi^-, \tag{9}$$

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

We formulate the production process for $\overline{\mathrm{K}}$ bound states based on the $\Lambda(1405)$ doorway model. For the simplest case, $\mathrm{d}(\mathrm{K}^-, \pi^-)\mathrm{K}^-\mathrm{pp}$, we obtain the following expression

$$F(E) = \frac{\mathrm{d}^2\sigma}{\mathrm{d}E_\pi\,\mathrm{d}\Omega_\pi} \Bigg/ \frac{\mathrm{d}\sigma^{\mathrm{elem}}_{\Lambda^*}}{\mathrm{d}\Omega^{(0)}_\pi}$$

$$= \alpha(k_\pi) \frac{|\langle \Lambda^* | V_{\overline{\mathrm{K}}\mathrm{N}}^{I=0} | \Lambda^* \rangle|^2}{(\widetilde{E} - \overline{E}_{\Lambda^* \mathrm{p}})^2 + \frac{1}{4}\Gamma_{\Lambda^*}^2} S(E) \tag{10}$$

with

$$S(E) = \left(-\frac{1}{\pi}\right) \mathrm{Im}\left[\int \mathrm{d}\vec{r}_\mathrm{K}\, \mathrm{d}\vec{r}\,'_\mathrm{K}\, \tilde{f}^*(\vec{r}_\mathrm{K}) \times \left\langle \vec{r}_\mathrm{K} \right| \frac{1}{E - H_{\mathrm{K}^-\mathrm{pp}} + i\epsilon} \left| \vec{r}\,'_\mathrm{K} \right\rangle \tilde{f}\left(\vec{r}\,'_\mathrm{K}\right) \right], \tag{11}$$

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

$$\tilde{f}(\vec{r}\,) = 2^3 \mathrm{e}^{\mathrm{i}\,2\beta\vec{q}\vec{r}} C(r) \frac{\Phi_{\mathrm{pp}}^*(2r)\Psi_\mathrm{d}(2r)}{|\Phi_{\Lambda^*}(0)|}, \tag{12}$$

with $\vec{q} = \vec{k}_\mathrm{K} - \vec{k}_\pi$, $\beta = M_\mathrm{p}/(M_{\Lambda^*} + M_\mathrm{p})$ and $C(r) = 1 - \exp[-(r/1.2\ \mathrm{fm})^2]$. In this derivation we have used a zero-range approximation for $V_{\overline{\mathrm{K}}\mathrm{N}}^{I=0}$ and closure approximation to doorway states. The strength of the $\overline{\mathrm{K}}$N interaction in Λ^*, calculated by using the wavefunction of the K^-p system, is

$$\left\langle \Lambda^* \middle| V_{\overline{\mathrm{K}}\mathrm{N}}^{I=0} \middle| \Lambda^* \right\rangle = -138 - \mathrm{i}\,20\ \mathrm{MeV}. \tag{13}$$

The momentum transfer q in the (K^-, π^-) reaction to produce this state is around 300 MeV/c. The elementary cross section for $\mathrm{n}(\mathrm{K}^-, \pi^-)\Lambda(1405)$, obtained from the experiment of Hepp et al. [12], is about 3 mb. The calculated spectral function $S(E)$ in Eq. (11) shows a broad peak at $B = 48$ MeV below the K^-pp threshold with a width $\Gamma = 61$ MeV. The weighted spectral function $F(E)$, Eq. (10), is shifted toward the doorway state $\Lambda(1405)$. The calculated total strength over the bound state region is 0.023. Thus, the cross section for $\mathrm{d}(\mathrm{K}^-, \pi^-)\mathrm{K}^-$pp in this mechanism is estimated to be

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\left[\mathrm{d}(\mathrm{K}^-, \pi^-)\mathrm{K}^-\mathrm{pp}\right] \sim 6\ \mu\mathrm{b/sr}. \tag{14}$$

Details of the calculations will be published elsewhere.

4. Production via Λ(1520) formation

The process we have considered above is a "direct reaction" type. There is another process, that is, the "resonant formation of a compound nucleus". The production cross section for $\Lambda(1405)$ observed in a bubble-chamber experiment [12,13] shows a resonance-like plateau at a c.m. energy of $E^* \sim 1660$ MeV (Fig. 8 of Ref. [12]). This indicates the resonant formation of a compound state,

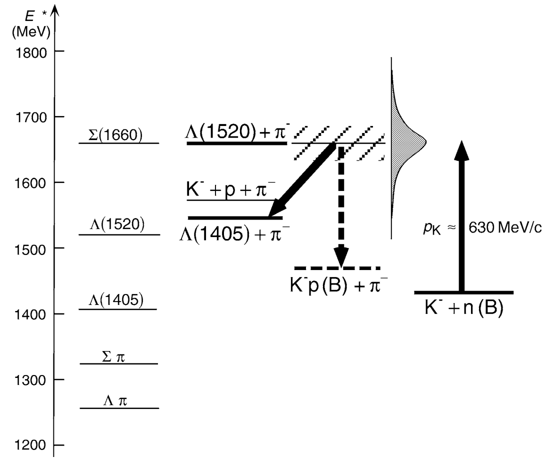

Fig. 4. Energy diagram relevant to the formation of $\overline{\mathrm{K}}$ bound states in (K^-, π^-) reactions through $\Lambda(1520) + \pi^-$ resonance as a doorway.

$$\mathrm{K}^- + \text{“n”} \leftrightarrow \Lambda(1520) + \pi^- \leftrightarrow \mathrm{K}^- + \mathrm{p} + \pi^-, \tag{15}$$

which decays in vacuum as

$$\mathrm{K}^- + \text{“n”} \to \text{“}\Lambda(1405)\text{”} + \pi^-, \tag{16}$$

as shown in Fig. 4. When this resonant formation of $\Lambda(1520) + \pi^-$ takes place in a nucleus,

$$\mathrm{K}^- + \mathrm{A} \leftrightarrow \mathrm{B} + \Lambda(1520) + \pi^- \tag{17}$$

$$\leftrightarrow \mathrm{B} + \mathrm{K}^- + \mathrm{p} + \pi^-, \tag{18}$$

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

$$\to \mathrm{B} + \Lambda(1405) + \pi^-, \tag{19}$$

$$\to \mathrm{K}^-\mathrm{C}(\equiv {}_{\overline{\mathrm{K}}}\mathrm{A}) + \pi^-. \tag{20}$$

Namely, the resonating particles, $\Lambda(1520) + \pi^- \leftrightarrow \mathrm{K}^- + \mathrm{p} + \pi^-$, together with the nucleus B form a "compound nucleus" which decays to a $\overline{\mathrm{K}}$ bound state in C without producing a $\Lambda(1405)$. A diagram for this process is shown in Fig. 3(b). In this $\Lambda(1520)$ doorway process, the productions of a free $\Lambda(1405)$ and of a $\overline{\mathrm{K}}$ bound state are two competing final channels having the common origin. The branching ratio, $\sigma[\overline{\mathrm{K}}\text{-nucleus}]/\sigma[\Lambda(1405)]$, is expected to be large.

5. Past experiments

It is an intriguing question to ask whether or not the $\mathrm{K}^- + \mathrm{d}$ bubble-chamber experiment [12,13] showed any evidence for the presence of a bound $\mathrm{K}^-\mathrm{pp}$ state. In fact, the invariant mass spectra of $(\Sigma\pi)^0$ in the $\mathrm{K}^- + \mathrm{d} \to (\Sigma\pi)^0 + \pi^- + \mathrm{p}_s$ reaction channel revealed not only $\Sigma(1385)$, $\Lambda(1405)$ and $\Lambda(1520)$ peaks but also a substantial continuum (Fig. 11(a) of Ref. [12]), which might be accounted for as due to the three-body final states in the decay of a hypothetical $\mathrm{K}^-\mathrm{pp}$ bound state, as

$$\mathrm{K}^-\mathrm{pp} \to \Sigma^{\pm} + \pi^{\mp} + \mathrm{p}. \tag{21}$$

The "spectator proton" spectrum in the $\mathrm{K}^- + \mathrm{d} \to (\Sigma\pi)^0 + \pi^- + \mathrm{p}_s$ reaction channel (Fig. 3(c) of Ref. [12]) seems to show an extra high momentum component, which might be compatible with the interpretation that those protons with a high momentum ($\sim 400\ \mathrm{MeV}/c$) were not spectator protons but were "emitted" from the above decay process. Unfortunately, no missing mass spectrum of $\mathrm{d}(\mathrm{K}^-, \pi^-)$, which would have contained a direct information on the predicted bound state, has been reported. Thus, we have to wait for a new experiment which we are proposing.

6. Concluding remarks

In the present Letter we have shown theoretically that very exotic species of $\overline{\mathrm{K}}$ bound states can be formed in (K^-, π^-) and (π^+, K^+) reactions, where $\Lambda(1405)$ and $\Lambda(1520)$ play important roles as doorways. Such "bound-$\overline{\mathrm{K}}$ 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 obey the present $\overline{\mathrm{K}}\mathrm{N}$ interactions at such a high density ($\rho \sim 5 \times \rho_0$) is an extremely interesting question. To prove all the underlying assertions, in particular, concerning the bound-state nature of $\Lambda(1405)$ and its propagation in nuclei, it is vitally important to examine experimentally the simplest case of $\mathrm{K}^-\mathrm{pp}$, which will provide an important gateway toward more complicated and more exotic systems.

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