Strange tribaryons as $\bar{K}$-mediated dense nuclear systems

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$\bar{K}$ nuclei, which means that a K^- meson is deeply bound in nuclei, are considered to have lots of interesting properties. Recently, two $\bar{K}$ nuclei, $ppnK^-$ and $pnnK^-$ which are called "strange tribaryons", have been experimentally confirmed by Iwasaki group. Their experimental results brought us two puzzles; i) $ppnK^-$ is more deeply bound than our prediction, and ii) How is $pnnK^-$ that is more deeply bound than $ppnK^-$? We point out that i) relativistic effect and enhancement of $\bar{K}N$ interaction and ii) nucleon configuration of $pnnK^-$ are important to solve these puzzles. The observed $pnnK^-$ is considered to have an excited configuration, $(0s)^2(0p)$, not the ground one, $(0s)^3$. Due to such excited configuration, it can gain attraction from $I = 0$ $\bar{K}N$ interaction and NN LS interaction.

1 Introduction

Due to the strongly attractive $\bar{K}N$ interaction, especially in $I = 0$ $\bar{K}N$ channel (I: isospin),[1] a K^- meson can be deeply bound in a light nucleus to form a $\bar{K}$ nucleus. We have pointed out theoretically that $\bar{K}$ nuclei are expected to have a lot of interesting properties as follows: 1. As a result of the calculation with our phenomenological $\bar{K}N$ interaction, K^- meson is bound by more than 100 MeV in various light nuclei. Such deep binding makes the main decay channel ($\Sigma\pi$ emission) closed. $\bar{K}$ nuclei can exist as a discrete nuclear state. [1, 2, 3] 2. K^- meson attracts nucleons around itself to form highly dense state in a nucleus. The maximum density amounts to more than 4 ρ_0. [2, 3] ($\rho_0 = 0.17$ fm^{-3}, normal density) 3. Such a strong $\bar{K}$ attraction causes so strange nuclear structures that we have never seen in usual nuclei. The most impressive result obtained with the method of antisymmetrized molecular dynamics (AMD) is drastic change of nuclear structure. Fig. 1 shows the density contour of normal ^{8}Be and ^{8}BeK^-. ^{8}Be has a

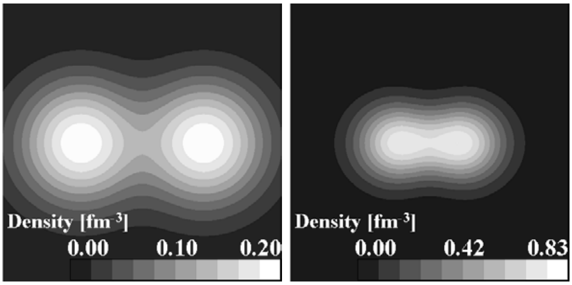

Figure 1: Comparison of density contour of ^{8}Be and ^{8}BeK^-. The left (right) panel shows the nucleon density distribution of ^{8}Be (^{8}BeK^-). The framework of each figure is 4×4 fm^2.

well-developed clustering structure, whereas such a clustering structure almost disappears in ^{8}BeK^-. $\bar{K}$ nuclei are found to have lots of interesting structures other than such a drastic shrinkage by our study with AMD; isovector deformation in ^{8}BeK^-,[2] proton satellite in $pppK^-$,[3] and strongly isospin-dependent structures in $J^\pi = 1/2^+$ excited states of ^{11}CK^-; $T = 0$ state has a cluster-like structure, whereas $T = 1$ state does a shell-like structure.[4] (T: total isospin) Readers are directed to each reference to know in more detail.

Do such exotic objects, $\bar{K}$ nuclei, really exist? Nowadays, some experimental groups try to explore the $\bar{K}$ nuclei in various ways. Recently, Iwasaki group has confirmed experimenrally $ppnK^-$ and $pnnK^-$, which are called "strange tribaryons".[5] These results brought us new puzzles on $\bar{K}$ nuclei. According to their experiment, the total binding energy and decay width are (169 MeV, $<$ 25 MeV) for $ppnK^-$ and (194 MeV, $<$ 21 MeV) for $pnnK^-$, respectively. Certainly, these results support our prediction of deeply bound $\bar{K}$ nuclei being discrete state. The obtained binding energies, however, are much larger than our prediction (118 MeV for $ppnK^-$). We have another question "How is the observed $pnnK^-$?". We have not predicted such a deep binding of $pnnK^-$.

In this report, we consider the new puzzle brought by the recent experiment, in particular the deep binding of $pnnK^-$.

2 Methods

We employ the method of antisymmetrized molecular dynamics to study $\bar{K}$ nuclei. In AMD, each particle is represented by superposition of several Gaussian wave packets. The position of the center of each wave packet is determined by a frictional cooling equation,[2, 3] which is one of energy variation. AMD treats a system in a fully microscopic way and it has no assumption on the structure of the system, such as existence of clusters and deformation of the system. Therefore, this method is suitable to the study of $\bar{K}$ nuclei, which has unknown structures.

However, we need an improvement of AMD when it is applied to $\bar{K}$ nuclei. As mentioned in Introduction, the $I = 0$ $\bar{K}N$ interaction plays an important role in $\bar{K}$ nuclei. This interaction causes a coupling of K^--proton pair and $\bar{K}^0$-neutron pair in such a charge-base treatment as AMD. We solve this problem with charge-mixed wave function;

$$
\begin{aligned}
|N_i\rangle &= x_i \,|\,\mathrm{proton}\,\rangle \,+\, \mathrm{y_i} \,|\,\mathrm{neutron}\,\rangle \\
|K\rangle &= a \,|\,\bar{K}^0\,\rangle \,+\, b \,|\,K^-\,\rangle,
\end{aligned}
$$

where x_i, y_i, a and b are variational parameters. The nucleon wave function $|N_i\rangle$ can describe both states of proton and neutron. In the same way, the kaon wave function $|K\rangle$ can describe both states of $\bar{K}^0$ and K^-. We notice that the charge of total system is restored by the charge-number projection. Details of our wave function are explained in Ref. [3].

The Hamiltonian used in our study is as follows;

$$\hat{H} = \hat{T} \,+\, \hat{V}_{NN\,Central} \,+\, \hat{V}_{NN\,LS} \,+\, x\,\hat{V}_{KN} \,+\, \hat{V}_{Coulomb} \,-\, \hat{T}_{CM}. \tag{1}$$

$\hat{T}$ is kinetic energy part. $\hat{V}_{NN\,Central}$ and $\hat{V}_{NN\,LS}$ are effective NN central and LS interactions, respectively. $\hat{V}_{KN}$ is effective $\bar{K}N$ interaction. $\hat{V}_{Coulomb}$ is Coulomb force for both of proton-proton and K^--proton. The center-of-mass motion energy $\hat{T}_{CM}$ is removed. The effective NN and KN are derived with G-matrix method[1] from Tamagaki potential (OPEG)[6] which is a realistic potential, and a phenomenological $\bar{K}N$ potential[1] which is constructed by Y. A. and T. Y., respectively. The effective LS interaction is derived quite in the same way as the effective central interaction. In the present study, we modify the strength of effective $\bar{K}N$ interaction by a factor x in front of $\hat{V}_{KN}$ in Eq. (1).

3 Understanding of the experimental results

We try to understand two puzzles brought by Iwasaki's experiment; i) The observed $ppnK^-$ is more deeply bound than that of our original prediction. and ii) How is the observed $pnnK^-$ which is more deeply bound than $ppnK^-$? Hereafter, we assigned the observed $ppnK^-$ to $T = 0$ state, though it might be $T = 1$ state. The observed $pnnK^-$ is uniquely assigned to $T = 1$ state.

3.1 Relativistic effect

The first puzzle i) is solved by the relativistic effect and the slight enhancement of the strength of $\bar{K}N$ interaction. Since $\bar{K}$ nuclei obtained by our calculation are very dense, the relativistic effect is important which we have not taken into account in the previous study. Y. A. proposed a prescription to transfer the non-relativistic energy of kaon (ε_S) to the relativistic energy (ε_{KG}). ε_S is obtained by solving a Schrödinger equation (non-relativistic equation) as we have done, whereas ε_{KG} is obtained by solving a Klein-Gordon equation (relativistic equation). The Klein-Gordon equation can be rewritten in a Schrödinger-equation-like form. Comparing it with our Schrödinger equation, we notice that the energy terms in both equations are corresponding to each other as follows;

$$\varepsilon_S \;\longrightarrow\; \varepsilon_{KG} + \frac{\varepsilon_{KG}^2}{2m_K c^2},$$

Table 1: Ratio of $I = 0$ and $I = 1$ $\bar{K}N$ pairs in three nucleons and a $\bar{K}$ systems. "T" means the total isospin of the system. "N. Config." shows the nucleon configuration. "$I = 0$" and "$I = 1$" show the ratio of $I = 0$ and $I = 1$ $\bar{K}N$ pairs included in each state.

T	N. Config.	$I = 0$	$I = 1$
1	$(0s)^3$	1/6	5/6
1	$(0s)^2(0p)$	2/3	1/3
0	$(0s)^3$	1/2	1/2

where m_K is mass of K^- meson. According to Y. A.'s analysis of $ppnK^-$ with a model calculation, its total binding energy increases from 118 MeV (original result) to 134 MeV, by transferring the non-relativistic kaon energy ε_S to the relativistic one ε_{KG} with the above prescription. When we enhance the strength of bare $\bar{K}N$ interaction by 15%, we can reproduce the experimental value (169 MeV) with this relativistic correction. Details on this point are explained in Ref. [7].

3.2 Configuration of $pnnK^-(T = 1)$

Nucleon configuration in $pnnK^-(T = 1)$ is a key point in the second puzzle ii), We consider that it is not $(0s)^3$ but $(0s)^2(0p)$. By a simple consideration, the ratio of $I = 0$ and $I = 1$ $\bar{K}N$ components in each state is found to be as shown in Table 1. Thus, the $T = 1$ state with the excited configuration $(0s)^2(0p)$ contains the $I = 0$ $\bar{K}N$ component *the most*, although that with the ground configuration $(0s)^3$ contains it the least. Therefore, due to the large attraction of the $I = 0$ $\bar{K}N$ interaction, the $T = 1$ state with the excited configuration is expected to gain the binding energy more than the $T = 0$ state, in spite that a $0p$-shell nucleon is less bound than a $0s$-shell one.

As a result of AMD calculations with 14% modified $\bar{K}N$ interaction ($x = 1.14$ in Eq. (1)), the binding energies of $ppnK^-(T = 0)$ and $pnnK^-(T = 1)$ [1] are equal to 177 MeV and 162 MeV, respectively. In case of no modification of the $\bar{K}N$ interaction, they are 117 MeV and 87 MeV, respectively. The energy gain of the $T = 1$ state (75 MeV) is larger than that of the $T = 0$ state (60 MeV) by the modification, because the $T = 1$ state has the very attractive $I = 0$ $\bar{K}N$ component more than the $T = 0$ state, as mentioned before. Thus, when the $\bar{K}N$ interaction is modified to reproduce the binding energy of the observed $ppnK^-$, the energy difference between the $T = 0$ and $T = 1$ states decreases to be only 15 MeV.

3.3 Effect of Nucleon-Nucleon LS interaction

So far, we have not treated Nucleon-Nucleon LS interaction, because we have avoided introducing complex ingredients in the first step of our study of unknown objects, $\bar{K}$

[1] In our calculation, $pnnK^-(T = 1)$ are projected onto the negative parity state, corresponding to the $(0s)^2(0p)$ configuration.

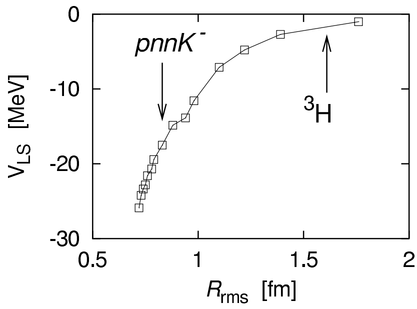

Figure 2: The contribution of LS interaction (V_{LS}) in $pnnK^-$ with various size (R_{rms}). V_{LS} is in unit of MeV. R_{rms} means the root-mean-square radius of $pnnK^-$ in unit of fm.

nuclei. But now, we should consider the effect of the NN LS interaction, because it gives extra attraction to a nucleon occupying $0p_{3/2}$ state in $pnnK^-(T=1)$.

We have re-calculated the same systems with the NN LS interaction, using the modified $\bar{K}N$ interaction as explained above. The result of the $T=0$ state has no change and its binding energy remains to be 177 MeV, because all nucleons are in $0s$ shell and are not influenced by the LS interaction. On the other hand, the $T=1$ state obtains extra binding by the LS interaction. Its binding energy is equal to 187 MeV. Namely, $pnnK^-(T=1)$ is energetically lower than $ppnK^-(T=0)$ by 10 MeV.

The contribution of LS interaction is -25 MeV in $pnnK^-$ obtained by our calculation. This value is rather large, comparing to cases of normal nuclei. It is known that the contribution of LS interaction is only $1 \sim 2$ MeV in ^{5}He which has one nucleon in $0p$ shell as well as $pnnK^-(T=1)$. Such large LS contribution is attributed to the shrinkage and dense state of $\bar{K}$ nuclei. Figure 2 shows the LS contributions in $pnnK^-$ with various size. When the size of $pnnK^-$ is equal to that of normal nucleus ($R_{rms} \simeq 1.5$ fm), the LS contribution is only 1 MeV. As the system is shrunk, the LS contribution increases continuously and drastically. It amounts to 20 MeV when the size of system is as small as that of $\bar{K}$ nuclei ($R_{rms} \simeq 0.8$ fm). Thus, it is confirmed that the LS interaction gives large contribution to shrunk and dense $\bar{K}$ nuclei, even though it gives small contribution in normal nuclei. Such a large LS contribution in $\bar{K}$ nuclei is consistent with $^3P_2$ pairing caused by strong attraction of LS interaction in dense neutron star.[8]

3.4 Role of satellite structure

We mention the structure of $pnnK^-(T=1)$. Since it has the same quantum numbers as $pppK^-$ ($J^\pi = 3/2^-$ and $T=1$), the present $pnnK^-$ is the isobaric analog state of $pppK^-$. Actually as shown in the left panel of Figure 3, it has a *satellite structure* similar to $pppK^-$.[3] The satellite is formed by a neutron, not a proton in case of $pppK^-$. We have found a local-minimum state (B.E. = 170 MeV) which has no satellite structure as shown

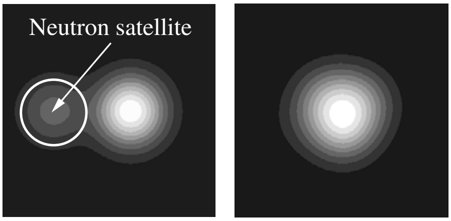

Figure 3: Nucleon density contour of $pnnK^-$. True minimum state (left) and local minimum state (right). The framework of each figure is 3×3 fm^2.

in the right panel of Figure 3. Comparing these two states, it is found that the satellite structure contributes to gain the binding energy. Table 2 shows the energy contributions in both of satellite and no-satellite cases. Since the no-satellite state is much compacter than the satellite state, the NN LS interaction (and $\bar{K}N$ interaction also) gives it larger attraction. However, since it is too compact, it has very large kinetic energy and large repulsion of NN central interaction, which cancel the large LS attraction. On the other hand, in the satellite state, the kinetic energy is not so large, the central interaction is less repulsive and the LS interaction is still attractive, because the satellite neutron is separated from others. As a result of the energy balance, the satellite state appears as the true-minimum state.

4 Summary and some comments

We have tried to solve two puzzles brought by "strange tribaryons" which have been discovered experimentally by Iwasaki group. The first puzzle "The observed $ppnK^-$ is more deeply bound than our prediction." can be solved by the relativistic effect with 15% enhancement of the strength of bare $\bar{K}N$ interaction. In the present calculations of AMD, we enhanced the strength of effective $\bar{K}N$ potential by 14%, instead of explicitly treating the relativistic effect. This enhancement is considered to include the relativistic effect.

In this report, we focused on the second puzzle, "How is the observed $pnnK^-$ which

Table 2: Energy contributions in $pnnK^-$ with and without the satellite structure. T is kinetic energy. $V_{NN\ Central}$ and $V_{NN\ LS}$ are NN central and LS potential energies, respectively. V_{KN} is $\bar{K}N$ potential energy. $V_{Coulomb}$ is Coulomb energy. B.E. means binding energy. All values are in unit of MeV.

Satellite	T	$V_{NN\ Central}$	$V_{NN\ LS}$	V_{KN}	$V_{Coulomb}$	B.E.
with	488	59	−26	−708	0	187
without	576	93	−55	−783	−1	170

Table 3: Summary of the present study on $ppnK^-$ and $pnnK^-$. This table shows the total binding energy in unit of MeV. "x" is the $\bar{K}N$ modification factor in Eq. (1). Parity (π) does not include the eigen-parity of K^- meson.

x [times]	1.00	1.14	1.14	
NN LS interaction	w/o	w/o	w	Experiment[5]
$ppnK^-(J^\pi = 1/2^+, T = 0)$	118	177	177	169
$pnnK^-(J^\pi = 3/2^-, T = 1)$	87	162	187	194

is more deeply bound than $ppnK^-$?". Our answer to this puzzle, at the present stage, is as follows. *The observed $pnnK^-(T = 1)$ has an excited configuration of nucleons, $(0s)^2(0p)$, not a ground one,* $(0s)^3$. This excited configuration has two advantages to gain the binding energy, in spite of less binding of a $0p$-shell nucleon. As one advantage, the $T = 1$ state with the excited configuration has the $I = 0$ $\bar{K}N$ component, which gives extremely attractive $\bar{K}N$ interaction, more than the $T = 0$ and 1 states with the ground configuration. Therefore, when the effective $\bar{K}N$ interaction is modified slightly (14% enhanced) to reproduce the binding energy of the observed $ppnK^-(T = 0)$, the $T = 1$ state can gain the binding energy more than the $T = 0$ state. Thus, the energy difference between these two states decreases to be 10 MeV. As the other advantage, this excited configuration can gain the binding energy by NN LS interaction, because a nucleon occupies $0p_{3/2}$ state. Since $\bar{K}$ nuclei are very shrunk and dense, the LS contribution is rather large than in normal nuclei. Of course, the NN LS interaction gives no influence to the $T = 0$ state where all nucleons are in $0s$ shell. Thus, only the $T = 1$ state can gain the binding energy to come down energetically below the $T = 0$ state. The $T = 1$ state has a neutron satellite structure, which contributes to gain the binding energy. The results of the $T = 0$ and $T = 1$ states considered in this report are summarized in Table 3.

We introduce shortly recent results of other $\bar{K}$ nuclei calculated by AMD with the 14% enhanced $\bar{K}N$ potential and the NN LS interaction. The binding energies of such $\bar{K}$ nuclei as $ppnK^-$ to $^{11}CK^-$ increase to 200 MeV measured from each nucleus-K^- threshold, whereas they were 100 MeV in our previous study.

We would like to say a few requests to experimentalists. First, we hope the measurement of J^π, at least parity, of $ppnK^-$ and $pnnK^-$, although it is very difficult to do. If our scenario mentioned in this report is correct, $pnnK^-$ should be positive-parity state because one nucleon is in $0p$ orbit, whereas $ppnK^-$ is negative-parity state. (Here, we denote the parity including the eigen-parity of a K^- meson.) We can check our scenario by the measurement of parity. Second, we hope the measurement of size of $\bar{K}$ nuclei. Although the deeply bound states were certainly confirmed by Iwasaki's experiment, we have not confirmed yet whether the observed objects are dense or not. We consider that LS splitting between $J^\pi = 3/2^-$ and $1/2^-$ in $pnnK^-$ is useful to obtain the information on the density, if $pnnK^-$ has the $(0s)^2(0p)$ nucleon configuration. Finally, we hope more measurements of other $\bar{K}$ nuclei and their excited states. Compiling various informations on $\bar{K}$ nuclei, we can know properties of $\bar{K}$ nuclei more accurately.

Theoretical studies are also needed. As for my study, the effect of other type $\bar{K}N$ interaction, such as $I = 1$ p-wave interaction,[9] should be investigated. Studies from the viewpoint of quarks are thought to be important, because the maximum density amount to $10\rho_0$ in case of such small systems as $ppnK^-$ and $pnnK^-$, as a result of our calculation with hadrons.

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