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DEEPLY BOUND MESONIC NUCLEAR STATES

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Abstract

Strongly bound $\bar{\mathrm{K}}$ nuclear systems have been predicted, which are shown to have large binding energies about 100 MeV. The separation energies of a K^- in ^{2}He, ^{3}He and ^{4}He are calculated non-relativistically to be 48, 108 and 86 MeV with widths of 61, 20 and 34 MeV, respectively. A substantial contraction of the $\bar{\mathrm{K}}$ nuclei is induced due to the $I = 0$ $\bar{\mathrm{K}}$N strong attraction, thus forming an unusually dense nuclear object. Since these $\bar{\mathrm{K}}$ nuclei have large densities, *i.e.* several times the normal density, they provide a unique playground for studying possible QCD structure in dense and cold nuclear systems. We discuss implications of recent report on a strange tri-baryon $\mathrm{S}^1(3135)$ from ^{4}He(stopped K^-, n) experiment at KEK, which corresponds to the expected $T = 0$ ppnK^- state. The observed separation energy is substantially larger than the predicted non-relativistic value, which can be accounted for by introducing the relativistic effect and an in-medium $\bar{\mathrm{K}}$N interaction enhanced by 17%. A new paradigm is discussed, which would be deeply related to chiral symmetry restoration, kaon condensation and strange matter.

1 Introduction

In a series of publications [1, 2, 3, 4, 5, 6] we have predicted the possible existence of deeply bound $\bar{\mathrm{K}}$ nuclear states. The $\bar{\mathrm{K}}$N interaction used is derived from the available empirical data of $\bar{\mathrm{K}}$N scattering lengths [7] and kaonic hydrogen level shift [8] together with the supposition that $\Lambda(1405)$ is a bound state of $\bar{\mathrm{K}}$N. The existence of such exotic $\bar{\mathrm{K}}$ nuclear states results from the strongly attractive $\bar{\mathrm{K}}$N interaction in the two-body isospin $I = 0$ state. The interaction causes not only a large binding but also an enormous shrinkage of $\bar{\mathrm{K}}$ nuclei against the hard nuclear incompressibility. Thus, a $\bar{\mathrm{K}}$ produces a bound state with a "condensed nucleus". This extremely interesting possibility for studying dense and cold nuclei is worth pursuing theoretically and experimentally. An observation of such deeply bound states would confirm the underlying physics framework, providing profound information on in-medium modification of the $\bar{\mathrm{K}}$N interaction.

Very recently, experimental evidences have been reported by Iwasaki *et al.*'s E471 group. The first one was observed in the search for the predicted $T = 0$ ppnK$^-$ in the ^{4}He(stopped K$^-$, n) reaction at KEK [9]. A bump corresponding to a total mass of $M = 3137 \pm 4$ MeV/c^2 is seen, which is referred to as S^1(3135) and can be identified as $T = 0$ ppnK$^-$. The indicated separation energy, however, is much larger than the predicted value. The second one is a discovery of another species of $\bar{\mathrm{K}}$ nucleus, pnnK$^-$. A distinct peak appears at a mass of $M = 3117 \pm 5$ MeV/c^2, which is named S^0(3115) [10].

In this paper we survey works about various nuclear states of a $\bar{\mathrm{K}}$ in light nuclei done in collaboration with A. Doté and T. Yamazaki, and show that the recent experimental data can be understood within a framework of deeply bound $\bar{\mathrm{K}}$ states in condensed nuclei. Finally, future prospects are foreseen about physics of $\bar{\mathrm{K}}$ nuclear systems.

2 Deeply bound $\bar{\mathrm{K}}$ nuclei

2.1 ppK$^-$ and pppK$^-$

The $^2_{\bar{\mathrm{K}}}$H system is the lightest multi-baryon system, where the conventional nomenclature is employed, that is, $^2_{\bar{\mathrm{K}}}$H is the state of K$^-\otimes^2$He + $\bar{\mathrm{K}}^0\otimes^2$H ($T = 1/2$). Hereafter, we use ppK$^-$ as the abbreviation of $^2_{\bar{\mathrm{K}}}$H. This system is treated with a variational method named ATMS [11]. Although the pp

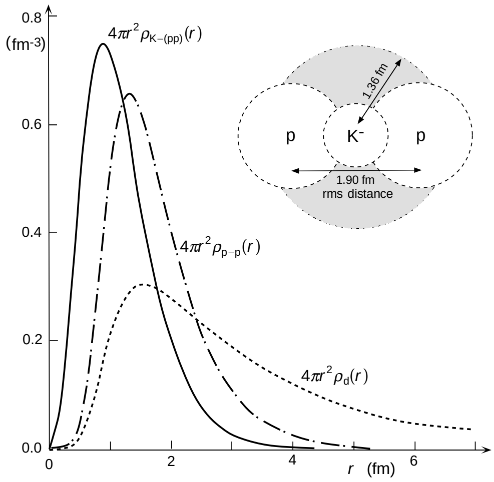

Figure 1: *K^- and proton density distributions in the ppK^- system. As a reference the p-n density distribution in the deuteron is also shown.*

system is unbound, the presence of a $\bar{\mathrm{K}}$ attracts two protons to form a bound state with $E_{\mathrm{K}} = -48$ MeV and $\Gamma = 61$ MeV. The density distributions of the K^- and the protons in the ppK^- system are shown in Fig. 1. The average distances of the K^- from the center of the pp and from the proton are 1.36 and 1.18 fm, respectively, while the r.m.s. radius between K^- and p is 1.31 fm for $\Lambda(1405)$. The average distance between the two protons is 1.90 fm, which is similar to that in ordinary nuclei. This distance, however, is much smaller than the p-n distance in the deuteron (3.90 fm).

The other NNK^- strange di-baryon systems, namely, nnK^- and dK^-, are found to be unbound and less bound compared to ppK^-, respectively. The reason is easily understood from the comparison of the weight of the strongly attractive $I = 0$ $\bar{\mathrm{K}}$N interaction:

$$2\ (v^{I=1}) \quad \text{for nnK}^-(T = 3/2), \tag{1}$$

$$2\ (\frac{1}{4}v^{I=0} + \frac{3}{4}v^{I=1}) \quad \text{for dK}^-(T = 1/2), \tag{2}$$

$$2\ (\frac{3}{4}v^{I=0} + \frac{1}{4}v^{I=1}) \quad \text{for ppK}^-(T = 1/2), \tag{3}$$

On the picture of pK^-=Λ^*(=$\Lambda(1405)$) one may suppose that d$\mathrm{K}^-(T = 1/2)$=nΛ^*

and ppK$^-$($T=1/2$)=pΛ^* have the same energy. This, however, is not true, because the NΛ^* model contains a Pauli forbidden NN component. To remove the unphysical component one must consider the coupling of NΛ^* with the isospin partner, NΣ^*. Thus, the proton-rich ppK$^-$ is distinguished from the dK$^-$ and is most deeply bound among all the NNK$^-$'s.

The proton-rich ${}^{3}_{\mathrm{K}}$He ($T=1$) system (pppK$^-$) is a more exotic one, in which three protons (non-existing ^{3}Li) form a bound state with the aid of the strong attraction from a K$^-$, where a contraction of the nuclear core against the Pauli exclusion is again essential. A strange structure of "ppK$^-$ plus a satellite p" is realized with a separation energy of 97 MeV from an *ab initio* calculation with the Antisymmetrized Molecular Dynamics (AMD) method [6].

2.2 ppnK$^-$ and ppnnK$^-$

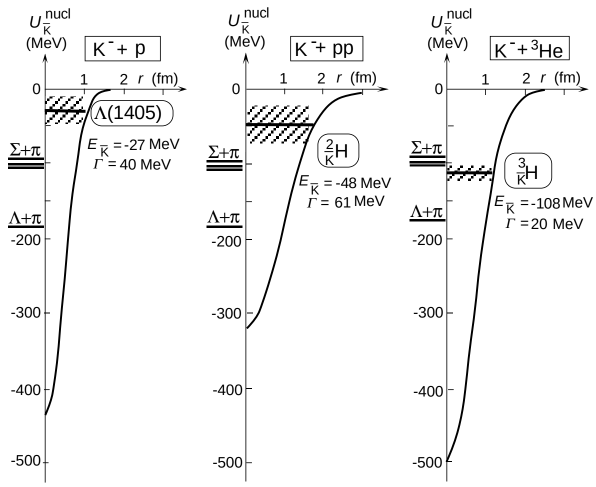

Figure 2: *Calculated* $\bar{\mathrm{K}}N$ *and* $\bar{\mathrm{K}}$*-nucleus potentials and bound levels:* $\Lambda(1405)$, ${}^{2}_{\bar{\mathrm{K}}}H$ *and* ${}^{3}_{\bar{\mathrm{K}}}H$ *for pK$^-$, ppK$^-$ and ppnK$^-$ systems, respectively. The nuclear contraction effect is taken into account. The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

Now, let's proceed to $\bar{\mathrm{K}}$ bound states in ^{3}He and ^{4}He. Due to the strong $\bar{\mathrm{K}}$N attraction, a $\bar{\mathrm{K}}$ acts as a *contractor* to combine all nucleons closer. Such a shrinkage induced by the $\bar{\mathrm{K}}$ is counterbalanced by the hard incompressibility of the core nucleus. The optimized r.m.s. radius of the core nucleus is 76 % of the free one (1.47 fm) for ppnnK$^-$($T = 1/2$) and, similarly, 60 % of the free one (1.61 fm) for ppnK$^-$($T = 0$).

Figure 2 depicts the bound states of ppK$^-$ and ppnK$^-$, which are extensions of the basic K$^-$+ p system with $\Lambda(1405)$ as its bound state, together with the optimized $\bar{\mathrm{K}}$-nucleus potentials $U_{\bar{\mathrm{K}}}$ of the K$^-$+ ^{2}He and K$^-$+ ^{3}He systems. The predicted bound states can be called *strange di-baryon* and *strange tri-baryon*, respectively. The system, ppnK$^-$($T = 0$), composed of K$^-\otimes^3$He + $\bar{\mathrm{K}}^0\otimes^3$H, lies by 108 MeV below the ^{3}He + K$^-$ threshold, *i.e.* by 13 MeV below any threshold of the $\Sigma + \pi$ main decay channels: the level width is suppressed to 20 MeV which is only about 20 % of the separation energy. Thus, the deeply bound ppnK$^-$ nucleus, $^3_{\bar{\mathrm{K}}}$H($T = 0$), has been predicted with a narrow width.

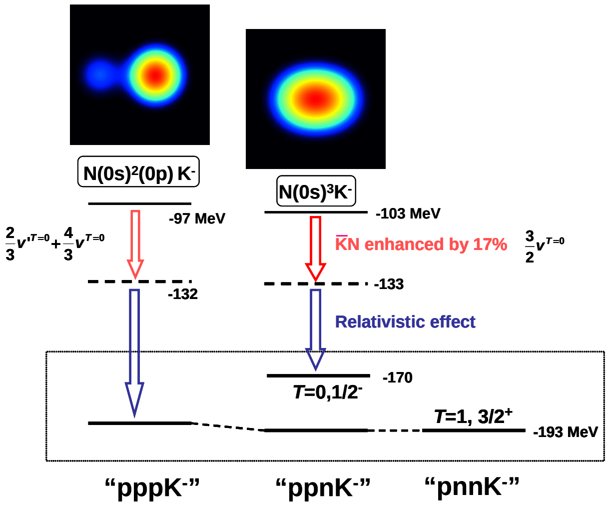

Figure 3: *Isospin-spin structure of strange tri-baryon systems. The relativistic corrections can explain about half of the discrepancy between theoretical values and experimental data of* S^1*(3135) and* S^0*(3115). The remaining parts are ascribed to a medium-modified* $\bar{\mathrm{K}}N$ *interaction enhanced by 17%.*

3 Relativistic correction and enhanced $\bar{\mathrm{K}}$N interaction

The calculations made so far are based on the non-relativistic treatment of many-body systems. For deeply bound $\bar{\mathrm{K}}$, however, relativistic corrections are indispensable. The relativistic effect can be estimated by using a Klein-Gordon equation for $\bar{\mathrm{K}}$,

$$\left\{-\frac{\hbar^2}{2m_{\mathrm{K}}}\nabla^2 + U_{\mathrm{opt}}\right\}|\Phi\rangle = \left(\varepsilon_{\mathrm{K}} + \frac{\varepsilon_{\mathrm{K}}^2}{2m_{\mathrm{K}}c^2}\right)|\Phi\rangle, \tag{4}$$

where ε_{K} is the energy of $\bar{\mathrm{K}}$ without its rest mass. An optical potential, U_{opt}, is provided by *a shrunk nuclear core*. When we make a transformation of the KG energy as

$$\left(\varepsilon_{\mathrm{K}} + \frac{\varepsilon_{\mathrm{K}}^2}{2m_{\mathrm{K}}c^2}\right) \longrightarrow \varepsilon_{\mathrm{S}}, \tag{5}$$

Eq.(4) becomes equivalent to a Schrödinger equation with an energy solution of ε_{S}. Thus, the KG energy can be estimated from the Schrödinger solution as

$$\varepsilon_{\mathrm{K}} = m_{\mathrm{K}}c^2\left(\sqrt{1+\frac{2\,\varepsilon_S}{m_{\mathrm{K}}c^2}} - 1\right) \tag{6}$$

In this treatment, we make consistent transformations on the threshold energies of decay channels and the complex energy of $\Lambda(1405)$, and obtain re-fitted $\bar{\mathrm{K}}$N interaction parameters (the ppnK$^-$ energy changes from -108 MeV to -103 MeV). As the internal energy of the shrunk core is largely positive, the U_{opt} must be very deep. Thus, the relativistic treatment gives a substantial negative correction on the energy. Since the $T = 1$ state has a larger internal energy than the $T = 0$ state, the relativistic correction is larger for the former and is calculated to be $\Delta E_{\mathrm{rel}}(T = 1) = -61$ MeV and $\Delta E_{\mathrm{rel}}(T = 0) = -36$ MeV. Roughly speaking, the relativistic effect accounts for about a half of the discrepancies as shown in Fig. 3.

The remaining discrepancies between the non-relativistic predictions and the data of the tri-baryons [9, 10] may now be ascribed to a modification of $\bar{\mathrm{K}}$N interaction which could occur in the dense nuclear medium. In the case of ppnK$^-$, the average nucleon density attains to about 3 times the normal density, where a chiral-symmetry restoration [12, 13] is naturally expected. By considering such and other possibilities, we make phenomenologically a change in the bare $\bar{\mathrm{K}}$N interaction. An enhancement of the $\bar{\mathrm{K}}$N interaction by

17% is required so as to reproduce both the $S^1(3135)$ and $S^0(3115)$. If this enhancement is of other origin and also applicable to ppK^-, its separation energy changes from -48 MeV to -91 MeV with a width of 60 MeV. Thus, an experimental information on ppK^- would greatly help the understanding of the binding mechanism of $\bar{K}$ nuclear systems.

4 Concluding remarks

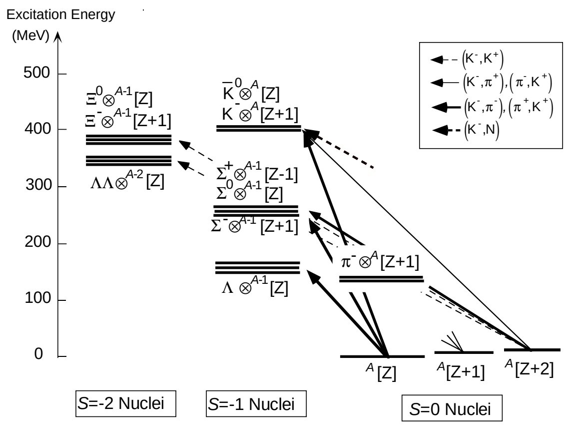

Figure 4: *Generalized diagram of nuclear excited states in the strangeness 0, -1 and -2 sectors. The possible exotic* $\bar{K}$ *states appear at 300∼400 MeV excitations. Some of possible connecting reactions are indicated.*

We predicted the possible existence of $\bar{K}$ nuclear states with narrow widths in ^{2}He, ^{3}He and ^{4}He. In the deeply bound $\bar{K}$ states the core nuclei are largely compressed due to the strong attraction from a $\bar{K}$, which plays a unique role as a *contractor* to bind nucleons tightly, and accommodates a nucleus of high density. The formation of deeply bound $\bar{K}$ nuclear states would provide a means to investigate properties of hadrons in a dense and cold nuclear medium. A search for the ${}^3_K\mathrm{H}(T=0)$ state was conducted with the ^{4}He (stopped K^-, n) reaction, and an evidence of $S^1(3135)$ has been obtained [9]. Further experiments of missing-mass spectroscopies in formation channels and of invariant-mass spectroscopies in decay channels are planned in order to detect exotic $\bar{K}$ bound states. It is vitally important to experimentally examine the simplest case of ppK^-, which can provide a gateway toward more complicated and more exotic systems.

Figure 4 shows a diagram of nuclear excited states generalized to the strangeness sectors. The $\bar{K}$ nucleus region is quite exotic: "bound-kaon nuclear spectroscopy" would create *a new paradigm* in nuclear physics. Many impacts are foreseen. *i)* Discrete structures of $\bar{K}$ nuclear systems would be formed at excitation energies of 300∼400 MeV. Nuclear dynamics under extreme conditions (nuclear compression, isovector deformation etc.) can be studied. *ii)* High-density cold nuclear matter would be locally formed around a K^-, which can provide information concerning a modification of the $\bar{K}N$ interaction in a nuclear medium and a transition from hadronic to quark structures. *iii)* Empirical information on the possibility for kaon condensation and for strange matter would be obtained.

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