Dense K̄ nuclei and their excited states

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We have investigated the excited states as well as the ground state of various K̄ nuclei, based on the improved version of antisymmetrized molecular dynamics method with a phenomenological K̄N interaction. Our calculation shows that the ground state of K̄ nuclei forms dense state; more than 4 ρ_0 (ρ_0 being normal density). The two excited states of ^{11}CK$^-$, $(J^\pi, T) = (\frac{1}{2}^+, 0)$ and $(\frac{1}{2}^+, 1)$, are also deeply bound below the $\Sigma\pi$-emission threshold. They are the same J^π state but have quite different structures from each other; $T = 0$ state has a well-developed clustering structure, while $T = 1$ state has a shell-like structure.

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We point out that a K$^-$ meson could form a new type of a dense object, "K̄ nucleus". Y. A. and T. Y. constructed a phenomenological K̄N potential (AY potential [1]) which can reproduce the low energy K̄N scattering data [2], the 1s level shift of kaonic hydrogen atom [3] and the binding energy and width of $\Lambda(1405)$ being the $I = 0$ quasi-bound state of K̄N. As shown in our previous studies [1, 4] based on the AY potential, a K$^-$ attracts nucleons around itself to form dense state in light nuclei and is very deeply bound below the $\Sigma\pi$-emission threshold, which is a main decay mode, to form discrete state. Such interesting properties are attributed to the strong attraction of the $I = 0$ K̄N interaction. Thus, a K$^-$ seems to play such a role as a seed of strong attraction. We have a key question: how do A-nucleons behave if we put such a seed, a K$^-$ meson, into a normal nucleus? What kind of structure is realized in various K̄ nuclei as a result that the $A + 1$ particles organize themselves?

To study the K̄ nuclei from such a viewpoint, we employ the method of antisymmetrized molecular dynamics (AMD), because it treats K̄ nuclei as a fully $(A+1)$-body system. In the AMD, the $A + 1$ particles form dynamically such a configuration that they favor energetically without any assumption on their structures. Since the $I = 0$ K̄N interaction is the most important ingredient in the study of K̄ nuclei, the AMD framework should be improved to treat it adequately. It couples a pair of K$^-$ and proton with that of K̄^{0} and neutron in a particle-basis treatment, such as the AMD method. Therefore, respecting the $I = 0$ K̄N interaction, the AMD method should be improved so as to treat the K$^-$p/K̄^{0}n mixing. A nucleon wave function $|\varphi_i\rangle$ and a K̄ wave function $|\varphi_K\rangle$ are represented by superposition of several Gaussian wave packets:

$$|\varphi_i\rangle = \sum_{\alpha=1}^{N_n} C_\alpha^i \exp\left[-\nu\left(\mathbf{r} - \frac{\mathbf{Z}_\alpha^i}{\sqrt{\nu}}\right)^2\right] |\sigma_i\rangle|\tau_\alpha^i\rangle, \quad (1)$$

$$|\varphi_K\rangle = \sum_{\alpha=1}^{N_K} C_\alpha^K \exp\left[-\nu\left(\mathbf{r} - \frac{\mathbf{Z}_\alpha^K}{\sqrt{\nu}}\right)^2\right] |\tau_\alpha^K\rangle. \quad (2)$$

The i-th nucleon is described with the superposition of N$_\mathrm{n}$ Gaussian wave packets whose centers $\{\mathbf{Z}_\alpha^i\}$ are different from each other. $|\sigma_i\rangle$ means a spin wave function, $|\uparrow\rangle$ or $|\downarrow\rangle$. $|\tau_\alpha^i\rangle$ and $|\tau_\alpha^K\rangle$ mean isospin wave functions and have the form as following:

$$|\tau_\alpha^i\rangle = \left(\frac{1}{2} + \gamma_\alpha^i\right)|\mathrm{p}\rangle + \left(\frac{1}{2} - \gamma_\alpha^i\right)|\mathrm{n}\rangle, \quad (3)$$

$$|\tau_\alpha^K\rangle = \left(\frac{1}{2} + \gamma_\alpha^K\right)|\bar{\mathrm{K}}^0\rangle + \left(\frac{1}{2} - \gamma_\alpha^K\right)|\mathrm{K}^-\rangle \quad (4)$$

where γ_α^i and γ_α^K are variational parameters. To treat the K$^-$p/K̄^{0}n mixing, we prepare such isospin wave functions that can describe proton-neutron mixed state and K$^-$-K̄^{0} mixed state. We construct a total wave function from single wave functions Eq.(1) and (2): $|\Phi\rangle = \det[|\varphi_i(j)\rangle] \otimes |\varphi_\mathrm{K}\rangle$. It is projected onto the eigen-state of parity: $|\Phi^\pm\rangle = |\Phi\rangle \pm \mathcal{P}|\Phi\rangle$. We perform the charge projection to conserve the total charge of the system:

$$|\hat{P}_M \Phi^\pm\rangle = \int d\theta \ \exp[-i\theta(\hat{T}_z - M)]|\Phi^\pm\rangle. \quad (5)$$

The $|\hat{P}_M \Phi^\pm\rangle$ is used as a trial wave function. After the $|\hat{P}_M \Phi^\pm\rangle$ is determined by energy-variation, it is projected onto the eigen state of angular momentum and isospin. The more detailed explanation on this improvement is shown in Ref. [5]. We investigate the various K̄ nuclei, using the improved version of AMD with the effective NN and K̄N interaction, which are derived from Tamagaki potential (OPEG) [6] and AY potential by the G-matrix method [1], respectively.

As summarized in Table 1, the ground states of K̄ nuclei are deeply bound by about 100 MeV below the nucleus-K̄ threshold. They form dense state being more than 4 ρ_0 ($\rho_0 = 0.17\mathrm{fm}^{-3}$). The binding energy measured from the nucleus-K̄ threshold, E(K), seems to be saturated to be ~100 MeV. We can understand the saturation of the E(K) as following: We have investigated how many nucleons are near a K$^-$ meson. The last column of the Table 1, N_K, shows the number of nucleons

TABLE I: Summary of our calculation. J^π and T: spin-parity and isospin. E(K): binding energy measured from the threshold of nucleus+$\bar{\mathrm{K}}$. Γ: decay width to $\Sigma\pi$ and $\Lambda\pi$ channels. Density: maximum value of nucleon density. R_{rms}: root-mean-square radius of nucleon system. N_K: number of nucleons being near a K^- meson. (see text)

	J^π	T	E(K) [MeV]	Γ [MeV]	Density [fm^{-3}]	R_{rms} [fm]	N_K
ppnK^-	$\frac{1}{2}^+$	0	110.3	21.2	1.50	0.72	1.67
pppK^-	$\frac{3}{2}^-$	1	96.7	12.5	1.56	0.81	1.14
pppnK^-	1^-	$\frac{1}{2}$	105.0	25.9	1.29	0.97	1.78
^{6}BeK^-	0^+	$\frac{1}{2}$	104.2	33.3	0.91	1.17	2.55
^{9}BK^-	$\frac{3}{2}^-$	0	118.5	33.0	0.71	1.45	2.53
^{11}CK^-	$\frac{3}{2}^-$	0	117.5	46.0	0.81	1.48	2.80
ppnK^- (excited)	$\frac{3}{2}^-$	1	71.5	128.2	2.04	0.84	
^{11}CK^- (excited)	$\frac{1}{2}^+$	0	108.0	46.2	0.81	1.53	
^{11}CK^- (excited)	$\frac{1}{2}^+$	1	106.2	48.5	0.81	1.50	

being in the region where the density of the K^- meson falls down from the maximum value $\rho_{max}(K)$ to one-fifth of $\rho_{max}(K)$. In the case of ppnK^- and pppnK^- which have the one-center structure, there are 1.7 nucleons near the K^- meson, while there are 2.6 nucleons in the case of ^{6}BeK^- and ^{9}BK^- which have the two-center structure [5]. The single K^- meson can interact with not all nucleons but the limited numbers of nucleons. This fact is related to the saturation of the E(K).

We have investigated the excited states of ppnK^- and ^{11}CK^- which have opposite parity to the ground state. In the case of ppnK^-, the total binding energy of $J^\pi = \frac{3}{2}^-, T = 1$ state is obtained to be 80 MeV. Since this state is above the $\Sigma\pi$-emission threshold, the decay width is very large; $\Gamma = 128$ MeV. This excited state of ppnK^- has a strange structure as depicted in Fig. 1, which is very similar to the proton-satellite structure appeared in pppK^- [5]. Since a single neutron exists in the region enclosed by a circle in Fig. 1, this state has a neutron-satellite structure. We notice that the ground state of pppK^- is also $J^\pi = \frac{3}{2}^-, T = 1$ state. This excited state of ppnK^- state has the same quantum number (J^π, T) as pppK^- and it has a similar structure to pppK^-. Therefore, it is found to be an isobaric analog state of pppK^-.

The case of ^{11}CK^- seems very interesting. We have obtained two excited states, $(J^\pi, T) = (\frac{1}{2}^+, 0)$ and $(\frac{1}{2}^+, 1)$. Namely, they have the same J^π but different T. The total binding energy is 182 MeV for the $T = 0$ state and 180 MeV for the $T = 1$ state. Contrary to ppnK^-, they are also below the $\Sigma\pi$-emission threshold (-169 MeV). Fig. 2 shows the density distributions of two excited states as well as of the ground state. As shown in the left panel, the ground state has the tri-angular shape. The clustering structure is somewhat developed. A K^- meson exists at the center of the system (in the region enclosed by a circle) and it attracts all of three clusters. As shown in the middle and right panels, the structures of two excited states are quite different from each other: the $T = 0$ state has a well-developed clustering structure, while the $T = 1$ state has a shell-like structure. In the $T = 0$ state, the K^- exists in the region enclosed by a circle in the panel. We think that it is reasonable that the $T = 0$ state has such a configuration as ^{4}He+ppnK^-+^{4}He, because each component is a $T = 0$ state.

We make a comment on the experiment. According to the experimental result of ^{4}He(stopped K^-, n)ppnK^- done by Iwasaki group in KEK, the total binding energy of ppnK^- is found to be 173 MeV [7]. This result supports a deep $\bar{\mathrm{K}}$N potential such as AY potential. However, the binding energy by the experiment is much larger than that by our prediction (118 MeV). Since our calculation is done in the non-relativistic framework, we take into account the relativistic effect based on Klein-Gordon equation. Although such correction increases the binding energy to 135 MeV, there still remains large discrepancy

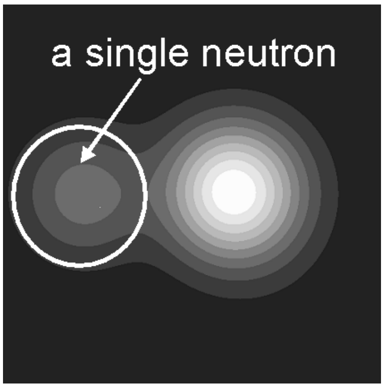

FIG. 1: Nucleon density contour of the excited state of ppnK^-: $J^\pi = \frac{3}{2}^-, T = 1$ state. The framework is 3 × 3 fm^2.

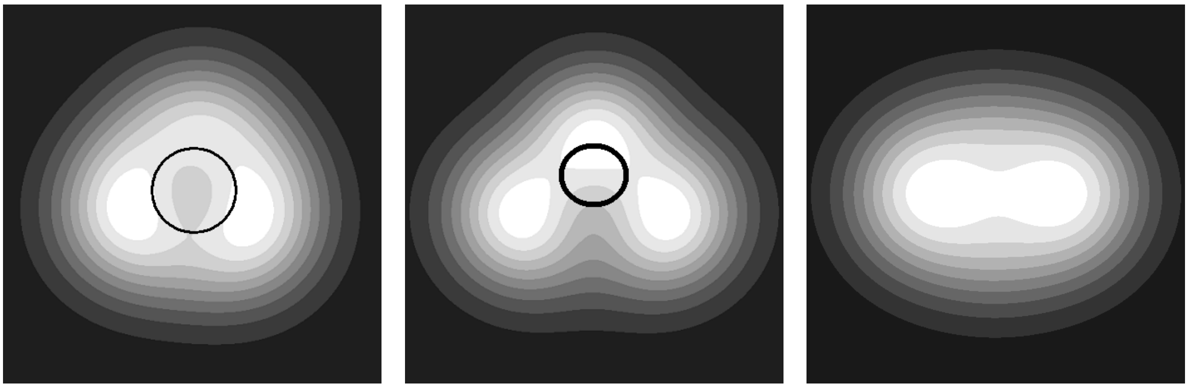

FIG. 2: Nucleon density contour of various states of ^{11}CK$^-$: The left panel shows the nucleon distribution in the ground state $J^\pi = \frac{3}{2}^-, T = 0$ state. The middle and right panels show the nucleon distribution in the excited states $J^\pi = \frac{1}{2}^+, T = 0$ state and $J^\pi = \frac{1}{2}^+, T = 1$, respectively. Each framework is 5×5 fm^2.

between the experimental result and our one. It is likely that the bare $\bar{\mathrm{K}}$N interaction is modified by some effect, such as the partial restoration of chiral symmetry in the dense matter. According to the estimation by Y.A., the $\bar{\mathrm{K}}$N interaction should be more attractive by 17% than the original one, to reproduce the experimental result. If this enhancement is true, more $\bar{\mathrm{K}}$ nuclei could be deeply bound below the $\Sigma\pi$-emission threshold to be a discrete state. For example, the exited state of ppnK$^-$ could be a discrete state. Anyway, we need further investigation.

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