High-density $\bar{K}$ nuclear systems with isovector deformation

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Using a phenomenological $\bar{K}N$ potential which reproduces $\Lambda(1405)$ as an $I = 0$ bound state of $KN$, we investigated deeply bound kaonic nuclei, $ppnK^-$ and $^8BeK^-$, with the method of Antisymmetrized Molecular Dynamics. Our calculations show that strongly bound kaonic nuclear systems with unusual exotic structures are formed around the $K^-$, which attracts the surrounding nucleons to an extremely high-density assembly and induces a proton-neutron separation, “isovector deformation”.

Recently, exotic nuclear systems involving a $\bar{K}$ ($K^-$ or $K^0$) as a constituent have been studied theoretically by Akaishi and Yamazaki [1] (to be abbreviated as AY), who constructed $KN$ interactions phenomenologically so as to reproduce low energy $KN$ scattering data [2], kaonic hydrogen atom data [3] and the binding energy and decay width of $\Lambda(1405)$, which is asserted to be an $I = 0$ quasi-bound state of $KN$. These interactions are characterized by a strongly attractive $I = 0$ $\bar{K}N$ interaction helped by the nuclear shrinkage effect so that the bound states lie below the threshold of the main interaction. The present paper reports the first results on $ppnK^-$ and $^8BeK^-$. The AMD method has a great advantage: it treats “a nucleus + $K^-$” as a full $(A+1)$-body system without any assumption concerning a priori structure (shell or cluster). Actually, AMD has succeeded to explain a variety of exotic shapes and clusters in light unstable nuclei [4]. If a $\bar{K}$ nuclear system prefers a structure where the proton distribution differs from the neutron distribution, such a structure will be dynamically formed in the AMD treatment.

In the usual AMD, a single nucleon wave function, $|\varphi_i\rangle$, is represented by a single Gaussian wave packet. In the present study, however, it is given as a superposition of several Gaussian wave packets as follows, in order to describe the system more precisely, and the $\bar{K}$ is represented in the same way:

$$|\varphi_i\rangle = \sum_{\alpha=1}^{n_N} C^i_\alpha \exp \left[ -\nu \left( r - \frac{Z^i_\alpha}{\sqrt{\nu}} \right)^2 \right] |\sigma_i \tau_i\rangle,$$

$$|\varphi_K\rangle = \sum_{\alpha=1}^{n_K} C^K_\alpha \exp \left[ -\nu \left( r - \frac{Z^K_\alpha}{\sqrt{\nu}} \right)^2 \right] |\eta_K\rangle,$$

where $|\sigma_i \tau_i\rangle$ is a spin-isospin wave function, which is $|p \uparrow\rangle, |p \downarrow\rangle, |n \uparrow\rangle$, or $|n \downarrow\rangle$; $|\eta_K\rangle$ indicates the isospin wave function of $\bar{K}$. We use two Gaussian wave packets for a single nucleon ($n_N = 2$) and five for a $\bar{K}$ ($n_K = 5$). We must antisymmetrize the nucleon wave functions, which are then combined with a $\bar{K}$ wave function as

$$|\Phi\rangle = \det(\{\varphi_i(j)\}) \otimes |\varphi_K\rangle.$$  

Finally, we project the intrinsic wave function $|\Phi\rangle$ onto the eigen-state of parity: $|\Phi^\pm\rangle = |\Phi\rangle \pm \mathcal{P}|\Phi\rangle$. We utilize $|\Phi^\pm\rangle$ as a trial function, which contains complex variational parameters $(C^i_\alpha, Z^i_\alpha, C^K_\alpha, Z^K_\alpha)$ and a real variational parameter, $\nu$. They are determined by the fractional cooling equation with constraint $\mathcal{P}$.

The Hamiltonian,

$$\hat{H} = \hat{T} + \hat{V}_{NN} + \hat{V}_{KN} + \hat{V}_C - \hat{T}_G,$$
is composed of the kinetic energy, $\hat{T}$, two-body NN interaction, $\hat{V}_{\text{NN}}$, KN interaction, $\hat{V}_{\text{KN}}$, and Coulomb force, $\hat{V}_{C}$. The center-of-mass motion energy, $\hat{T}_{G}$, is subtracted. In the kinetic energy and the c.m. motion energy, we treat the mass difference between a nucleon and $K^{-}$ exactly. Since the system is likely to be extremely dense due to the strongly attractive KN interaction, we can use no existing effective interactions. Therefore, we use the Tamagaki potential (OPEG) \[8\] as a bare NN interaction, and the AY KN interaction as a bare KN interaction, and construct the effective NN-central force and the KN force with the G-matrix method \[1\]. Since the Tamagaki potential reproduces the NN phase shifts up to 660 MeV in laboratory energy \[8\], we expect that it is applicable to extremely high-density states of relevant concern.

We have calculated systems of ppn$K^{-}$ and $^{8}\text{Be}K^{-}$. These systems were previously treated with a Brueckner-Hartree-Fock method by AY \[1\]. We summarize our calculations for ppn$K^{-}$ and $^{8}\text{Be}K^{-}$ in Table I. We also show the AMD results of the normal $^{3}\text{He}$ and $^{8}\text{Be}$ for a comparison. $^{3}\text{He}$ was calculated with the Volkov No.1 force \[9\] and $^{8}\text{Be}$ with the MV1 Case-3 force \[10\]. However, we did not perform an angular momentum projection for simplicity. $\Gamma_{K}$ is the width for decaying to $\Lambda\pi$ and $\Sigma\pi$, and is evaluated by calculating the expectation value of the imaginary potential contained in the effective AY KN interaction with the wave function obtained by the AMD calculation. “ppn$K^{-}$ †” and “$^{8}\text{Be}K^{-}$ †” are the results of AY.

Our result shows that the ppn$K^{-}$ ($T = 0$) system is bound by 113 MeV ($B_{K} = 105$ MeV below the $^{3}\text{He} + K^{-}$ threshold). Since the obtained state lies under the $\Sigma\pi$ threshold ($-80$ MeV), the $\Sigma\pi$ channel, which is the main decay-channel, is closed and the decay width, $\Gamma_{K}$, becomes narrow to be 24 MeV. The present result is very similar to the AY prediction: $B_{K} = 108$ MeV and $\Gamma_{K} = 20$ MeV. We have not considered the decay width from the non-mesonic decay ($KNN \rightarrow \Lambda N/\Sigma N$), but according to AY it is estimated to be about 12 MeV \[1\]. The width of ppn$K^{-}$ remains still narrower than that of $\Lambda(1405)$, even when the non-mesonic decay is taken into account.

![Density contours of ppn$K^{-}$](image1)

**FIG. 1**: Calculated density contours of ppn$K^{-}$. Comparison between (a) usual $^{3}\text{He}$ and (b) $^{3}\text{He}K^{-}$ 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.

**TABLE I**: Summary of the present calculations. $\rho(0)$: nucleon density at the center of the system. $R_{\text{rms}}$: root-mean-square radius of the nucleon system. $\nu$: width parameter of a Gaussian wave packet used in the calculation. $\beta$: deformation parameter for the nucleon system. ppn$K^{-}$ † and $^{8}\text{Be}K^{-}$ †: AY’s results.

| | B.E. | $\Gamma_{K}$ | $\rho(0)$ | $R_{\text{rms}}$ | $\nu$ | $\beta$ |
|---|---|---|---|---|---|---|
| $^{3}\text{He}$ | 5.95 | — | 0.14 | 1.59 | 0.20 | 0.0 |
| ppn$K^{-}$ | 113 | 24 | 1.39 | 0.72 | 1.12 | 0.19 |
| ppn$K^{-}$ † | 116 | 20 | 1.10 | 0.97 | | |
| $^{8}\text{Be}$ | 48.72 | — | 0.10 | 2.46 | 0.205 | 0.63 |
| $^{8}\text{Be}K^{-}$ | 159 | 43 | 0.76 | 1.42 | 0.52 | 0.55 |
| $^{8}\text{Be}K^{-}$ † | 168 | 38 | $\sim$ 0.85 | | | |
Surprisingly, the central density (“uncorrelated density”) of the system amounts to 8.2-times the normal density due to the shrinkage effect. Figs. 1(a) and (b) show a comparison between \(^3\)He and \(^3\)HeK\(^-\). In order to see how the bound K changes the nucleus in more detail we show the calculated density distributions of the constituents in Figs.1(c)-(e). Apparently, the proton distribution is more compact than the neutron distribution. This phenomenon is attributed to the property of the KN interaction. Table II shows how protons and a neutron in ppmK\(^-\) contribute to the kinetic energy and the expectation value of the KN interaction per nucleon. \(R_{\text{rms}}\): root-mean-square radii of the proton and neutron distributions.

|        | \(\langle T \rangle\) | \(\langle V_{\text{KN}} \rangle\) | \(R_{\text{rms}}\) |
|--------|-----------------------|-------------------------------|-------------------|
| proton | 69.4                  | -170.2                        | 0.70              |
| neutron| 59.0                  | -42.4                         | 0.75              |

Now we proceed to \(^8\)BeK\(^-\). As expected, \(^8\)Be is extremely shrunk due to the presence of a K\(^-\). The K\(^-\) is bound by 159 MeV \((B_K = 104\ \text{MeV with respect to } ^8\text{Be})\). The binding energy of K\(^-\) and the decay width obtained by our calculation are very similar to those by AY, who employed the \(\alpha\)K\(^-\) model. We compare the density distribution of \(^8\)BeK\(^-\) with that of the normal \(^8\)Be in Figs.2(a) and (b). \(^8\)BeK\(^-\) becomes much more compact than \(^8\)Be, and attains a high density, 4.5-times the normal nuclear density. As shown in Table I, the root-mean-square radius decreases dramatically from 2.46 fm to 1.42 fm. Nevertheless, an \(\alpha\)-cluster like structure still remains in \(^8\)BeK\(^-\). We can see that the relative distance between the \(\alpha\) clusters becomes short and that the \(\alpha\) cluster, itself, in \(^8\)Be is also shrunk. The shrinkage of each \(\alpha\) cluster is indicated by that of the Gaussian wave packet, as shown in Table I. The width parameter, \(\nu\), is changed from 0.205 fm\(^{-2}\) for the normal \(^8\)Be to 0.52 fm\(^{-2}\) for \(^8\)BeK\(^-\). The deformation parameter, \(\beta\), becomes slightly smaller.

Figs.2(c)-(e) display contour mapping of the calculated density distributions of \(^8\)BeK\(^-\) in more detail. Although the two-\(\alpha\) like structure, as shown in (b), persists, it is
found that the proton distribution (c) is significantly different from the neutron distribution (d). As in the case of $^3$He$^-$, the protons feel a strongly attractive force from the $K^-$, which stays in the center of the total system (Fig.2(e)), and are attracted nearer to the $K^-$ than the neutrons. Namely, the proton distribution is separated from the neutron distribution in spite of $N = Z$. A more quantitative presentation of the proton and neutron density distributions is given in Fig.3. The $\bar{K}$ produces a new type of neutron halo; it is peripherally distributed, yet with quite a high density. We name such a new type of deformation as an “isovector deformation”. It should be noted that AMD enables us to predict such an isovector deformation without any assumption about resultant structure. Such a deformation cannot be seen in the calculation by AY because they assumed the existence of $\alpha$ clusters.

In summary, we have shown from our AMD calculations that a $K^-$ forms a deeply bound nuclear state by producing an extremely high-density nuclear system with isovector deformation. No such nuclear systems at “zero temperature and high density” have been created so far. Whereas an experiment to identify $^3$He$^-$ from $^4$He(stopped $K^-$, n) is under way at KEK, a new possibility to make use of ($K^-$, $\pi^-$) reactions to populate proton-rich systems has been proposed. We are extending our AMD calculations to such more exotic systems, as AMD is the only possible method to investigate their dynamics without any a priori structural assumption. If a deeply bound kaonic nucleus is confirmed experimentally, new developments of nuclear physics will follow. This new field of “bound-K nuclear spectroscopy” will create a new dense and cold environment, in contrast to hot and dense states expected to be realized by heavy-ion collisions. Restoration of chiral symmetry in a dense nuclear medium might be observed for the $KN$ system in the same way as in deeply bound pionic states. The bound-K nuclear spectroscopy will yield unique information about a transition from the hadron phase to a hitherto untouched “quark phase”. It will also provide experimental grounds for possible kaon condensation and strange matter formation.

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