Strange $\bar{\mathrm{K}}$ nuclear systems ($S=-1$)*

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Abstract $\Lambda(1405)$ is considered as a superposition of two resonances instead of a simple bound state of the kaon and proton. Within the framework of the Brueckner-Hartree-Fock(BHF) theory, we have investigated the $\bar{\mathrm{K}}$ nuclear systems ($S=-1$), especially $\mathrm{K^-pp}$ and $\mathrm{K^-pnn}(T=1)$. The binding energy B_{K^-} is 23 MeV (3 MeV) and the width Γ is 62 MeV (56 MeV) for $\mathrm{K^-pp}(\mathrm{K^-pnn}(T=1))$.

Key words phenomenological $\bar{\mathrm{K}}\mathrm{N}$ interaction, BHF

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1 Introduction

For the attractive interaction of kaons in nuclei, the resonance $\Lambda(1405)$ in the s-wave and $I=0$ channel $\bar{\mathrm{K}}\mathrm{N}$ scattering state plays an essential role. Based on the early data on $\mathrm{K^-p}$ scattering, Dalitz and Tuan[1] predicted the existence of a subthreshold $\bar{\mathrm{K}}\mathrm{N}$ resonance, $\Lambda(1405)$, and its width ($\Gamma=40$ MeV) is caused by the coupling to the $\pi\Sigma$ channel. Three years later, Alston et al.[2] first found it. However, several years ago J. A. Oller et al.[3] found the $\Lambda(1405)$ resonance which is described by two poles. This implies that there are two resonances instead of only one. Furthermore, using a chiral unitary approach for the meson-baryon interactions D. Jido et al. showed that two octets of the $J^\pi=1/2^-$ baryon states and a singlet are generated dynamically[4]. The two poles in the neighborhood of $\Lambda(1405)$ are produced by combinations of the singlet state and the two octets. As Oset[5] pointed out, there is not just one $\Lambda(1405)$ but two states, and the shape obtained in experiments comes from a superposition of the two resonances with different weights for different reactions; these two $\Lambda(1405)$ states are quite different, one appears around 1420 MeV, which has a width of about 40 MeV and couples mostly to $\bar{\mathrm{K}}\mathrm{N}$, while the other one which appears around 1392 MeV, has a width of about 130 MeV and couples mostly to $\pi\Sigma$. In order to look for the two poles, especially the first pole, the reaction $\mathrm{K^-p}\rightarrow\pi^0\pi^0\Sigma$ in the region of excitation of the $\Lambda(1405)$ was done by Prakhov et al.[6]. Together with the $\pi^-\mathrm{p}\rightarrow\mathrm{K}^0\pi\Sigma$ reaction[7], Magas et al.[8] have provided firm evidence of the two poles structure of $\Lambda(1405)$.

Over the last several years, many theoretical and experimental efforts have been devoted to the investigation of deeply-bound kaonic nuclei[9—13]. In order to seek possible narrow discrete nuclear bound states, Akaishi and Yamazaki (AY)[9, 10] have studied theoretically several few-body systems. They found deeply bound nuclear states with very small widths. They assumed the $\Lambda(1405)$ state to be a bound state of the kaon and proton and its width caused by coupling to the $\pi\Sigma$ channel. Based on Martin's empirical value[14] and the KpX measured value[15, 16], they gave a phenomenological $\bar{\mathrm{K}}\mathrm{N}$ interaction with zero $V_{\pi\Sigma,\pi\Sigma}$ and $V_{\pi\Lambda,\pi\Lambda}$. For B_{K^-} of the $\mathrm{K^-ppn}(T=0)$ ($\mathrm{K^-pp}$) they obtained 108 MeV (44 MeV) and for the width 20 MeV (61 MeV) within the framework of the BHF theory. A few years later, in search for quasi-bound states in the $\mathrm{K^-pp}$ system, a three-body $\mathrm{K^-NN}$-$\pi\Sigma N$ coupled-channel Faddeev calculation by Shevchenko et al.[11] obtained a quasi-bound state with B_{K^-} ∼55—70 MeV and Γ∼90—110 MeV. They assumed for the energy of $\Lambda(1405)$ 1406 MeV and for the width 50 MeV. Recently, using $E_\Lambda=1420$ MeV, A. Dote et al.[17] have studied the $\mathrm{K^-pp}$ system with a chiral $SU(3)$ effective interaction and they found the system to be weakly bound with a binding energy $B,=(19\pm3)$ MeV and a decay width

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$\Gamma(\mathrm{K^-pp} \to \pi\Sigma\mathrm{N})$ ∼40—70 MeV. However, T. Nishikawa and Y. Kondo[18] described the $\mathrm{K^-pp}$ system as two skyrmions, around which a kaon field fluctuates. They obtained a binding energy of the $\mathrm{K^-pp}$ state of 126 MeV. On the other hand, the strange tribaryons $S^1(3140)$ with $T=0$ and $S^0(3115)$ with $T=1$ were observed by T. Suzuki and M. Iwasaki et al[12, 19, 20] in the interaction of stopped $\mathrm{K^-}$ mesons with ^{4}He. But, recently, M. Iwasaki et al.[21] have performed a couple of experiments, KEK PS-E549/570, for a detailed study of the strange tribaryon $S^0(3115)$ obtained in KEK PS-E471. In contrast to the previous proton spectrum, no narrow peak structure was found; the strange tribaryon $S^0(3115)$ [12, 20] was an experimental artifact. Another indication of the $\mathrm{K^-pp}$ bound state was reported by the FINUDA Collaboration at DAΦ NE[22] with a binding energy (width) of 115 MeV (67 MeV), which is below $\pi\Sigma\mathrm{N}$ threshold energy.

We have investigated the $\mathrm{K^-ppn}(T{=}0)$ and $\mathrm{K^-ppnn}(T{=}1/2)$ within the the framework of the BHF theory[23] and obtained a binding energy of $\mathrm{K^-ppn}(T{=}0)$ ($\mathrm{K^-ppnn}(T{=}1/2)$) of 93 MeV (72 MeV) with a width of 13 MeV (25 MeV). The results show that these two states are deeply bound. In Ref. [23] we have constructed a phenomenological $\bar{\mathrm{K}}\mathrm{N}$ interaction which reproduces the two resonances: one appears around 1420 MeV, which has a width of about 40 MeV and couples mostly to $\bar{K}N$, while the other one appears around 1392 MeV, and has a width of about 135 MeV and couples mainly to $\pi\Sigma$. Instead of a simple bound state of the kaon and proton, $\Lambda(1405)$ is considered as a superposition of the two resonances with a fitted relative weight of the two resonances of 7:5, that is $7\Lambda(1420)/12+5\Lambda(1392)/12$. $\Lambda(1405)$ is obtained as $E_\Lambda = 1406.5 - i25$ MeV. We treat in this paper these $\bar{\mathrm{K}}$ nuclear systems ($S=-1$), especially $\mathrm{K^-pp}$ and $\mathrm{K^-pnn}(T=1)$, following Ref. [23]. For the $\mathrm{K^-pp}$ system many theoretical calculations[10, 11, 17, 18] showed different results, the range of the binding energy varying from 19—125 MeV and the width varying from 0—90 MeV. Though the measured value of the binding energy by the FINUDA spectrometer at DAΦ NE (LNF)[22] is 115 MeV, the result is incompatible with the measured value of the binding energy $B_{\mathrm{K^-ppn}} =$ 58 MeV[24], a fact criticized by Oset et al.[25]. For the $\mathrm{K^-pnn}(T=1)$ system the measured value by T.Suzuk et al[12] is 194 MeV, but this result has lost support[21].

2 Formalism

Following Ref. [23], we use a Gaussian type potential:

$$V_{ij} = \nu_{ij}^1 \exp\left[-\left(\frac{r}{u_1}\right)^2\right] + \nu_{ij}^2 \exp\left[-\left(\frac{r}{u_2}\right)^2\right], \quad (1)$$

where $u_1 = 0.85$ fm and $u_2 = 0.45$ fm.

The strength parameters are listed in Table 1 for the $I=0$ and $I=1$ interaction. Model A produces a resonance state Λ with $E_\Lambda = 1420 - i20$ MeV, Model B one with $E_\Lambda = 1392 - i67$ MeV, respectively. Both models, A and B, give the same scattering length $a^{I=0} = -1.90 + i0.88$ fm.

Table 1. Strength parameters V_{ij} for the $I=0$ and $I=1$ interaction potentials, corresponding to $a^{I=0} = -1.90{+}i0.88$ fm and $E_\Lambda = 1420{-}i20$ MeV for Model A and $E_\Lambda = 1392{-}i67$ MeV for Model B, and $a^{I=1} = 0.39 + i0.52$ fm for $I=1$, respectively. $V_{\pi\Sigma,\pi\Sigma}$ and $V_{\pi\Lambda,\pi\Lambda}$ are set equal to zero.

V_{ij}	Model A ($I=0$)MeV	Model B ($I=0$)MeV	$I=1$ MeV
$V^1_{\mathrm{K^-N,K^-N}}$	−179	−242	−47
$V^2_{\mathrm{K^-N,K^-N}}$	−165	−254	−35
$V^1_{\mathrm{K^-N},\pi\Sigma}$	−233	−140	−103
$V^2_{\mathrm{K^-N},\pi\Sigma}$	−220	−145	−77
$V^1_{\mathrm{K^-N},\pi\Lambda}$	0	0	−127
$V^2_{\mathrm{K^-N},\pi\Lambda}$	0	0	−95
$V^1_{\pi\Sigma,\pi\Sigma}$	0	−323	−169
$V^2_{\pi\Sigma,\pi\Sigma}$	0	−342	−126
$V^1_{\pi\Lambda,\pi\Sigma}$	0	0	0
$V^2_{\pi\Lambda,\pi\Sigma}$	0	0	0
$V^1_{\pi\Lambda,\pi\Lambda}$	0	0	0
$V^2_{\pi\Lambda,\pi\Lambda}$	0	0	0

Now let us investigate the nuclear $\bar{\mathrm{K}}$ bound states: $\mathrm{K^-pnn}(T=1)$, $\mathrm{K^-pp}$, $\mathrm{K^-pn}$ and $\mathrm{K^-nn}$. The $\mathrm{K^-N}$ g-matrix of Ref. [9] is:

$$g = \nu + \nu \frac{Q_\mathrm{n}}{E_\mathrm{st} - Q_\mathrm{n} \boldsymbol{T} Q_n} g\,. \quad (2)$$

The relative weight of $g^{I=0}$ with respect to $g^{I=1}$ is 1:5 for $\mathrm{K^-pnn}(T=1)$, 1:1 for $\mathrm{K^-ppn}(T=0)$, 3:1 for $\mathrm{K^-pp}$ and 1:3 for $\mathrm{K^-pn}$ respectively. That is $g^{I=0}/6 + 5g^{I=1}/6$ for $\mathrm{K^-pnn}(T=1)$, $g^{I=0}/2 + g^{I=1}/2$ for $\mathrm{K^-ppn}(T=0)$, $3g^{I=0}/4 + g^{I=1}/4$ for $\mathrm{K^-pp}$ and $g^{I=0}/4 + 3g^{I=1}/4$ for $\mathrm{K^-pn}$. The interaction in $\mathrm{K^-nn}$ is $2g^{I=1}$. We find that $\mathrm{K^-pnn}(T=1)$ is weaker than $\mathrm{K^-ppn}(T=0)$, so the binging energy is smaller and the width is broader. For the $\mathrm{K^-pp}$ system, though the p-p system is unbound, the presence of a $\bar{\mathrm{K}}$ attracts the two protons to form a bound state. The bound-state energy ($E_{\mathrm{K^-}}$) is obtained by solving the

K^--core relative motion equation[9]:

$$\left[-\frac{\hbar^2}{2\mu_{\mathrm{K^-A}}}\frac{\mathrm{d}^2}{\mathrm{d}r^2}+V_{\mathrm{K^-A}}(r)\right]u_{\mathrm{K^-}}(r)=E_{\mathrm{K^-}}u_{\mathrm{K^-}}(r), \quad (3)$$

with

$$V_{\mathrm{K^-A}}(r)=\int g(\boldsymbol{r}-\boldsymbol{r}')\rho(\boldsymbol{r}')\mathrm{d}\boldsymbol{r}'\,. \quad (4)$$

3 Results and discussion

The $\mathrm{K^-pp}$ system is the lightest nuclear system which can be called a strange dibaryon. We find a binding energy of $B_{\mathrm{K^-}}=23$ MeV and a width Γ of 62 MeV, while the corresponding result obtained by AY is $E_{\mathrm{K^-}}=-48$–$i30$ MeV. The binding energy we get is smaller than AY's about 25 MeV, but the width is broader. Using the first resonance as the bound state of the kaon and proton, A. Dote et al.[17] have investigated the $\mathrm{K^-pp}$ system with a chiral $SU(3)$ effective interaction and found that the system is weakly bound with a binding energy $B=(19\pm3)$ MeV and a decay width $\Gamma(\mathrm{K^-pp}\rightarrow\pi\Sigma\mathrm{N})\sim$40—70 MeV. We also treated this strange dibaryon considering the first resonance as the bound state of the kaon and proton. The binding energy we got is 22 MeV and the width is 56 MeV. The result is almost the same whether we use the superposition of the two resonances or the first one as the bound state of the kaon and proton. Our result is similar to Dote's but smaller than AY's. The reason is that AY considered $\Lambda(1405)$ as the bound state of the kaon and proton, and we take it as a superposition of the two resonances.

For the $\mathrm{K^-pnn}(T=1)$ state, the binding energy first obtained by AY was 21 MeV with a very broad width of 95 MeV. The strange tribaryons $\mathrm{K^-ppn}(T=0)(3140)$ and $\mathrm{K^-pnn}(T=1)(3115)$ were observed by T. Suzuki and M. Iwasaki et al.[12, 19, 20] in the interaction of stopped $\mathrm{K^-}$ mesons with ^{4}He. But, recently, M. Iwasaki et al.[21] have performed a couple of experiments, and no narrow peak structure was found, the strange tribaryon $S^0(3115)$ [11, 12] was an experimental artifact. For the strange tribaryon system $[(\mathrm{NNN})\bar{\mathrm{K}}]^Q_{T,T_3}$, with Q being a charge and (T,T_3) a total isospin and its 3rd component, the $S^0(3115)$ and $S^1(3140)$ are identified as the $(T,\ T_3)=(1,-1)$ and $T=0$ states, respectively[26]. But in this paper we consider the $\mathrm{K^-pnn}(T=1)$ state as a singlet instead of one of the triplets, the relative weight of $g^{I=0}$ with respect to $g^{I=1}$ is 1:5. This implies that the interaction is weaker, so the binding energy is smaller than the one of the $\mathrm{K^-ppn}(T=0)$. The binding energy we obtained is 3 MeV and the width 56 MeV.

We have investigated the $\mathrm{K^-ppn}(T=0)$ and $\mathrm{K^-ppnn}(T=1/2)$ systems within the framework of the BHF theory[23]. A binding energy for $\mathrm{K^-ppn}(T=0)$ ($\mathrm{K^-ppnn}(T=1/2)$) of 93 MeV (72 MeV), and a width of 13 MeV (25 MeV) has been obtained. We also studied the other members of the $\mathrm{K^-NN}$ strange dibaryon system: $\mathrm{K^-nn}$ and $\mathrm{K^-pn}$. The $\mathrm{K^-nn}$ system contains only two $g^{I=1}$ interactions, which cannot bind the unbound n-n. For the $\mathrm{K^-pn}$ system $g^{I=1}$ with respect to $g^{I=0}$ is 3:1, too weak to bind $\mathrm{K^-pn}$ below the $\Lambda(1420)+\mathrm{n}$ threshold. Though many theoretical and experimental efforts have been devoted to the investigation of deeply-bound kaonic nuclei, their results differ from each other and further detailed studies are required.

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