Deeply bound kaonic states in nuclei*

LI Yi-He(李宜和)[1)] WU Shi-Shu(吴式枢)[2)]

(Center For Theoretic Physics JiLin University, Changchun 130023, China)

Abstract Using a new phenomenological $\bar{\mathrm{K}}$N interaction which reproduces $\Lambda(1405)$ as an $I=0$ bound state of $\bar{\mathrm{K}}$N, we have investigated $\mathrm{K}^- - {}^3\mathrm{He}(T=0)$ and $\mathrm{K}^- - {}^4\mathrm{He}(T=1/2)$ within the framework of the Brueckner-Hartree-Fock(BHF) theory. Our calculations show that the above kaonic nuclear systems are both deeply bound. The binding energy $\mathrm{B}_{\mathrm{K}^-}$ is 124.4 MeV(94.1 MeV) and the width Γ is 11.8 MeV(25.8 MeV) for $\mathrm{K}^- - {}^3\mathrm{He}(T=0)(\mathrm{K}^- - {}^4\mathrm{He}(T=1/2))$.

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

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1 Introduction

Deeply bound hadronic states have attracted attention for many years, especially kaonic atoms. Based on early data on K^-p scattering, Dalitz and Tuan[1] predicted the existence of a subthreshold $\bar{\mathrm{K}}$N resonance, the $\Lambda(1405)$, 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. There have been many studies on the derivation of kaon-nucleus optical potential[3, 4]. For heavier nuclei, Batty et al.[3] reanalyzed all the existing data of K^- atoms, deduced an optical potential with a strongly attractive real part and also a strongly absorptive imaginary part. On the other hand, Friedman and Gal[4] expected theoretically a number of narrow deeply bound atomic states in all nuclei. In order to seek possible narrow discrete nuclear bound states, Akaishi and Yamazaki (AY) have investigated theoretically several few-body systems, they found the deeply bound nuclear states with very small widths. They consider the $\Lambda(1405)$ state as a bound state of kaon and proton and its width is caused by coupling to the $\pi\Sigma$ channel. Based on Martin's empirical value[5] and the KpX measurement value[6], they gave a phenomenological $\bar{\mathrm{K}}$N interaction, where $V_{\pi\Sigma,\pi\Sigma}$ and $V_{\pi\Lambda,\pi\Lambda}$ were set equal to zero. They have found, for example, the B_k of $\mathrm{K}^- - {}^3\mathrm{He}(T=0)(\mathrm{K}^- - {}^4\mathrm{He}(T=1/2))$ is 108 MeV(86 MeV) and the widths is 20 MeV(34 MeV)[7]. A few years later, in search for quasi-bound states in the K^-pp system a three-body $\mathrm{K}^-\mathrm{NN}-\pi\Sigma\mathrm{N}$ coupled-channel Faddeev calculation by Shevchenko et al.[8] yields a quasi-bound state with B_k ~55-70 MeV, and Γ ~90-10 MeV, in this letter the energy of the $\Lambda(1405)$ is 1406 MeV and width is 50 MeV. Somewhat later, Ikeda et al.[9] treated the same three body system using a similar method, the $\mathrm{K}^-\mathrm{NN}-\pi\mathrm{YN}$ coupled-channel was considered instead of $\mathrm{K}^-\mathrm{NN}-\pi\Sigma\mathrm{N}$ coupled-channel. They found that the binding energy of the strange dibaryons system is about 79 MeV and width is 74 MeV. The strange tribaryons $S^0(3140)$ with $T=0$ and $S^1(3115)$ with $T=1$ were observed in the interaction of stopped K^- mesons with ${}^4\mathrm{He}$[10]. Another indication of K^-pp bound state was reported by the FINUDA Collaboration at DAΦNE[11], the binding energy and width are 115 and 67 MeV, respectively. Recently, correlated Ad pairs emitted after the absorption of negative kaons at rest $\mathrm{K}^-\mathrm{A} \rightarrow \Lambda\mathrm{dA}'$ in light nuclei ${}^6\mathrm{Li}$ and ${}^{12}\mathrm{C}$ was perfromed by KEK-PS E549 collaboration[12]. They found that $M_{\Lambda\mathrm{d}}$ is 3220 MeV, and there are two distinct species of $S_{T=0,1}$ with quite similar masses and widths. From these theoretical calculations and experimented measurements we expect the existence of the deeply bound states.

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1) E-mail: lyhjlu@yahoo.com.cn

2) E-mail: wuss@jlu.edu.cn

However, the result of AY and the measured value of above experiments were criticized by Oset and Toki[13], who argued that the model of Ref.[7] is unrealistic. Within the SU(3) chiral unitary model, they found that there are not just one $\Lambda(1405)$ but two states, one appears around 1395 MeV, which has a width of about 130 MeV and couples mostly to $\pi\Sigma$, while the other one appears around 1420 MeV has a width about 30 MeV and couples mostly to $\bar{\mathrm{K}}\mathrm{N}$. However, lineshape of the $\Lambda(1405)$ hyperon through its $\pi\Sigma$ decay was measured by Zychor et al.[14], recently, they found that the properties (mass, width, and shape) of the $\Lambda(1405)$ resonance are essentially identical for three different production modes, this finding constitutes a challenging test for models that predict $\Lambda(1405)$ to be a two-state resonance. The $\Lambda(1405)$, as measured through its $\pi\Sigma$ decay, has a shape that is consisient with data on the charged decays[15], with a mass of 1400 MeV and width of 60 MeV. So in this paper, We consider the $\Lambda(1405)$ state as a bound state of the kaon and proton, using a new phenomenological $\bar{\mathrm{K}}\mathrm{N}$ interaction. We investigate these light K^--nuclear states within the framework of the Bruckner-Hartree-Fock theory.

2 Formalism

Although the phenomenological $\mathrm{K}^-\mathrm{N}$ interaction (PhI) proposed by AY is convenient for calculation, it seems somewhat too simple. It contains only one range parameter and has set not only $V_{\pi\Lambda,\pi\Lambda}=0$ but also $V_{\pi\Sigma,\pi\Sigma}=0$. It is known that the latter is very important for the coupled channel consideration. Thus, to make PhI more flexible, we have looked for a new phenomenological $\mathrm{K}^-\mathrm{N}$ interaction potential with two range parameters, and $V_{\pi\Sigma,\pi\Sigma}\neq 0$. For the new potential we use Gaussian type:

$$V_{\mathrm{ij}}=\nu^1_{\mathrm{ij}}\exp[-(\frac{r}{u_1})^2]+\nu^2_{\mathrm{ij}}\exp[-(\frac{r}{u_2})^2]. \qquad (1)$$

Table 1. Strength parameters V_{ij} for $I=0$ interaction potentials with two range parameters, corresponding to $a^{I=0}=-1.76+\mathrm{i}0.60$ fm and $E_\Lambda=1406.5-\mathrm{i}25\mathrm{MeV}$.

V_{ij}	range	strength
$V_{\mathrm{K^-N,K^-N}}$	0.85	-194
	0.45	-289
$V_{\mathrm{K^-N},\pi\Sigma}$	0.85	-178
	0.45	-276
$V_{\pi\Sigma,\pi\Sigma}$	0.85	-99
	0.45	-35

The strength parameters and range parameters are listed in Table 1 for $I=0$ and Table 2 for $I=1$ interaction. The $I=0$ interaction produces a resonance state $\Lambda(1405)$ with $E_\Lambda=1406.5-\mathrm{i}25$ MeV, and gives a scattering length of $a^{I=0}=-1.76+i0.6$ fm which can be compared to Martin's empirical value[5] $a^{I=0}=(-1.70\pm 0.07)+\mathrm{i}(0.68\pm 0.04)\mathrm{fm}$. The $I=1$ interaction fits Martin's $I=1$ empirical value $a^{I=1}=0.37+\mathrm{i}0.60$ fm.

Table 2. Strength parameters V_{ij} for $I=1$ interaction potentials with two range parameters, corresponding to $a^{I=1}=0.37+\mathrm{i}0.60\mathrm{fm}$, $V_{\pi\Sigma,\pi\Sigma}\neq 0$, $V_{\pi\Lambda,\pi\Lambda}$ and $V_{\pi\Lambda,\pi\Sigma}$ are set equal zero.

V_{ij}	range	strength
$V_{\mathrm{K^-N,K^-N}}$	0.85	-42
	0.45	-55
$V_{\mathrm{K^-N},\pi\Sigma}$	0.85	-96
	0.45	-126
$V_{\mathrm{K^-N},\pi\Lambda}$	0.85	-118
	0.45	-155
$V_{\pi\Sigma,\pi\Sigma}$	0.85	-168
	0.45	-220

Table 3. Scattering lengths and resonance poles of models for $I=0$ interaction.

model	scattering length /fm	resonance energy /MeV
A	$-1.70+\mathrm{i}0.60$	$1406-\mathrm{i}29$
B	$-1.70+\mathrm{i}0.68$	$1405-\mathrm{i}31$
C	$-1.76+0.60$	$1406.5-\mathrm{i}25$
D	$-1.76+\mathrm{i}0.68$	$1405.5-\mathrm{i}30$
E	$-1.76+\mathrm{i}0.68$	$1404.5-\mathrm{i}21$

We have also studied other potential for $I=0$ interaction, the corresponding scattering lengths and resonance energy are listed in Table 3, while model C already listed in Table 1. In order to investigate the influence of $V_{\pi\Sigma,\pi\Sigma}$, we have considered the interaction of model E:

$$V_{\mathrm{K^-N,K^-N}} = -200\exp\left[-\left(\frac{r}{0.85}\right)^2\right]- 295\exp\left[-\left(\frac{r}{0.45}\right)^2\right]\mathrm{MeV}, \qquad (2)$$

$$V_{\mathrm{K^-N},\pi\Sigma} = -199\exp\left[-\left(\frac{r}{0.85}\right)^2\right]- 273\exp\left[-\left(\frac{r}{0.45}\right)^2\right]\mathrm{MeV}, \qquad (3)$$

where $V_{\pi\Sigma,\pi\Sigma}=0$.

We consider two K^-−nuclear states: $\mathrm{K}^- - {}^3\mathrm{He}(T=0)$ and $K^- - {}^4\mathrm{He}(T=1/2)$. The binding of K^- in these nuclei is calculated within the framework of the Brueck-Hartree-Fork(BHF) theory. We use the K^-N g-matrix of Ref. [7]:

$$g=\nu+\nu\frac{Q_{\rm n}}{E_{\rm st}-Q_n\boldsymbol{T}Q_{\rm n}}g\,. \quad (4)$$

The starting energy $E_{\rm st}=E_{K^-}+E_{\rm n}$ which is to be self-consistent, and $Q_{\rm n}$ is Pauli projection .The relative weights of $g^{I=0}$ with respect to $g^{I=1}$ is 1:1 for $K^- - {}^3$He$(T=0)$ and 1:3 for $K^- - {}^4$He$(T=1/2)$. The Bound-state energy (E_{K^-}) is obtained by solving the K^--core relative motion Ref. [7]:

$$\left[-\frac{\hbar^2}{2\mu_{\rm k-A}}\frac{d^2}{{\rm d}r^2}+V_{\rm K-A}(r)\right]u_{K^-}(r)=E_{K^-}u_{K^-}(r). \quad (5)$$

3 Results and discussion

Our result on the $K^- - {}^3$He$(T=0)$ and $K^- - {}^4$He$(T=1/2)$ is summarized in Table 4. We find that the binding energy B_{K^-} is 124.4 MeV (94.1 MeV) and the width Γ is 11.8 MeV (25.8 MeV) for $K^- - {}^3$He$(T=0)$ ($K^- - {}^4$He$(T=1/2)$), while the corresponding result obtained by AY is E_{K^-} = -108-i10 MeV (−86-i17 MeV) respectively. Our result shows that these systems are more bound and stable comparing with AY's, and approach more closely the measured values of KEK-ps[10] where the tribaryons mass is 3140 MeV. We also find model E is similar to the model of AY[7], but the B_{K^-} is bigger and the width Γ is narrower. Because $V_{\pi\Sigma,\pi\Sigma}$ is set equal to zero in model E, the imaginary part of the scattering length is small, the binding energy is bigger and the width is narrower comparing with models A-D. So $V_{\pi\Sigma,\pi\Sigma}$ is very important for the coupled channel consideration, we can not discard it easily. On the other hand, we find that the strength is very sensitive to the range if the potential only contains one range parameter, we can not assure the range parameter 0.66 fm is suitable, so we use two range parameters based on interaction. We also studied several acceptable interaction models, the binding energy and the width can be in the range of $B_{K^-}\sim 123-131.2$ MeV and $\Gamma\sim 8.2-12.2$ MeV for $K^- - {}^3$He$(T=0)$.

Table 4. Calculated energy $E_{K^-} - {\rm i}\Gamma/2$ of $K^- - {}^3$He$(T=0)$ and $K^- - {}^4$He$(T=1/2)$.

model	$K^- - {}^3$He$(T=0)$ /MeV	$K^- - {}^4$He$(T=1/2)$ /MeV
A	$-124.1-i6.0$	$-94.8-$i12.8
B	$-123.0-i6.1$	$-94.1-$i12.8
C	$-124.4-i5.9$	$-94.1-$i12.9
D	$-125.6-i5.8$	$-95.0-$i12.7
E	$-131.2-i4.2$	$-97.4-$i12.6

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