Mesonic and non-mesonic branching ratios of $K^-$ absorption in the nuclear medium

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Abstract

The branching ratios of $K^-$ absorption at rest in nuclear matter are evaluated from the $K^-$ self-energy by using the chiral unitary approach for the $s$-wave $\bar{K}N$ amplitude. We find that both the mesonic and non-mesonic absorption potentials are dominated by the $\Lambda(1405)$ contributions. We also observe that the mesonic absorption ratio $\frac{\pi^-\Sigma^+}{\pi^+\Sigma^-}$ increases as a function of nuclear density due to the interference between $\Lambda(1405)$ and the $I=1$ non-resonant background, which is consistent with experimental results. The fraction of the non-mesonic absorption is evaluated to be about 30% at the saturation density. The branching ratios of the $K^-$ absorption at rest into deuteron and $^4$He are also calculated.

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1. Introduction

Antikaon ($\bar{K}$)-nucleus bound systems have attracted continuous attention because they are important tools to study the low-energy $\bar{K}N$ and $\bar{K}$-nucleus interactions and the in-medium properties of $\bar{K}$ [1,2]. Kaonic atoms, which are Coulombic bound states of $\bar{K}^-$-nucleus with the influence of strong interaction, provide us with unique information on strong interaction between $\bar{K}^-$ and nucleus at low-energy from their binding energies and decay widths [1,2]. In addition, strongly attractive $\bar{K}N$ interaction in the $I=0$ channel, which dynamically generates $\Lambda(1405)$ as a $\bar{K}N$ quasi-bound state [3] (see also [4]), stimulates recent studies on kaonic nuclei, which are the $\bar{K}$ few-nucleon systems bound mainly by the strong interaction [2,5]. Searches for kaonic nuclei have been done in recent experiments [6], although there is no clear evidence.

One of the important properties of the $\bar{K}$-nucleus systems to extract information on the $\bar{K}N$ and $\bar{K}$-nucleus interactions is their decay patterns. Branching ratios of stopped $K^-$ absorption were investigated experimentally as early as in the 1970s [7,8,9] and extended in recent studies, e.g., Ref. [10]. As a result, we have observed the increase of the absorption ratio $R_{\pi^-\Sigma^+}/[\pi^+\Sigma^-]$ for stopped $K^-$ on light nuclei as a function of nuclear number $A$, which implies sub-threshold modification of the $\bar{K}N$ interaction, in agreement with earlier calculations [11], and have determined non-mesonic fractions of stopped $K^-$ absorption in various nuclei.

In order to interpret these branching ratios, we investigate theoretically the mesonic and non-mesonic branching ratios for stopped $K^-$ absorption in nuclear matter by using a $\bar{K}N$ interaction model as an input [12]. In this study the branching ratios are evaluated from the imaginary part of the $K^-$ self-energy as functions of nuclear density as well
as kaonic energy and momentum. Actually there are several preceding studies on the in-medium $K^{-}$ self-energy [13]. Here we concentrate on the imaginary part of the self-energy to evaluate the branching ratios of the $K^{-}$-nuclear systems.

## 2. Mesonic and non-mesonic branching ratios of $K^{-}$ absorption

We evaluate the absorption potential for $K^{-}$ in nuclear matter as the imaginary part of the $K^{-}$ self-energy in nuclear matter as a function of nuclear density $\rho_N$. The mesonic absorption potential is obtained by considering the self-energy with one-body process as shown in Fig. 1(a). For the non-mesonic absorption, we calculate two-body absorption with one-meson exchange model where the Nambu-Goldstone bosons are exchanged between the baryons, as shown in Figs. 1(b–e). In the calculation, the $K^{-}N \rightarrow MB$ scattering amplitudes are determined by using the so-called chiral unitary approach [14], which is based on chiral dynamics and a unitarized framework. In the chiral unitary approach the low-energy $KN$ scattering is well reproduced and $\Lambda(1405)$ is dynamically generated. We describe nuclear matter using the Thomas-Fermi approximation, in which a bound nucleon with momentum $p$ has energy, $E_N = M_N + p^2/(2M_N) - k_F^2/(2M_N)$, with the nucleon mass $M_N$ and the Fermi momentum $k_F = (3\pi^2\rho_N/2)^{1/3}$. The details of the formulation for the absorption potential are given in Ref. [12].

One important feature of $K^{-}$ absorption in nuclei is that the center-of-mass energy of the $K^{-}N$ pair in the initial state can go below the threshold value, $m_K + M_N$, where $m_K$ is the in-vacuum $K^{-}$ mass, due to the off-shellness of the bound nucleon. For a kaon with a finite momentum and a binding energy, the two-body energy shifts farther downward compared to the kaon at rest owing to the off-shellness of the kaon. Furthermore, the $K^{-}N$ system in the initial state can have lower energies in higher densities. These facts mean that strength of the contributions from $\Lambda(1405)$, existing below the $K^{-}p$ threshold, to the absorption reactions depends on the nuclear density as well as the kaon energy and momentum. In our model setup, the $K^{-}p$ energy with $K^{-}$ at rest becomes around 1420 MeV at the nuclear density $\rho_N \approx 0.05$–0.1 fm$^{-3}$. This energy corresponds to the peak position of the $\Lambda(1405)$ spectra in $K^{-}p \rightarrow (\pi\Sigma)^0$. Even at the saturation density $\rho_0 = 0.17$ fm$^{-3}$ the $K^{-}p$ energy is around 1400 MeV, which is in the $\Lambda(1405)$ peak.

We now show in Fig. 2 the mesonic absorption potential for $K^{-}$ at rest in nuclear matter as a function of nuclear density $\rho_N$. As one can see from the figure, the absorption to the $(\pi\Sigma)^0$ states is dominant to the other channels. Bearing in mind that the $\Lambda(1405)$ appears selectively in the $K^{-}p \rightarrow (\pi\Sigma)^0$ transitions, this result shows that the $\Lambda(1405)$ contribution is important for the mesonic absorption of $K^{-}$ in these densities and $\Lambda(1405)$ can be a doorway to the absorption of $K^{-}$ at rest. We also note that the potential for the $(\pi\Sigma)^0$ channels does not show $\rho_N^{-1}$-like dependence owing to the energy dependence of the $KN$ amplitude coming from the $\Lambda(1405)$ resonance. Another interesting feature for the mesonic absorption is that the behaviors of the absorption to $\pi^{+}\Sigma^{+}$ are different from each other; while the ratio $R_{\pi^{+}\Sigma^{+}} = [\pi^{+}\Sigma^{+}]/[\pi^{+}\Sigma^{-}]$ is less than unity at $\rho_N < 0.08$ fm$^{-3}$, it gets larger as the density increases and becomes about 1.6 at the saturation density. This tendency comes from the facts that the $\Lambda(1405)$ peak in the $K^{-}p \rightarrow \pi^{+}\Sigma^{-}$ ($\pi^{-}\Sigma^{+}$) shifts upward (downward) due to the interference between $\Lambda(1405)$ and the $I = 1$ non-resonant background and the lower (higher) density probes the higher (lower) energy of the initial $K^{-}p$ system. We note that the behavior of the ratio $R_{\pi^{+}\Sigma^{+}}$ is consistent with the experimental results. Namely, while the ratio $R_{\pi^{+}\Sigma^{+}}$ is 0.42 for stopped $K^{-}$ on proton [7], which constrains the ratio at zero density in our model, it becomes large as off-shellness of bound nucleons increases, as 0.85 on deuteron and $1.8 \pm 0.5$ on $^{4}\text{He}$ [9], and $1.2$–$1.5$ on $p$-shell nuclei [10]. This indicates that the experimental results

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**Figure 1.** Feynman diagrams for the mesonic (a) and non-mesonic (b–e) $K^{-}$ absorption processes in nuclear matter [12]. In the mesonic diagram, $N_1$, $p$, and $Y$ denote nucleons, pions, and hyperons, respectively. In the non-mesonic diagrams, $N_1$ and $N_2$ denote nucleons, $A$ and $B$ baryons, and $a$ and $b$ mesons. The shaded ellipses represent the $K^{-}N \rightarrow MB$ amplitudes.
on $R_{\rho}$ of the stopped $K^-$ absorption in various nuclei could be explained by the nature of the $\Lambda(1405)$ resonance together with the $I = 1$ non-resonant background. We also note that the condition of $R_{\rho^0} = 1$ takes place at relatively lower density, $\rho_N \approx 0.08$ fm$^{-3}$, which means that the peak position of the $\Lambda(1405)$ spectrum in $K^- p \rightarrow (\pi\Sigma^0)$ should be at an energy close to the $KN$ threshold rather than at 1405 MeV.

Next we show in Fig. 3 the non-mesonic absorption potential for $K^-$ at rest in nuclear matter as a function of nuclear density squared. From the figure, we find large contributions from the $K^- p \rightarrow \pi^0 \Sigma^0$ and $\pi^0 \Sigma^-$ processes. We also note that the potential shows non-resonant background. We also note that the condition of $R_{\rho^0}$ dependence due to the $\Lambda(1405)$ existence. The deviation from $\rho^0_N$ dependence is most significant in the $K^- p \rightarrow \pi^+ \Sigma^-$ transition dominantly takes place, in which the transition strength is maximum at 1424 MeV from the $\Lambda(1405)$ resonance and the peak position is higher than the other channels as mentioned in the mesonic absorption. Furthermore, we have the absorption ratios $[\Lambda p]/[\Sigma^0 p] \approx [\Lambda n]/[\Sigma^0 n] \approx 1$ and $[\Sigma^+ n]/[\Sigma^0 n] \approx 2$ with marginal dependence on the nuclear density. Since in Ref. [12] the non-mesonic decay of $\Lambda(1405)$ in nuclear matter is found to be $[\Lambda N]/[\Sigma^0 N] = 1.2$ in the chiral unitary approach and $[\Sigma^+ N]/[\Sigma^0 N]$ is exactly two if the $KN$ is purely $I = 0$, the present result of the non-mesonic absorption ratios can be interpreted as the consequence of the $\Lambda(1405)$ dominance.

We now summarize the results of the mesonic and non-mesonic fractions of the $K^-$ absorption at rest. It is found

![Figure 2](image1.png)

**Figure 2.** Mesonic absorption potential ($\text{Im} V^{\text{mes}}$) for $K^-$ at rest in nuclear matter as a function of nuclear density $\rho_N$ [12]. The potentials for $K^- n \rightarrow \pi^+ \Sigma^0$ and $\pi^0 \Sigma^-$ have the same values owing to the isospin symmetry.

![Figure 3](image2.png)

**Figure 3.** Non-mesonic absorption potential ($\text{Im} V^{\text{non}}$) for $K^-$ at rest in nuclear matter as a function of nuclear density squared $\rho^0_N$ [12]. Left (right) panel shows the contributions from the $K^- p p \rightarrow \Lambda p, \Sigma^0 p$, and $\Sigma^+ n$ processes (the $K^- p n \rightarrow \Lambda n, \Sigma^0 n, \Sigma^- p$ and $K^- n n \rightarrow \Sigma^- n$ processes).
that the mesonic (non-mesonic) fraction almost linearly goes down (up) from unity (zero) as the nuclear density increases, because the non-mesonic reaction can more largely contribute to the absorption at higher densities. At the saturation density the mesonic and non-mesonic fractions are about 70% and 30%, respectively. These fractions are close to the empirical value for kaonic atoms with nuclei heavier than $^4$He (about 80% and 20%, respectively). However, it is suggested in Refs. [16,17] that the effective density where the absorption mainly takes place does not correspond to the nuclear saturation density but to a fraction of it and the effective density strongly depends on the strong interaction between $K^-$ and nucleus. Therefore, bearing in mind that for bound kaons the kaon momenta and energies are determined self-consistently in the equation of motion with the energy-momentum-dependent potential, a realistic treatment of the bound kaon with finite nuclei is necessary for quantitative discussions.

Finally we calculate the branching ratios of the $K^-$ absorption at rest in deuteron and $^4$He by using phenomenological wave functions for bound nucleons [13]. These light nuclei serve as environments of various nuclear densities inside nuclei due to the large varieties of the binding energies per one nucleon. The $R_{\pi^+}$ ratio is found to be 0.84 and 1.32 for deuteron and $^4$He targets, respectively. The non-mesonic fraction amounts to 3.4% in the $K^-$-deuteron case and to 18.6% in the $K^-$-$^4$He case. Both results are close to the experimental results. For quantitative comparison with experimental results, however, we have to take into account final state interactions such as $\Sigma$-A conversions, and also appropriate wave function of bound $K^-$ will be necessary because $K^-$ even in atomic states may have a large momentum inside nucleus due to the orthogonality to the kaonic nuclear states [19].

3. Summary

In this study we have investigated the mesonic and non-mesonic branching ratios of $K^-$ in nuclear matter from the $K^-$ self-energy as functions of nuclear density. By using the chiral unitary approach for the $s$-wave $KN$ interaction as an input, we have found that both the mesonic and non-mesonic absorptions of $K^-$ at rest are dominated by the $\Lambda(1405)$ contribution. The absorption ratio $R_{\pi^+} \equiv (\pi^+\Sigma^+)/[\pi^+\Sigma^-]$ becomes larger as the nuclear density increases and its behavior is consistent with the experimental results. The ratio $R_{\pi^+}$ becomes unity at relatively lower density, which means that the peak position of the $\Lambda(1405)$ spectrum in $K^-p \rightarrow (\pi\Sigma)^0$ should be at an energy close to the $KN$ threshold rather than at 1405 MeV. The non-mesonic absorption ratios $\langle\rho\rangle/\langle\sigma\rangle$ and $\langle\eta\rangle/\langle\Sigma^2n\rangle$ are about unity while $\langle\Sigma^*n\rangle/\langle\Sigma^0\rangle$ and $\langle\Sigma^-p\rangle/\langle\Sigma^2n\rangle$ are about two due to the $\Lambda(1405)$ dominance in absorption. The non-mesonic fraction is about 30% at the saturation density. We have also calculated the branching ratios of the $K^-$ absorption at rest in deuteron and $^4$He, and we have found that the evaluated $R_{\pi^+}$ ratio and the non-mesonic fraction are close to the experimental results.

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