Λ(1405)N → YN transition in nuclear medium for non-mesonic absorption of K in nucleus

T. Sekihara\textsuperscript{a}, D. Jido\textsuperscript{b}, Y. Kanada-En’yo\textsuperscript{b}

\textsuperscript{a}Department of Physics, Kyoto University, Kyoto 606-8502, Japan
\textsuperscript{b}Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

Abstract

Non-mesonic transition of Λ(1405)N → YN is investigated as one of the essential processes for the non-mesonic absorption of K in nuclei. Using one-meson exchange model in the calculation of the transition, we find that the non-mesonic transition ratio Γ\textsubscript{ΛN}/Γ\textsubscript{ΣN} depends strongly on the ratio of the Λ(1405) (Λ*) couplings to KN and πΣ. Especially a larger Λ*-KN coupling leads to enhancement of the transition to ΛN. Using the chiral unitary model for the description of the Λ*, we obtain Γ\textsubscript{ΛN}/Γ\textsubscript{ΣN} ≈ 1.2 which is almost independent of the nucleon density, and find the total non-mesonic decay width of the Λ* in uniform nuclear matter to be 22 MeV at the normal density.

Key words: Non-mesonic decay, kaonic nuclei; Λ(1405) doorway; Chiral unitary approach

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1. Introduction

The study of the in-medium properties of anti-kaon (K) has attracted continuous attention [1]. K has been theoretically expected to be bound by nuclear systems due to attractive strong interaction between K and nucleon N [2]. These K-nuclear bound systems assisted mainly by the strong interaction, which are so-called kaonic nuclei, have at least two important aspects; the kaonic nuclei are strongly interacting exotic many-body systems, and they provide favorable systems for the studies of the K properties at finite density. However, in spite of experimental efforts to search for the K-nuclear bound systems [3], there are no clear evidences observed yet.

In order to understand the K-nucleus systems, it is important to investigate theoretically the decay mechanism of the kaonic nuclei, or the absorption process of the K into nuclei. Especially the decay (absorption) ratios of various modes and explicit numbers of the decay (absorption) widths are key quantities for the K-nucleus systems. The decay of the kaonic nuclei in strong interactions can be categorized into two processes; one is the mesonic process such as \( \bar{K}N \rightarrow \pi Y \), and the other is the non-mesonic process such as \( \bar{K}NN \rightarrow YN \), where Y denotes hyperon (Λ or Σ). The non-mesonic decays have advantage in experimental observations, since signals from kaonic nuclei are readily distinguished from backgrounds and no extra mesons do not have to be detected. Therefore, systematic studies of the non-mesonic decay of the kaonic nuclei are desirable. Especially the ratios of the decay widths are interesting, since they will be insensitive to details of the production mechanism.

The absorption of the K in nuclei may take place dominantly through the Λ(1405) (Λ*) resonance, owning to the presence of the Λ* just below the \( \bar{K}N \) threshold. Namely the Λ* can
Figure 1: Feynman diagrams for the $\Lambda^* N \rightarrow YN$ transition in the one-meson exchange model. The left two diagrams are for the $\Lambda N$ final state and the right two are for the $\Sigma N$ state.

be a doorway of the $K$ absorptions in nuclei. The $\Lambda^*$ doorway picture is more probable, in case that the $\Lambda^*$ is a quasi-bound state of $\bar{K}N$ [4, 5], which has large $K\bar{N}$ components as almost real particles. Therefore the strong $K\bar{N}$ correlations are expected to be responsible for the $\Lambda^*$-induced decays of the $\bar{K}$ in nuclei. Motivated by the $\Lambda^*$ doorway picture, we study the non-mesonic transition of $\Lambda^*N \rightarrow YN$ ($\Lambda^* p \rightarrow \Lambda p$, $\Sigma^0 p$, $\Sigma^+ n$ and $\Lambda^* n \rightarrow \Lambda n$, $\Sigma^0 n$, $\Sigma^- p$) in uniform nuclear matter with a one-meson exchange approach.

2. $\Lambda(1405)$ doorway process for the non-mesonic decay in kaonic nuclei

Now let us define the transition rate of the $\Lambda^* N \rightarrow YN$ process by the transition probability divided by time $T$ as,

$$\gamma_{YN} \equiv \frac{1}{T} \frac{1}{\sqrt{\text{Vol}}} \frac{1}{4} \sum_{\text{spin}} \sum_{\text{spin}} |d\Phi_2|^2 |S| - 1|^2 = \frac{1}{T} \frac{1}{\sqrt{\text{Vol}}} \frac{1}{4} \sum_{\text{spin}} \sum_{\text{spin}} d\Phi_2 |T_{YN}|^2 (2\pi)^4 \delta^4 (p_{\Lambda^*} + p_n - p_N - p_Y), \quad (1)$$

with the $S$-matrix $S$ for the transition process given by the transition amplitudes $T_{YN}$ as $S = 1 - i (2\pi)^4 \delta^4 (P_N + P_m - P_N - P_Y) T_{YN}$. $\text{Vol}$ is volume of the system, and $d\Phi_2$ is the phase-space of the initial state. The transition rate depends on the center-of-mass energy $E_{c.m.}$, equivalently the initial nucleon momentum. Summing up the $\Lambda^* N \rightarrow YN$ transition rate in terms of the initial nucleon states, we can estimate the non-mesonic decay width of the $\Lambda^*$ in nuclear medium as a function of the nucleon density. The factor $1/\text{Vol}$ in the last form of Eq. (1) is responsible for the fact that only one $N$ exists in the initial state in the volume $\text{Vol}$.

We evaluate the transition amplitudes $T_{YN}$ with one-meson exchange diagrams shown in Fig. 1. The each diagram is composed of three parts: the $s$-wave $\Lambda^*MB$ coupling $G_{MB}$, the meson propagator including short-range correlation $\Pi(q^2)$ [7, 8], and the $p$-wave $MBB$ coupling $V_{MBB}$, which is determined by the flavor SU(3) symmetry. The explicit form is given in Ref. [6].

Among the three parts for the transition, only the $s$-wave $\Lambda^*MB$ coupling constants $G_{MB}$ are the model parameters, which are determined by the properties of the $\Lambda^*$. Therefore, in order to study the non-mesonic decay pattern in the $\Lambda^*$ doorway, let us discuss the $G_{MB}$ coupling dependence of the ratio of the transition rates, $\gamma_{AN}/\gamma_{YN}$. With the conditions that $G_{\phi \Lambda} = 0$, the initial nucleon momentum $p_m = 0$, and the $\Lambda^*$ mass $M_{\Lambda^*} = 1420$ MeV, we show the numerical result of the ratio of the transition rates, $\gamma_{AN}/\gamma_{YN}^*$ as a function of $G_{KN}/G_{\pi \Sigma^*}$ in Fig. 2, in which we assume $G_{KN}/G_{\pi \Sigma^*}$ to be a real number. As seen in the figure, the ratio $\gamma_{AN}/\gamma_{YN}^*$ has strong dependence on the coupling ratio $G_{KN}/G_{\pi \Sigma^*}$. This is because the transition to $\Lambda N$ is governed by the $K$ exchange and the transition to $\Sigma N$ is dominated by the $\pi$ exchange due to the coupling $V_{MBB}$ strength. This result suggests that larger $\Lambda^* K N$ coupling leads to enhancement of the decay ratio to $\Lambda N$ in the kaonic nuclei, although the $\Lambda^*$ in vacuum cannot decay into final states including $\Lambda$. 
Now we calculate the non-mesonic decay of the $\Lambda^*$ in uniform nuclear matter induced by the $\Lambda^* N \rightarrow YN$ transition, under the free Fermi gas approximation for nuclear matter. We evaluate the non-mesonic decay width $\Gamma_{YN}$ by summing up the transition rate $\gamma_{YN}$ for the nucleons:

$$\Gamma_{YN} \equiv \sum_{i=1}^{A_N} \gamma_{YN}(k_i) = \int_0^{k_{FN}} dk \frac{k^2}{\pi^2} V \gamma_{YN}(k),$$

where $A_N = k_{FN}^3/(3\pi^2) \times V (N = p \text{ or } n)$ is the numbers of the protons or neutrons in $V$.

Furthermore we fix the ratios of the $\Lambda^*$ coupling constants, $G_{MB}$, we plot the ratio of the non-mesonic decay widths of the in-medium $\bar{K}$ to $\Lambda N$ and $\Sigma^0 N$, as a function of the proton (or neutron) density.

Figure 3: (a) Non-mesonic decay width ratio of $\Lambda^*$ in nuclei. (b) Non-mesonic decay width of $\Lambda^*$ in nuclei. In both cases the $\Lambda^*$ coupling constants are determined by the chiral unitary approach.
in Fig. 3(a). This figure shows that the ratio of the non-mesonic decay widths $\Gamma_{\Lambda N}/\Gamma_{\Sigma N}$ is around 1.2 almost independently of the nucleon density. The density independence of the ratio of the decay widths is caused by sufficiently large phase-space in the final states.

We also obtain the absolute values of the non-mesonic decay widths of the $\Lambda^*$ in nuclear matter. We use the coupling constants of the $\Lambda^*$ to $\bar{K}N$, $\pi\Sigma$ and $\eta\Lambda$ obtained by the chiral unitary approach, which gives the in-vacuum mesonic decay as $\Gamma_{\Lambda^*\rightarrow\pi\Sigma} = 40$ MeV with $M_{\Lambda^*} = 1420$ MeV as observed in a $K^-$ initiated channel [11, 12]. We show the non-mesonic decay widths in Fig. 3(b). The linear dependence of the decay widths is caused by the large phase-space in the final states. At the normal nuclear density ($\rho_B = 0.17$ fm$^{-3}$), the total non-mesonic decay width is 22 MeV, which is almost half of the mesonic decay width of $\Lambda^*$ ($\sim 40$ MeV).

3. Conclusion

We have investigated the non-mesonic transition $\Lambda^*Y \rightarrow YN$ in nuclear medium as one of the essential processes for the non-mesonic absorption of $\bar{K}$ in nucleus. Calculating the $\Lambda^*N \rightarrow YN$ transition rates in the one-meson exchange processes, we have found that the ratio of the $\Lambda^*N$ transition rates to $\Lambda N$ and $\Sigma N$ strongly depends on the ratio of the $\Lambda^*$ couplings, $G_{\bar{K}N}/G_{\pi\Sigma}$. Especially, larger $\Lambda^*$ couplings to $\bar{K}N$ lead to enhancement of the non-mesonic $\Lambda^*$ decay with $\Lambda N$ emission. Furthermore, describing the $\Lambda^*$ properties by the chiral unitary approach, we have obtained the ratio of the non-mesonic decay widths to $\Lambda N$ and $\Sigma N$ as $\Gamma_{\Lambda N}/\Gamma_{\Sigma N} = 1.2$ almost independently of the nucleon density. We have also estimated that the total non-mesonic decay width is 22 MeV at the saturation density. This study can be extend to the calculation of the absorption width of the $\bar{K}$ in nuclear medium [13].

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