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Range correction in the weak-binding relation for unstable states

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Most of hadrons consist of two or three quarks and they are called mesons and baryons. Those which are not classified into mesons and baryons are called exotic hadrons. The exotic hadrons are considered as, for instance, multiquark states with more than three quarks, or hadronic molecular states which are weakly bound states of hadrons. Many candidates for exotic hadrons are discovered in recent experiments and intensive studies are performed to determine the internal structure of those candidates.
The weak-binding relation is one of the approaches to analyze the internal structure of the candidates for exotic hadrons [1,2]. With the weak-binding relation, we can model-independently determine the compositeness which is the fraction of the hadronic molecular component of hadrons. The compositeness is estimated with the scattering length and the binding energy where the uncertainty arises from the finite interaction range. In Ref. [2], the internal structures of $\Lambda(1405)$, $f_0(980)$ and $a_0(980)$ were investigated by using the weak-binding relation. To apply the weak-binding relation to $\Lambda_c(2595)$ in the charm sector, on the other hand, we need to consider the systems with a large effective range. The effective range is the next to leading length scale in the effective range expansion and it characterizes low-energy hadron scatterings together with the scattering length. We show that the weak-binding relation cannot be applied to the system with a large effective range, because the range correction was neglected in the previous works [1,2].
We introduce the range correction to the weak-binding relation by modifying the correction terms which is the origin of the uncertainty. We perform the numerical calculations to check whether the modification of the weak-binding relation works or not. For the calculation, we consider the effective field theory called effective range model. In this model, the exact value of the compositeness is known by definition, and we can control the scattering length and effective range independently by varying the model parameters such as cutoff and coupling constants. To estimate the compositeness precisely with the weak-binding relation, two conditions need to be satisfied. First one is the validity condition which means that the exact value of the compositeness is contained in the uncertainty region. Second one is the precision condition which means that the uncertainty is sufficiently small. From the numerical calculations, we find the parameter region where only the improved weak-binding relation can be applied, so the modification of correction terms of the relation works well. We further discuss the method of the quantitative evaluation of the uncertainty of the weak-binding relation.

[1] S. Weinberg, Phys. Rev. 137, B672 (1965).
[2] Y. Kamiya and T. Hyodo, PTEP 2017, 023D02 (2017).

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