Analysis of the $\Lambda(1405)$ resonance by energy-dependent complex $\bar{K}N$ potential

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The $\Lambda(1405)$ baryon resonance has been a hot topic for its several peculiar natures. The first is the difference from the usual three-body quark model. In contrast to ordinary hadrons, the $\Lambda(1405)$ is considered as the hadronic molecular state with an antikaon $\bar{K}$ and a nucleon N. The second peculiar nature is the so-called double pole structure, which indicate that the $\Lambda(1405)$ is expressed by the two resonance poles derived from the $\bar{K}N$ and $\pi\Sigma$ attractive interactions. In this work, to analyze the $\Lambda(1405)$ quantitatively, we construct the realistic $\bar{K}N$ local potential, and estimate the spatial structure of the $\Lambda(1405)$.

Our potential construction procedure is based on chiral unitary approach, which respects the chiral SU(3) symmetry in QCD. The $\bar{K}N$ local potential is constructed to reproduce the scattering amplitude. Here, we establish the method to accurately reproduce the amplitude even in the complex energy plane. Because the resonance pole lies in the complex plane, such construction procedure is necessary for the $\Lambda(1405)$ analysis. Furthermore, we consider the recent experimental data by the SIDDHARTA Collaboration for the first time. This precise data can significantly reduce the theoretical uncertainty, and is necessary to construct the realistic potential for the quantitative analysis.

The $\bar{K}N$ local potential is complex and energy dependent. To satisfy the essential conditions for quantum mechanics like the orthogonality condition, a careful treatment is necessary for a system with an energy-dependent potential. In the case of a real and energy-dependent potential, the treatment has been established respecting the continuity equation. We extend the treatment to the complex and energy-dependent potential with the Gamow vector. However, it is known that the physical value becomes complex with the Gamow vector, and it is difficult to extract the physical meaning from such complex value. In this work, we consider the root-mean distance of the $\bar{K}N$ system to analyze the spatial structure of the $\Lambda(1405)$, and find the way to extract the real value as the distance paying attention to the dump of the wave function. As a result, we find that the $\bar{K}N$ distance is relatively larger (~ 1.4 fm) than the typical hadronic scale (~ 0.8 fm) and the hadronic molecular picture of the $\Lambda(1405)$ is reasonable.

The realistic $\bar{K}N$ local potential is applicable to the calculation of the $\bar{K}$-nuclei, which may be qualitatively different from the usual nuclei because of the strong $\bar{K}N$ interaction. In the few-body calculation, the treatment with the complex and energy-dependent potential is important, and should be established based on the above way for the two-body calculation.