Impurity effects of the $\Lambda$ particle on the $2\alpha$ cluster states of $^9$Be and $^{10}$Be$^\dagger$

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A unique and interesting aspect of hypernuclei is the structure change caused by the addition of a $\Lambda$ particle as an impurity, which is the so-called "impurity effect." From this point of view, the structure of Be hyper-isotopes is of particular interest, because Be isotopes have a $2\alpha$ cluster core surrounded by valence neutrons$^{1-3)}$. For example, in $^9$Be, the first excited state $1/2^+$ is considered to have a $^8$Be($0^+$) + $n(s_{1/2})$ configuration, which can be regarded as a Hoyle analogue state with the replacement of an $\alpha$ particle by a neutron, while the ground state has a relatively compact $2\alpha + n$ structure. In the neutron-rich side, exotic structures associated with $2\alpha$ clustering appear. In $^{10}$Be, the coexistence of different structures has been discussed based on the concept of the molecular orbits of valence neutrons around the $2\alpha$ clustering$^3)$. Since the two valence neutrons are considered to occupy different molecular orbits in the $0^+_2$, $0^+_3$, and $1^-_1$ states, the degree-of-clustering varies depending on the neutron occupation. In particular, the $0^+_2$ state is considered to be largely deformed with a well-developed $2\alpha$ cluster structure, whereas the ground state is rather compact. Therefore, we can expect the modification of the excitation spectra by the addition of a $\Lambda$ particle. Furthermore, it is interesting to investigate the dynamical changes of these structures.

To investigate such phenomena, we applied an extended version of the antisymmetrized molecular dynamics for hypernuclei, which we call HyperAMD$^5)$. to $^{10}$Be and $^{11}$Be in the same manner as our previous work for $^{12}$Be$^6)$. Figures 1(a) and (b) compare the excitation spectra of $^{10}$Be and $^{11}$Be with those of the core nuclei. It is clearly seen that the excited states of these hypernuclei are shifted up in the excitation spectra, namely the positive-parity states in $^{10}$Be and the $K^\pi = 0^+_2 \otimes \Lambda$ band built on the $1/2^+_3$ state in $^{11}$Be. In other words, the excitation energies of the well-pronounced $2\alpha$ cluster states are increased significantly. This is because the energy gain of the $\Lambda$ particle is considerably different between the ground and these excited states. To see the difference of the energy gain clearly, we calculate the binding energy of the $\Lambda$ particle $B_\Lambda$ defined as,

$$B_\Lambda = E(J^\pi;A;^\Lambda\text{Be}) - E(J^\pi \otimes \Lambda;A;^\Lambda\text{Be}),$$

for each state. In Figs. 1(c) and (d), it is found that the $B_\Lambda$ of the well-pronounced cluster states are much smaller than those of the ground states. The difference of $B_\Lambda$ is mainly due to the difference in the deformation of each state, essentially coming from the degrees of the $2\alpha$ clustering.

In this article, we also discuss the changes caused to the $2\alpha$ clustering by the addition of a $\Lambda$ particle. It is found that the $\Lambda$ particle largely reduces the rms radii of the excited states with large nuclear quadrupole deformation $\beta$, which mainly comes from the reduction of the inter-cluster distance between $2\alpha$.

Fig. 1. (a) Calculated excitation spectra of $^9$Be and $^{10}$Be. (b) Same as (a) but for $^{11}$Be and $^{12}$Be. (c) Calculated values of $B_\Lambda$ by using YNG-ESC08c as the $\Lambda N$ interaction in $^{11}$Be (d) Same as (c) but for $^{12}$Be.

References