Cluster-shell competition and the effect of adding hyperons†

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One of the most intriguing phenomena in nuclear structure physics is the competition between shell and cluster structures. This is largely attributed to the effect of the spin-orbit interaction; the spin-orbit interaction strengthens the symmetry of the jj-coupling shell model, where each single particle has a good total angular momentum j. This means that the spin-orbit interaction has the effect of breaking up clusters, in which some of the strongly correlated nucleons are spatially localized.

Nevertheless, the α cluster structure is known to be important in the light-mass region. Be isotopes are known to have an α-α cluster structure; ^{8}Be decays into two α clusters, and the molecular-orbital structure of the valence neutrons appears in the neutron-rich Be isotopes. The structure has been confirmed by the recent *ab initio* shell-model calculation. The persistence of the α-α cluster structure may be due to the optimal α-α distance, which is approximately 4 fm larger than the interaction range of the spin-orbit interaction.

Although the α-α cluster structure may persist in ^{8}Be, when another α cluster is added in ^{12}C, the interaction between the α clusters increases, and the system has a shorter α-α distance. In this case, the α clusters are trapped in the spin-orbit interaction region. Although the traditional α cluster model (Brink model)[1)] cannot address the spin-orbit interaction, its effect becomes significant if we allow for the breaking of the α clusters. The ground state of ^{12}C is found to contain shell and cluster components.[2)]

The present study aims to show the effect of further addition of hyperons. When Λ particles are added, the optimal distances between clusters reduces. This is known as the glue-like effect,[3)] and as the spin-orbit interaction operates in the inner regions of the nuclear systems, the breaking of α clusters is expected to be enhanced. The ground state would therefore be closer to the jj coupling shell model side.

This spin-orbit contribution is included by extending the cluster model; we have developed the antisymmetrized quasi-cluster model (AQCM).[4)] This method allows us to smoothly transform the α cluster model wave functions into jj-coupling shell model wave functions, and we call the clusters that are subjected to the effect of the spin-orbit interaction due to this model quasi clusters, which can be done by introducing an α breaking parameter λ inside the wave function.

In ^{12}C, the minimum energy point appears at a relative distance of 2.5–3.0 fm, which is 1 fm shorter than in the ^{8}Be case before the breaking of α clusters is allowed. It is therefore suggested that the three α clusters step into the interaction region of the spin-orbit interaction. We introduce a finite value of λ (α breaking parameter), and the states with $\lambda = 0.1$ and $\lambda = 0.2$ nearly degenerate in the region of the lowest energy, where the relative cluster-cluster distance shrinks to 2 fm.

As shown in Fig. 1, this tendency is enhanced in $^{14}_{\Lambda\Lambda}$C. The optimal distance between the ^{4}He nuclei (energy minimum point) is approximately 2.2 fm before the α clusters break (solid line). If we allow the breaking, the energy minimum point appears at the relative cluster-cluster distance of $\sim$1.4 fm, where the dashed line ($\lambda = 0.2$) gives the lowest energy, and the α clusters are significantly broken. We can confirm that the optimal cluster distance reduces and the breaking of the α clusters increases as the number of Λ particles (0, 1, and 2) added to the system increases.

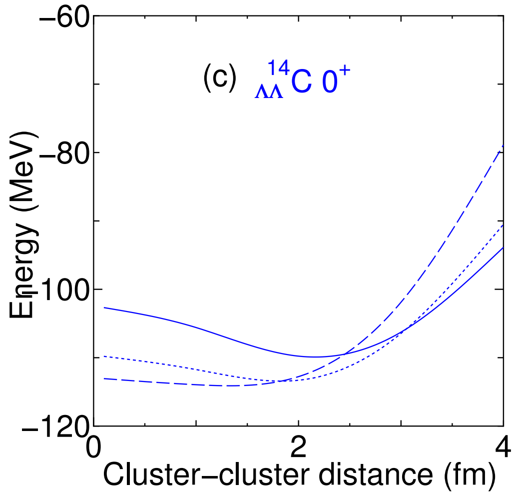

Fig. 1. Energy curves of the 0^+ state of $^{14}_{\Lambda\Lambda}$C as a function of the distance between three ^{4}He clusters with equilateral triangular configuration. The solid line is $\lambda = 0$ (pure three α's) and the dotted and dashed lines are three quasi-clusters with $\lambda = 0.1$ and 0.2, respectively, where λ is an α breaking parameter.

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