# Energies of the $s$- and $p$-shell alpha-cluster hypernuclei with strangeness $S = -1$ to $-4$

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In the last few years, theoretical investigations for the study of the properties of hypernuclei have made tremendous progress using the data obtained from state-of-the-art experimental facilities. Now it has become possible to explore those areas of strange particles hypernuclei which hitherto were inaccessible. An extensive programme to produce and identify light hypernuclei with strangeness content $S = -1$ and $-2$ is being planned in the very near future at J-PARC and in a few years from now for $S = -1$ at DAΦNE and for $S = -3$ hypernuclei at $\bar{P}$ANDA. In future, we hope to have data on $S = -3$ and $-4$ multi-strange hypernuclei as well. The data on these systems are likely to constraint the parameters of $YN$, $YY$, $\Lambda\Xi$ and $\Xi\Sigma$ etc. interaction models.

In view of the above, we have calculated the energies of the $s$- and $p$-shell multi-strange hypernuclei [1], namely ${}^{6}_{\Lambda\Xi^0}$He, ${}^{7}_{\Lambda\Lambda\Xi^0}$He, ${}^{9}_{\Xi^0}$Be, ${}^{10}_{\Lambda\Lambda}$Be, ${}^{10}_{\Lambda\Xi^0}$Be, ${}^{11}_{\Lambda\Lambda\Xi^0}$Be, ${}^{13}_{\Lambda}$C and ${}^{13}_{\Xi^0}$C in the $\alpha$ cluster model with strangeness content $S = -1$ to $-4$ in a variational Monte Carlo (VMC) framework. Three types of $\Lambda\alpha$ and two-type of $\Xi^0\alpha$ potentials and a variety of three-range Gaussian $\Lambda\Lambda$ and NSC97e $\Lambda\Xi^0$ potentials simulated from one-boson-exchange models of Nijmegen group are used. To calculate the energies of the excited $4^+$ state of ${}^{10}_{\Lambda\Lambda}$Be [2] and of the ground states of other systems, the $\Lambda\Lambda$ potential that reproduces the $B_{\Lambda\Lambda}$ of ${}^{6}_{\Lambda\Lambda}$He has also been employed. Woods-Saxon $\Xi^0\alpha$ potential with two extreme values of attractive central depth, a fairly strong 24.0 MeV and 14.0 MeV, a very weak is considered. The stronger potential deduced from older $B_{\Xi^-}$ data with poor statistics from photographic emulsions is retained for comparison with the calculation of earlier work and the weaker one, seems more reasonable, extracted from a fit to the observed excitation energy spectra in the reaction ${}^{12}$C$(K^-, K^+){}^{12}_{\Xi}$Be of the experiment E885, is used for predicting the energies of hypernuclei containing $\Xi^0$ hyperon. Unlike the earlier Faddeev-Yakubovsky results, the system ${}^{7}_{\Lambda\Lambda\Xi^0}$He is found to be as strongly bound for the Isle $\Xi^0\alpha$ potential as for Woods-Saxon shape. The hypernuclei of the ${}^{8}$Be core with strange baryons $\Xi^0$ and $\Lambda\Lambda\Xi^0$ are also found to be stable but latter one is overbound without dispersive $\Lambda\alpha\alpha$ force. This is the first study of the hypothetical multi-strange Be systems. The strong conversion $\Xi N \longrightarrow \Lambda\Lambda$ makes $S = -3$ hypernucleus ${}^{10}_{\Lambda\Xi^0}$Be unstable and no definitive conclusion about the stability of ${}^{6}_{\Lambda\Xi^0}$He can be drawn. The attractive three-body $\alpha\alpha\alpha$ force is needed to satisfactorily reproduce the ground state energy and root mean square radius of ${}^{12}$C for an $\alpha\alpha$ potential, similar to the case as reported in the earlier Faddeev calculations. The $B_\Lambda$ of ${}^{13}_{\Lambda}$C in the cluster model is not consistent with the experimental data without $\Lambda\alpha\alpha$ dispersive force. The ${}^{10}_{\Lambda\Lambda}$Be in the $4^+$ state is not particle stable and the system ${}^{13}_{\Xi^0}$C has been found to be stable.

The energy of the degenerate doublet $(3^+/2, 5^+/2)$ of ${}^{9}_{\Lambda}$Be [3] has been calculated variationally in the Monte Carlo framework. The hypernucleus is treated as a partial nine-body problem in the $\Lambda\alpha\alpha$ cluster model where nucleonic degrees of freedom of $\alpha$s are taken into consideration ignoring the antisymmetrization between the nucleons in the two $\alpha$s. The central two-body Urbana-type $\Lambda N$ and the three-body dispersive and two-pion exchange $\Lambda NN$ forces, constrained by the $\Lambda p$-scattering data and the observed ground state energy of ${}^{5}_{\Lambda}$He, are employed. A simplified wave function constructed from the product of central two- and

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three-body correlations compatible with the central two-body $\Lambda N$ and the three-body dispersive and two-pion exchange $\Lambda NN$ forces, respectively, is found to be adequate in explaining the energy of observed $\gamma$-ray transition from the excited degenerate doublet to the ground state of ${}^{9}_{\Lambda}$Be. The hypernucleus ${}^{9}_{\Lambda}$Be in the excited state is highly deformed and has an oblate shape. The results of the partial nine-body problem are consistent with the earlier three-body cluster model analyzes of ${}^{9}_{\Lambda}$Be. To our knowledge, this is the first application of VMC method for the calculation of the excited state of partial nine-body system ${}^{9}_{\Lambda}$Be.

We have also analyzed in the VMC approach the energies of the ground and excited $2^+$ states of ${}^{10}_{\Lambda\Lambda}$Be [4], treating it as a partial ten-body system in the $\Lambda\Lambda+\alpha\alpha$ model following the work done in the previous paragraph. We use the same central two-body $\Lambda N$ and the three-body dispersive and two-pion exchange $\Lambda NN$ forces as used for ${}^{9}_{\Lambda}$Be, and input $\Lambda\Lambda$ potential is constrained by the observed ground state energy of ${}^{6}_{\Lambda\Lambda}$He. The product-type trial wave function predicts binding energy for the ground state considerably less than for the event reported by Danysz *et al.*; however, it is consistent with the value deduced assuming a $\gamma$-ray of 3.04 MeV must have escaped undetected in the decay of the product ${}^{9}_{\Lambda}\mathrm{Be}^* \longrightarrow {}^{9}_{\Lambda}\mathrm{Be} + \gamma$ of the old emulsion record of the event ${}^{10}_{\Lambda\Lambda}\mathrm{Be} \longrightarrow \pi^- + p + {}^{9}_{\Lambda}\mathrm{Be}^*$. Furthermore, calculated energy for the excited $2^+$ state has been found to be close to the value measured in the Demachi-Yanagi event. The hypernucleus ${}^{10}_{\Lambda\Lambda}$Be has an oblate shape in the excited state. These results are consistent with the earlier four-body $\alpha$ cluster model approach where $\alpha$s are assumed to be structureless entities. Thus earlier cluster model analyzes and the present partial ten-body problem for ${}^{10}_{\Lambda\Lambda}$Be assign Demachi-Yanagi event as $2^+$ excited state of Be hypernucleus. Further, energy of Demachi-Yanagi event is not found to be consistent with the ground state energy of ${}^{10}_{\Lambda\Lambda}$Be and thus making a strong case for the remeasurement of ground state energy. To our knowledge, this is the first time that ${}^{10}_{\Lambda\Lambda}$Be is being studied as a partial ten-body problem in VMC approach.

In the thesis, we have made a comparative study of results of classical $\alpha$ cluster model and partial $A(=9,\ 10)$-body model for ${}^{9}_{\Lambda}$Be and ${}^{10}_{\Lambda\Lambda}$Be. In the former, $\alpha$s are assumed to be rigid and devoid of structure while in the latter, the existence of nucleonic degrees of freedom in the $\alpha$s has been assumed from the outset. From the study of the partial nine- and ten-body problems and of earlier cluster model work we note that the former models will be a preferred option as it will ultimately guide the latter in its modifications and improvements.

The details of the results for all the systems will be presented in the conference.

## References


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