Cluster and shell correlations in Ne isotopes

T Yoshida, N Itagaki and T Otsuka
Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan

Abstract. Structure of Ne isotopes are investigated by a microscopic model, where thousands of Slater determinants are stochastically generated, and important ones are selected out of them. The importance of the \(\alpha\)-cluster correlation is systematically shown, and also, the single-particle parity of each nucleon is studied, and deviation from the pure shell-model-like picture is discussed.

Recently, cluster structure of light nuclei has been studied by many microscopic models. Studies of Be isotopes based on AMD and Molecular-orbit are successful examples[1, 2]. For heavier nuclei, it is well known that \(^{20}\)Ne has a \(^{16}\)O+\(\alpha\)-like cluster structure, although it is naively expected that the shell-model-like configuration becomes important as neutron number increases. Our interest here is to study which configuration (shell or cluster) dominates the ground state property as the mass number increase. For this purpose, we perform a microscopic calculation for the Ne isotopes systematically by using AMD-like basis states based on the stochastic variational method (SVM)[3].

The total wave functions is fully antisymmetrized, and each nucleon is described by local Gaussian. For simplicity, the \(^{16}\)O core is assumed as the tetrahedron configuration of four \(\alpha\)-clusters with short relative distances, which agrees with the closed-shell configuration of the shell-model, and angular momentum projection was not performed in the present calculation. For the Ne isotopes, the positions of valence nucleons are randomly generated around \(^{16}\)O. In addition cluster-model-like configurations are independently generated, where four of the valence nucleons share the same spatial wave function. As for the nucleon-nucleon interaction, we use Volkov No.2 for the central part and G3RS for the spin orbital part. These interactions well reproduce the phase shift of the \(\alpha\)-\(\alpha\) and \(\alpha\)-\(N\) scattering with the parameters of \(M = 0.60\) and \(V_{ls} = 2000\), respectively. Here, we optimize the Majorana parameter as \(M = 0.615\) to reproduce the binding energy of \(^{20}\)Ne.

To make the basis states stochastically generated more effective, we adopted the cooling method of AMD[1]. However, here, only the imaginary part of the Gaussian centers of the valence nucleons are optimized[4], because the basis states become not independent if we optimize the both real and imaginary parts of the Gaussian centers. By having the imaginary part of the Gaussian centers, the wave functions of the valence nucleons approach to the \(jj\)-coupling picture, and the contribution of the spin-orbit interaction is well taken into account.

The energy convergence of the lowest positive-parity (left) and negative-parity (right) states are shown in Fig. 1. Horizontal axes show the number of trial basis states. For each case, from 1 to 1000 of the basis states are shell-model-like configuration of \(^{16}\)O plus valence nucleons, while cluster-model-like configurations of \(^{16}\)O+\(\alpha\) plus valence neutrons is introduced after 1001. For the positive parity states, the energies monotonically converge with increase of the number

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Figure 1. The energy convergence of the positive-parity (left) and negative-parity (right) states of the Ne isotopes. The horizontal axes show the number of trial basis set. From 1 to 1000 are shell-model-like basis, and after 1001, cluster-model-like basis are introduced.

Table 1. The energy (in MeV) and expectation value of sum of parity inversion operator ($P_{sm}$: shell model limit, $P_{cal}$: calculated value) for the Ne isotopes. $\Delta E$ (MeV) shows the decrease of the energy after introducing the the cluster-model-like basis set. The left table is for the positive parity states and the right table is for the negative parity states.

| A   | E(exp.) | E  | $\Delta E$ | $P_{sm}$ | $P_{cal}$ | A   | E(exp.) | E  | $\Delta E$ | $P_{sm}$ | $P_{cal}$ |
|-----|---------|----|------------|----------|-----------|-----|---------|----|------------|----------|-----------|
| 20  | -160.652| -161| 4.0        | -4       | -3.93     | 20  | -155.685| -152| 14.4       | -6        | -3.21     |
| 22  | -177.779| -175| 5.6        | -2       | -2.01     | 22  | -170.727| -163| 10.2       | -4        | -2.37     |
| 24  | -191.845| -187| 5.5        | 0        | -0.07     | 24  | -171    | 10.1| -2        | 1.21      |           |
| 26  | -202.229| -202| 4.7        | 2        | 1.86      | 26  | -182    | 6.3 | 0         | 0.07      |           |

of the basis states. However, for the negative parity states, the energy decrease by around 10 MeV when the cluster-model-like basis set starts to be added in the case of $^{20}$Ne and $^{21}$Ne. Therefore, $\alpha$-cluster correlation is more important in the negative parity states than in the positive ones. As the mass number increases, this drastic jump in energy disappears even in the case of negative-parity states, since the shell-model-like configurations become more important.

To confirm the importance of the cluster-correlation in the negative-parity states, we calculate the expectation values of the single particle parity\cite{5}, which is the sum of parity inversion operator for each nucleon. The calculated value ($P_{cal}$) is compared with the value for the shell-model limit ($P_{sm}$) in Table 1. For instance, the positive parity state of $^{20}$Ne corresponds to (s)$^4$(p)$^{12}$(sd)$^4$(pf)$^0$ in the shell model, and $P_{sm}$ is $4+12-4 = -4$. In the case of negative parity states, $P_{sm}$ is $-6$ corresponding to the 1p1h excitation from the sd-shell to the pf-shell. The $P_{sm}$ and $P_{cal}$ values are very much different in the negative-parity states contrary to the positive-parity states, especially in light isotopes. Therefore, we can confirm that $\alpha$-cluster configuration is more important in the negative parity states.

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