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Structure of $p$-$sd$ shell $\Lambda$ hypernuclei studied with AMD

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Abstract. The structures of the ground and low-lying states of $^{21}$Ne and $^{12}$Be hypernuclei are studied with the antisymmetrized molecular dynamics. In these hypernuclei, first, the difference of the $\Lambda$ binding energy on structures is discussed. Particularly, in $^{12}$Be, it is found that the parity-inverted ground state of $^{11}$Be is reverted by adding a $\Lambda$ particle. Furthermore, in $^{21}$Ne, it is discussed that the reduction of nuclear radii is larger in the $^{16}$O + $\Lambda$ band than the ground band and the difference appears as the difference of the $B(E2)$ reduction.

1. Introduction
We focus on the ground and low-lying states of $^{21}$Ne and $^{12}$Be and discuss the difference of the $\Lambda$ binding energy as well as structure changes by a $\Lambda$ particle based on the antisymmetrized molecular dynamics (AMD). In $sd$-shell nuclei and neutron-rich nuclei, it is discussed that the many kinds of (cluster) structures coexist in the ground and low-lying energy regions. For example, $^{20}$Ne is a typical $sd$-shell nucleus having the various structures within the small excitation energy [1, 2, 3]. The ground band ($K^\pi = 0^+_1$) and the $K^\pi = 0^+_1$ band built on the $1^+_1$ state at 5.79 MeV constitute the parity doublet associated with $\alpha + ^{16}$O clustering. It is known that the $K^\pi = 0^+_1$ band has the pronounced $\alpha + ^{16}$O clustering, while the ground band has the mixing of deformed shell structure and $\alpha + ^{16}$O cluster structure. Therefore, it is of interest to investigate how a $\Lambda$ particle affects and modifies their structures. In the neutron-rich nucleus $^{11}$Be, the ground state is $1/2^+$, which is inconsistent with the ordinary shell-model picture where the seven neutrons may have a $1/2^-$ state as the ground state. One of the main reasons for the parity inversion is molecular-orbit structure of $^{11}$Be [4]. In the $1/2^+$ state, one of the extra neutrons occupies the $\sigma$ orbit around the $2\alpha$ cluster structure and enhance the $2\alpha$ clustering. The deformation of the $1/2^-$ state is smaller than that of the $1/2^+$ state because the extra neutrons occupy the $\pi$ orbit and reduce the clustering. By adding a $\Lambda$ hyperon to such nuclei, it is expected that the $\Lambda$ binding energy is different depending on the deformations and the level structure will be changed.

In this article, we focus on the low-lying structure of $^{21}$Ne and $^{12}$Be hypernuclei with the coexistence of various (exotic) cluster structures. Especially, first, we focus on the difference of the $\Lambda$ binding energy ($B_\Lambda$) depending on the structure. In neutron-rich $^{12}$Be, the difference of $B_\Lambda$ may affect the parity-inverted ground states of $^{11}$Be. Furthermore, in $^{21}$Ne, it is expected that the $\Lambda$ particle modifies the $\alpha + ^{16}$O cluster structure in the $K^\pi = 0^+_1$ band and the structure change is different from the $K^\pi = 0^+_1$ band. To study such phenomena, we have applied the AMD model extended to hypernuclei (HyperAMD) to these hypernuclei[5]. Combined with the
generator coordinate method (GCM), it is possible to predict the low-lying level structure and structure changes of Λ hypernuclei[6].

2. Theoretical Framework
In this study, we have applied the HyperAMD [5, 6]. The Hamiltonian used in this study is given as,

\[ \hat{H} = \hat{T}_N + \hat{T}_\Lambda - \hat{V}_g + \hat{V}_{NN} + \hat{V}_{AN} + \hat{V}_C \]  

(1)

where \( \hat{T}_N \), \( \hat{T}_\Lambda \) and \( \hat{V}_g \) are the kinetic energies of nucleons, Λ hyperon and the center-of-mass motion. We used the Gogny D1S interaction as an effective nucleon-nucleon interaction \( V_{NN} \), which has been successfully applied to the stable and unstable nuclei. The YNG interactions have been employed as Λ-nucleon interaction \( V_{AN} \) [7, 8]. Since the YNG interactions depend on the nuclear density through the Fermi momentum \( k_F \), we adopted \( k_F = 1.17 \text{ fm}^{-1} \) and \( k_F = 0.97 \text{ fm}^{-1} \) for \( ^{\Lambda}_{\text{He}} \) and \( ^{\Lambda}_{\text{Be}} \), respectively. The Coulomb interaction is approximated by the sum of seven Gaussians.

The variational wave function of a single Λ hypernucleus is described by the parity-projected wave function,

\[ \Psi^\pi = \hat{P}^\pi \{ \Psi_N \otimes \varphi_\Lambda \}, \quad \Psi_N = \frac{1}{\sqrt{A!}} \det \{ \phi_i (r_j) \}, \]  

(2)

\[ \phi_i \propto e^{-\sum \nu_\sigma (r_\sigma - Z_{\sigma\iota})^2 (u_\iota_1 + v_\iota_1)} \eta_i \]

(3)

\[ \varphi_\Lambda \propto \sum_{m=1}^M c_m (a_m \chi_1 + b_m \chi_1)e^{-\sum \nu_\sigma (r_\sigma - z_{\sigma m})^2}, \]  

(4)

where \( \phi_i \) is the nucleon single-particle wave packet consisting of spatial, spin and isospin \( \eta_i \) parts. The single particle wave function of Λ, \( \varphi_\Lambda \) is represented by a superposition of Gaussian wave packets. The variational parameters \( Z_{\sigma\iota}, \nu_\sigma, u_\iota, v_\iota, a_m, b_m, \) and \( c_m \) are set to minimize the total energy under the constraint on the matter quadrupole deformation \( \beta \).

After the variation, we perform the angular momentum projection and the generator coordinate method (GCM) calculations [9],

\[ \Psi_{MK}^J(\beta) = \frac{2J + 1}{8\pi^2} \int d\Omega D_{MK}^J(\Omega)R(\Omega)\Psi^\pi(\beta), \quad \Psi_{nK}^J = \sum_{\beta} \sum_{K=-J}^J c_{nK} \Psi_{MK}^J(\beta), \]  

(5)

where the wave functions with differing values of \( K \) and \( \beta \) are superposed. The coefficients \( c_{nK} \) are determined by solving the Griffin-Hill-Wheeler equation.

To analyze each state obtained after the GCM calculation, we calculate the overlap between the \( \Psi_{MK}^J(\beta) \) and \( \Psi_{nK}^J(\beta) \), so called GCM overlap, defined as,

\[ O^J(\beta) = |(\Psi_{MK}^J(\beta) | \Psi_{nK}^J(\beta))|^2. \]  

(6)

It is noted that the GCM overlap \( O^J(\beta) \) is a function of \( \beta \). In this study, we regard the deformation of each state as the \( \beta \) which gives the largest \( O^J(\beta) \) in each state.

Finally, we introduce the energy gain of the \( J^\pi \) state in hypernuclei from the core state \( j^\pi \) to investigate the Λ binding energy, as,

\[ B_\Lambda = E(AZ(j^\pi)) - E(A+1Z(J^\pi)), \]  

(7)

where \( E(AZ(j^\pi)) \) and \( E(A+1Z(J^\pi)) \) are the calculated energies of the \( j^\pi \) and \( J^\pi \) states, respectively.
Let us compare $B_\Lambda$, defined by the equation(7), of the band head states of the $K^\pi = 0^+_1 \otimes \Lambda_s$ and $K^\pi = 0^-_1 \otimes \Lambda_s$ bands. As mentioned above, the mean-field like and $\alpha + ^{16}\text{O}$ structures are mixed in the $K^\pi = 0^+_1$ band, while the $K^\pi = 0^-_1$ band has a pronounced $\alpha + ^{16}\text{O}$ cluster structure. In table 1, the total energy $E$, excitation energy $E_x$, and $\Lambda$ binding energy $B_\Lambda$ are listed. It shows that the $B_\Lambda$ of the $K^\pi = 0^+_1 \otimes \Lambda_s$ (ground) state is larger than that of the $K^\pi = 0^-_1 \otimes \Lambda_s$ band head state. In figure 2, the density distributions of the band head states

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**3. Results and Discussions**

**3.1. Ground and $\alpha + ^{16}\text{O} + \Lambda$ bands in $^{21}_\Lambda\text{Ne}$**

By performing the GCM calculations, it is found that many excited states with positive parity appear in $^{21}_\Lambda\text{Ne}$. Among them, we obtain the two rotational bands of $^{21}_\Lambda\text{Ne}$, which correspond to the $K^\pi = 0^+_1$ and $K^\pi = 0^-_1$ bands of $^{20}\text{Ne}$. Therefore, we denote these bands in $^{21}_\Lambda\text{Ne}$ as $K^\pi = 0^+_1 \otimes \Lambda$ and $K^\pi = 0^-_1 \otimes \Lambda$, respectively. The resulting excitation spectra of these bands are shown in figure 1.

Let us compare $B_\Lambda$, defined by the equation(7), of the band head states of the $K^\pi = 0^+_1 \otimes \Lambda_s$ and $K^\pi = 0^-_1 \otimes \Lambda_s$ bands. As mentioned above, the mean-field like and $\alpha + ^{16}\text{O}$ structures are mixed in the $K^\pi = 0^+_1$ band, while the $K^\pi = 0^-_1$ band has a pronounced $\alpha + ^{16}\text{O}$ cluster structure. In table 1, the total energy $E$, excitation energy $E_x$, and $\Lambda$ binding energy $B_\Lambda$ are listed. It shows that the $B_\Lambda$ of the $K^\pi = 0^+_1 \otimes \Lambda_s$ (ground) state is larger than that of the $K^\pi = 0^-_1 \otimes \Lambda_s$ band head state. In figure 2, the density distributions of the band head states
of $K^\pi = 0^+_1 \otimes \Lambda_s$ and $K^\pi = 0^+_1 \otimes \Lambda_s$ bands of $^{21}_\Lambda$Ne are presented. It is clearly seen that the $\Lambda$ hyperon coupled to the $K^\pi = 0^+_1$ band head state of $^{20}$Ne is localized around the $^{16}$O cluster. This is because the single-particle potential of $\Lambda_s$ is not parity symmetric due to the $\alpha + ^{16}$O clustering and is deeper around $^{16}$O cluster. Indeed, $B_{\Lambda}$ of $^{17}_\Lambda$O may be more than 12 MeV, while that of $^{5}_\Lambda$He is about 3 MeV. On the other hand, the $\Lambda$ hyperon coupled to the $K^\pi = 0^+_1$ band head state locates at the center of $^{20}$Ne nucleus and interacts with all nucleons. Therefore, the $\Lambda_s$ in the the $K^\pi = 0^+_1 \otimes \Lambda_s$ band head state is more deeply bound than that in the $K^\pi = 0^+_1 \otimes \Lambda_s$ band head state.

Since the $\Lambda$ particle in the $K^\pi = 0^+_1 \otimes \Lambda_s$ band is located around the $^{16}$O cluster, it is not an eigenstate of parity of single particle state of $\Lambda_s$. Thus, the $p$-orbit component of the $\Lambda$ hyperon should contribute to the $K^\pi = 0^-_1 \otimes \Lambda_s$ state. Such mixed nature was called “parity coupling”[10] for $^{21}_\Lambda$Ne or “inter-shell coupling”[11]. It was argued that parity coupling could occur because the energy difference between the positive and negative parity states in the core nucleus is similar to that between the $s$- and $p$-orbits of the $\Lambda$ hyperon [10]. However, in the present result, the parity coupling is due to the asymmetry of $\alpha + ^{16}$O clustering. To see the contribution of the $\Lambda$ particle in $p$ orbit, as discussed in the reference [10], we also analyze the GCM overlap, defined by the equation (6), of the $1/2^-$ state which is the band head state of the $K^\pi = 0^-_1 \otimes \Lambda_s$. The details are discussed in the reference [6].

Table 2. RMS radii (fm) for the $K^\pi = 0^+_1$ band in $^{20}$Ne and the corresponding band in $^{21}_\Lambda$Ne. $\Delta r_{rms}$ is defined as a subtraction of RMS radius: $\Delta r_{rms} = r_{rms}(^{21}_\Lambda$Ne) - $r_{rms}(^{20}$Ne) for each state.

| $^{20}$Ne | $r_{rms}$ | $^{21}_\Lambda$Ne | $r_{rms}$ | $\Delta r_{rms}$ |
|-----------|-----------|-----------------|-----------|-----------------
| $0^+$     | 2.97      | 1/2+            | 2.92      | -0.05          |
| $2^+$     | 2.96      | 3/2+            | 2.91      | -0.05          |
|           | 5/2+      | 2.91            | -0.05     |                |
| $4^+$     | 2.93      | 7/2+            | 2.87      | -0.06          |
|           | 9/2+      | 2.88            | -0.04     |                |
| $6^+$     | 2.87      | 11/2+           | 2.81      | -0.06          |
| $8^+$     | 2.82      | 15/2+           | 2.77      | -0.04          |

Table 3. Same as table 2 but for the $K^\pi = 0^-_1$ band in $^{20}$Ne and the corresponding band in $^{21}_\Lambda$Ne.

| $^{20}$Ne | $r_{rms}$ | $^{21}_\Lambda$Ne | $r_{rms}$ | $\Delta r_{rms}$ |
|-----------|-----------|-----------------|-----------|-----------------
| $1^-$     | 3.27      | 1/2-            | 3.15      | -0.11          |
|           | 3.15      |                 | -0.11     |                |
| $3^-$     | 3.24      | 5/2-            | 3.13      | -0.11          |
|           | 3.14      |                 | -0.10     |                |
| $5^-$     | 3.23      | 9/2-            | 3.11      | -0.12          |
|           | 3.11      |                 | -0.13     |                |
| $7^-$     | 3.23      | 13/2-           | 3.06      | -0.17          |

Next, we discuss the difference in the reduction of the nuclear radii by adding a $\Lambda$ particle, so called "shrinkage effect", between the $K^\pi = 0^+_1 \otimes \Lambda_s$ and $K^\pi = 0^-_1 \otimes \Lambda_s$ bands in $^{21}_\Lambda$Ne. In tables
2-3, the nuclear RMS radii for the \( K^\pi = 0^+ \) and \( K^\pi = 0^- \) bands of \(^{20}\text{Ne}\) and the corresponding bands with \( \Lambda \) are listed. The RMS radii for the \( K^\pi = 0^- \) band change more than those of the \( K^\pi = 0^+ \). This is due to the difference in the clustering of these bands. Since the \( K^\pi = 0^- \) band has well developed \( \alpha + ^{16}\text{O} \) cluster structure, \( \Lambda \) hyperon reduces the inter-cluster distance.

The difference of the shrinkage effect in \(^{21}\text{Ne}\) affect the reduction of the intra-band \( B(E2) \) values in \( K^\pi = 0^+_1 \otimes \Lambda_s \) and \( K^\pi = 0^-_1 \otimes \Lambda_s \) bands. To compare \( B(E2) \) values of \(^{21}\text{Ne}\) with those of \(^{20}\text{Ne}\), we corrected them under the assumption that a \( \Lambda \) hyperon occupies the \( s \)-orbit for each hypernuclear state in the \( K^\pi = 0^+_1 \otimes \Lambda_s \) and \( K^\pi = 0^-_1 \otimes \Lambda_s \) bands [6]. Both the corrected and uncorrected \( B(E2) \) values for the \( K^\pi = 0^+_1 \otimes \Lambda_s \) and \( K^\pi = 0^-_1 \otimes \Lambda_s \) bands are presented in tables 4-5.

Tables 4-5 shows that a \( \Lambda \) particle causes the \( B(E2) \) reduction in the \( K^\pi = 0^-_1 \otimes \Lambda_s \) and the \( K^\pi = 0^+_1 \otimes \Lambda_s \) bands. In the reference [10], the \( B(E2) \) reductions predicted by Yamada et al. are more than 20 \( \% \) for those bands. However, in the present study, the corrected \( B(E2) \) values for the \( 0^+_1 \otimes \Lambda_s \) band reduce less than 20 \( \% \), while those for the \( K^\pi = 0^+_1 \otimes \Lambda_s \) band is almost about 20 \( \% \), as shown in tables 4-5. We consider the difference in the \( B(E2) \) reduction mainly comes from the difference in the reduction of RMS radii between these two bands, as discussed above.

**Table 4.** Intra-band \( B(E2) \) values in \( e^2 \text{fm}^4 \) for the \( K^\pi = 0^+_1 \) in \(^{20}\text{Ne}\) and the corresponding band in \(^{21}\text{Ne}\). \( B(E2) \) and \( cB(E2) \) represent the uncorrected and corrected \( B(E2) \) values, respectively. The correction of the \( B(E2) \) values is explained in the reference [6].

| \( K^\pi = 0^+_1 \) | \( B(E2) \) | \( 0^+_1 \otimes \Lambda_s \) | \( B(E2) \) | \( cB(E2) \) | \( (%) \) |
|-----------------|----------|-----------------|----------|----------|---------|
| \( 2^+ \rightarrow 0^+ \) | 72.2     | \( 3/2^+ \rightarrow 1/2^+ \) | 63.7     | 63.7     | -11.8   |
|                  |          | \( 5/2^+ \rightarrow 1/2^+ \) | 63.9     | 63.9     | -11.5   |
| \( 4^+ \rightarrow 2^+ \) | 86.9     | \( 7/2^+ \rightarrow 3/2^+ \) | 64.3     | 71.4     | -17.8   |
|                  |          | \( 9/2^+ \rightarrow 5/2^+ \) | 75.7     | 75.7     | -13.0   |
| \( 6^+ \rightarrow 4^+ \) | 55.1     | \( 11/2^+ \rightarrow 7/2^+ \) | 40.3     | 41.9     | -23.9   |
|                  |          | \( 13/2^+ \rightarrow 9/2^+ \) | 48.0     | 48.0     | -12.9   |
| \( 8^+ \rightarrow 6^+ \) | 17.0     | \( 15/2^+ \rightarrow 11/2^+ \) | 15.9     | 16.2     | -4.6    |
|                  |          | \( 17/2^+ \rightarrow 13/2^+ \) | 17.1     | 17.1     | 0.8     |

**Table 5.** Same as table 4 but for the \( K^\pi = 0^-_1 \) band in \(^{20}\text{Ne}\) and the corresponding band in \(^{21}\text{Ne}\).

| \( K^\pi = 0^-_1 \) | \( B(E2) \) | \( 0^-_1 \otimes \Lambda_s \) | \( B(E2) \) | \( cB(E2) \) | \( (%) \) |
|-----------------|----------|-----------------|----------|----------|---------|
| \( 3^- \rightarrow 1^- \) | 221.2    | \( 5/2^- \rightarrow 1/2^- \) | 139.2    | 179.0    | -19.1   |
|                  |          | \( 7/2^- \rightarrow 3/2^- \) | 178.5    | 178.5    | -19.3   |
| \( 5^- \rightarrow 3^- \) | 249.3    | \( 9/2^- \rightarrow 5/2^- \) | 184.2    | 195.4    | -21.6   |
|                  |          | \( 11/2^- \rightarrow 7/2^- \) | 189.3    | 189.3    | -24.1   |
| \( 7^- \rightarrow 5^- \) | 240.3    | \( 13/2^- \rightarrow 9/2^- \) | 164.3    | 166.7    | -30.6   |
Table 6. Quadrupole deformation $\beta$, calculated energy $E$ and excitation energy $E_x$ for the $1/2^+_1$ and $1/2^-_1$ states in $^{11}$Be and the corresponding $0^+$ and $0^-$ states in $^{12}_{\Lambda}$Be. A binding energy $B_{\Lambda}$ is also listed for $^{12}_{\Lambda}$Be.

| State       | $J^\pi$ | $\beta$ | $E$(MeV) | $E_x$(MeV) | $B_{\Lambda}$(MeV) |
|-------------|---------|---------|----------|------------|-------------------|
| $^{12}_{\Lambda}$Be(HyperAMD) | $0^+_1$ | 0.70    | -74.44   | 0.25       | 9.67              |
| $^{12}_{\Lambda}$Be(HyperAMD) | $0^-_1$ | 0.47    | -74.69   | 0.00       | 10.24             |
| $^{11}$Be(AMD) | $1/2^+_1$ | 0.72   | -64.77   | 0.00       | -                 |
| $^{11}$Be(AMD) | $1/2^-_1$ | 0.52   | -64.45   | 0.32       | -                 |
| $^{11}$Be(Exp.) | $1/2^+_1$ |        | -65.48   | 0.00       | -                 |
| $^{11}$Be(Exp.) | $1/2^-_1$ |        | -65.16   | 0.32       | -                 |

3.2. Parity reversion of the $^{12}_{\Lambda}$Be ground state

First, let us discuss the structure of the core nucleus $^{11}$Be. As shown in figure 3(a), the $^{11}$Be ground state has positive parity, and the order of the $p_{3/2}$ and $sd$ shells looks inverted, which is called “parity inversion” [12, 13]. In the present study, the AMD calculation successfully describes the parity inversion of the ground state in $^{11}$Be as shown in figure 3(b).

The low-lying states of Be isotopes are known to have a $2\alpha$ cluster core and valence neutrons occupying the molecular orbits around the core, which are called $\pi$ and $\sigma$ orbits [14]. The formation of the $2\alpha$ cluster core in each state is confirmed by the proton density shown in figure 4. In the ground state $1/2^+_1$, two of the valence neutrons occupy the $\pi$ orbit, and the third valence neutron occupies the $\sigma$ orbit. In terms of the spherical shell model, a neutron is promoted to $sd$ shell across the $N = 8$ shell gap (breakdown of magic number $N = 8$). On the contrary, in the first excited state $1/2^-_1$, all valence neutrons occupy the $\pi$ orbit or $p$ shell, which corresponds to the normal shell order. As we can see from figure 4 and table 6, the ground state has a more pronounced $2\alpha$ clustering and a larger quadrupole deformation $\beta$ than the first excited state.

Figure 3(c) shows the level structure of $^{12}_{\Lambda}$Be with a $\Lambda$ hyperon in $s$ orbit. It is found that the ground state parity of $^{12}_{\Lambda}$Be becomes negative. Namely, the parity reversion of the $^{12}_{\Lambda}$Be ground state will occur by adding a $\Lambda$ particle. As shown in table 6, the $B_{\Lambda}$ for the $0^-_1$ state is larger than the $0^+_1$ state by about 500 keV. The difference in $B_{\Lambda}$ mainly comes from the $\Lambda N$ potential
energy $V_{\Lambda N}$, and it originates in the difference of the nuclear deformation. It is expected that the difference of the deformation between the $1/2^+$ and $1/2^-$ states can be confirmed by observing the parity-reverted ground state of $^{12}_\Lambda$Be.

4. Summary

In summary, we applied an extend version of AMD to hypernuclei to $^{21}_\Lambda$Ne and $^{12}_\Lambda$Be. We discussed the difference of the Λ binding energy ($B_\Lambda$) depending on the structure of the core states. In $^{21}_\Lambda$Ne, it is discussed that $B_\Lambda$ is different between the ground and $K^\pi = 0^+_1 \otimes \Lambda_s$ band, reflecting the difference of their structure. In $^{12}_\Lambda$Be, it is found that the parity reversion in the ground state will occur by a Λ particle due to the difference of $B_\Lambda$, originated in the difference of deformations between the $1/2^+$ and $1/2^-$ states in $^{11}$Be. Furthermore, in $^{21}_\Lambda$Ne, intra-band $B(E2)$ reduction in the $K^\pi = 0^+_1 \otimes \Lambda_s$ band is larger than that in the $K^\pi = 0^+_1 \otimes \Lambda_s$ band. This is mainly due to the reduction of the inter-cluster distance between $\alpha$ and $^{16}$O clusters in the $K^\pi = 0^-_1$ band.

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