Excitation and charged particle decay of the analogs of the dipole resonance in the alpha cluster of $^6\text{Li}$

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Abstract. Intrinsic excitation of $\alpha$ cluster in $A=6$ nuclei were searched for by using the $^6\text{Li}(3\text{He},t)$ and $^6\text{Li}(7\text{Li},7\text{Be})$ charge exchange reactions at the incident energy of 450 and 455 MeV at $0^\circ$. Charged particle decay from the dipole resonance at around 25 MeV in $^6\text{Be}$ and $^6\text{He}$ was measured. The dominant decay channels of the resonance are found to be $d+3\text{He}+n$ for $^6\text{Be}$ and $d+t+p$ for $^6\text{He}$. The invariant mass spectra for $3\text{He}+n$ and $3\text{H}+p$ show clear enhancement in comparison with phase-space spectra, and suggests that $\alpha$ cluster in $^6\text{Be}$ and $^6\text{He}$ are excited to $^4\text{Li}$ and $^4\text{H}$.

Introduction
Clusters in nuclei play an important role in nuclear structure and nuclear reactions. Clusters in nuclear systems are spatially localized subsystem composed of strongly correlated nucleus [1]. Therefore we can expect two types of excitation in the clustering nuclei. One is the excitation due to an inter-cluster relative motion. The other is due to an intrinsic excitation of the cluster. Such a cluster excitation is a new concept of nuclear excitation [2] and not well understood. Due to the nuclear medium effect, the excited cluster may have characteristics different from the excitation of the cluster itself.

In the photonuclear excitation, Costa et al. reported a possibility of the $\alpha$ cluster excitation in $^6\text{Li}$ [3]. At excitation energy of 26 MeV, they observed a resonance in $^6\text{Li}(\gamma,n)$ reaction. It was assigned to be the excited $\alpha$ cluster, namely the giant dipole resonance of $^4\text{He}$ in the $^6\text{Li}$ nucleus. However, in other reports on $^6\text{Li}(\gamma,n)$ reaction [4-6], no such evidence has not been observed. Recently, Yamagata et al. [7,8] reported the GDR of $\alpha$ cluster in $^6\text{Li}$, $^7\text{Li}$, and its analogs in $^6,^7\text{Be}$ and $^6,^7\text{He}$ via $^6,^7\text{Li}(p,p')$, $^6,^7\text{Li}(\text{He},t)$, and $^6,^7\text{Li}(\text{Li},\text{Be})$ reactions at intermediate energies. They decomposed the energy spectra for these reactions into resonances. According to DWBA analysis of angular distribution, they...
assigned the resonances in $^6$Li, $^4$He, and $^6$Be at $E_x=27.0$, 23.5.0 and 24.0 MeV to the dipole resonance. In figure 1, schematic level diagrams for $A=6$ and $A=4$ nuclei are shown. The analog relations between the ground states in $^6$He and $^6$Be and $^0^+ (3.56 \text{ MeV})$ state in $^6$Li are shown in dashed line. The vertical position for $^4$He is set to the excitation energy for the separation energy for $^4\alpha + d$. The excitation energies for the dipole resonance in $A=6$ nuclei are well agree with that of GDR in $A=4$ nuclei.

In this work, we investigated charged particle decay of the resonance in $^6$Be and $^6$He at excitation energy of 24 and 23.5 MeV. If these resonances excited via charge exchange reaction from $^\alpha$ cluster in $^6$Li and deuteron acts as a spectator, it is natural to expect that the excitation energy spectra for $^4$Li and $^4$H (the invariant mass of $^4$Li and $^4$H) in $^6$Be and $^6$He has different structure from the flat phase-space spectrum. We consider the sequential decay process shown as,

$$^6\text{Li} \rightarrow ^6\text{Be}^* \rightarrow ^4\text{Li}^+ + d$$

$$\rightarrow \text{p} + ^3\text{He}$$

$$^6\text{Li} \rightarrow ^6\text{He}^* \rightarrow ^4\text{H}^+ + d$$

$$\rightarrow \text{p} + t$$

The excitation energies of $^4$Li and $^4$H are determined from the measurement of the excitation energy of $^6$Be and $^6$He and the kinetic energies of the deuteron.

**Experiment**

The experiment was performed at the Research Center for Nuclear Physics (RCNP), Osaka University. The detailed explanation of the experiment is reported in our previous works [7-9]. The 450 MeV $^3$He and 455 MeV $^7$Li beam from the ring cyclotron were used. A target used was self supporting metallic foil of enriched $^6$Li (95.4%). Reaction particles were analyzed by using the magnetic spectrometer “Grand Raiden”, and war detected with the focal plane detector system, which consists of two layer telescopes [10]. Charged particles emitted from $^6$Be and $^6$He excited via ($^3$He,t) and ($^7$Li,$^7$Be) reactions were detected in coincidence with t and $^7$Be by using eight Si detectors (SSD’s) telescopes, each of them consisting of 500 $\mu$m $\Delta$E and 300 $\mu$m E detectors with an aperture of 3.8 cm$^2$. A time of
flight (TOF) technique was utilized for identification of low energy particles. Although, \(^{3}\)He and t are not distinguishable with TOF technique, \(^{3}\)He were assumed to be dominant for decay of \(^{6}\)Be and t for \(^{4}\)He for A=3 decay particle.

The solid angle of the spectrometer was set to ±20 mrad vertically and ±40 mrad horizontally. The excitation energy of \(^{6}\)Be and \(^{6}\)He were determined from positions of t and \(^{7}\)Be at the focal plane. The recoiled angle and the energy of \(^{6}\)Be or \(^{6}\)He were estimated from scattering angle by ray-tracing technique. The kinetic energy of the decay particles were converted to the energy in the rest frame of \(^{6}\)Be or \(^{4}\)He.

Figure 2 shows two dimensional scatter plot of \(^{6}\)Be decay particle coincident events for 2(a) proton, 2(b) deuteron, 2(c) \(^{3}\)He, and 2(d) \(\alpha\). Figure 3 shows two dimensional scatter plot of \(^{4}\)He decay particle coincident events for 3(a) proton, 3(b) deuteron, 3(c) t, and 3(d) \(\alpha\). Apparently, proton channel is much prominent in \(^{6}\)Be, because the ground state of \(^{6}\)Be is a proton unbound nucleus. On the contrary, both scatter plots for \(^{6}\)Be and \(^{4}\)He have similar structure, for decay channels of A=2, 3, 4 particles. The clear loci appeared in 3(c) and 4(c) correspond to two body (\(^{3}\)He+\(^{3}\)He) and (t+t) decay. The nature of this decay mode is discussed in previous work [9].

Result and summary

The \(\alpha\) decay channel shown in Figure 2(d) and 3(d) are related to the excitation of deuteron in \(^{6}\)Li, because \(\alpha\) cluster acts as a spectator in such mode. On the other hand, the deuteron decay channel shown in Figure 2(b) and 3(b) are due to the three body decay channels, such as \(^{6}\)Be→\(^{3}\)He + d + p and \(^{4}\)He→t + d + p. Existence of correlation between the excitation energy of \(^{3}\)Be and the energy of deuteron means \(^{6}\)Be and \(^{4}\)He decay via intermediate states, such as \(^{4}\)He+d or \(^{4}\)H+d.

Figure 4 shows the excitation energy spectra in \(^{4}\)Li (Fig 4(a)) and \(^{3}\)He (Fig. 4(b)) obtained by projecting the events from 2(b) and 2(c) onto the axis of excitation energy for \(^{4}\)Li and \(^{3}\)He. These figures were obtained by applying a gate on the excitation energy region of the dipole resonance at \(E_x=24 \pm 5\) MeV. Figure 5 shows the excitation energy spectra in \(^{4}\)He (Fig. 5(a)) and \(^{3}\)H (Fig. 5(b)) obtained by projecting the events from 2(b) and 2(c) onto the axis of excitation energy for \(^{4}\)H and \(^{3}\)H. These figures were also obtained by applying a gate on excitation energy at \(E_x=23.5 \pm 5\) MeV. The
prominent peaks in 4(b) and 5(b) are due to two body decay such as, $^6\text{Be} \rightarrow ^3\text{He} + ^3\text{He}$ and $^6\text{He} \rightarrow \text{t} + \text{t}$. The dashed lines in Fig. 4 and Fig. 5 represent the result of a simple phase-space calculation. In this calculation, the size of phase space was normalized to the singles excitation energy spectra for $^6\text{Li}(\text{He},t)$ and $^6\text{Li}(\text{Li},\text{Be})$ reactions. Although, the excitation energy spectra for $^3\text{He}$ and $^4\text{H}$ well reproduced by this simple model, clear enhancements at low excitation energy region was observed in excitation energy spectra for $^4\text{Li}$ and $^4\text{H}$. The shape of the enhancement in Fig. 4(a) and Fig. 5(a) well agree with the excitation energy spectra of the GDR in $^4\text{He}$. The present experimental results are consistent with the picture that the DR’s in $^6\text{Be}$ and $^6\text{He}$ at around 24 MeV are analogs of the GDR in $\alpha$ clusters in $^6\text{Li}$.

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