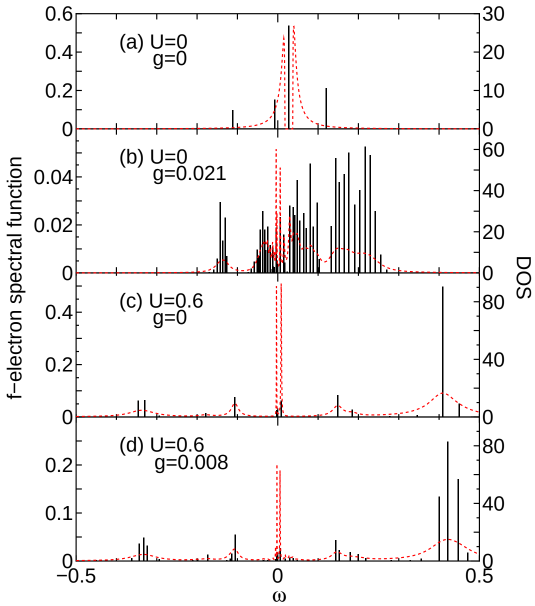

Fig. 8. (Color online) The f-electron spectral function (vertical bars) and the DOS (dotted lines) as functions of ω for several values of U and g at quarter-filling, where the Fermi level is set to zero.

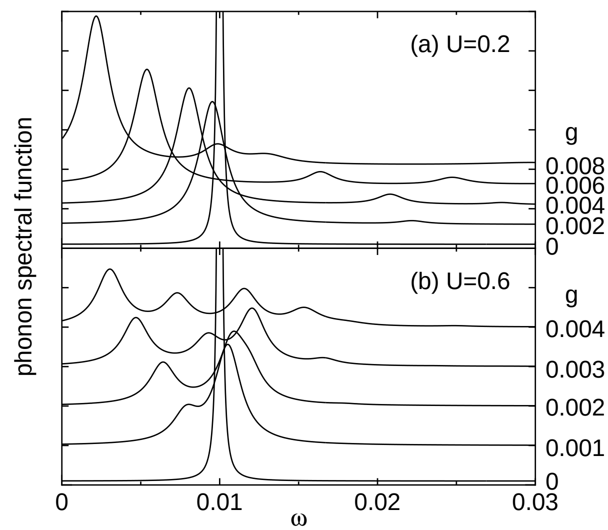

Fig. 9. The phonon spectral function as a function of ω at half-filling for several values of g with $U = 0.2$ (a) and $U = 0.6$ (b).

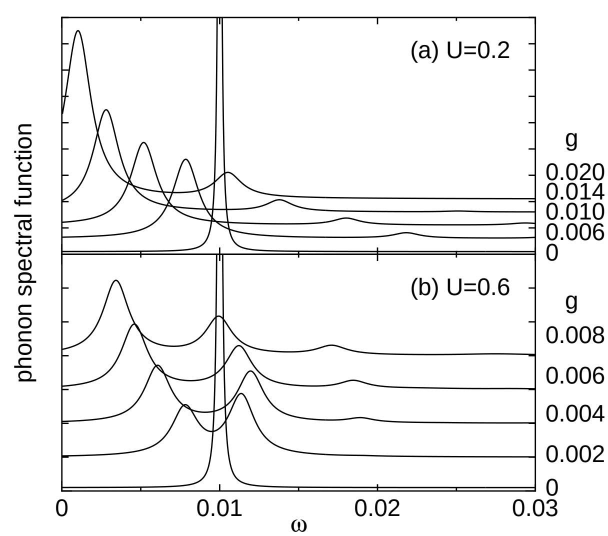

Fig. 10. The phonon spectral function as a function of ω at quarter-filling for several values of g with $U = 0.2$ (a) and $U = 0.6$ (b).

a large value of $U = 0.6$, the spectral weight of the lowest excited state is relatively small and a considerable amount of the spectral weight remains around the original phonon level. This result is consistent with that obtained for the Hubbard-Holstein model in the strong coupling regime, where the sharp soft phonon mode with a large spectral weight is observed for small-U, while the broad soft phonon mode with a small spectral weight is observed for large-U.[26]

To see the energy shift in more detail, we show the lowest excited energy $\tilde{\omega}_0$ in the phonon spectral function as a function of g in Fig.11. Remarkably, the softening, i. e., the decrease in $\tilde{\omega}_0$, observed in the strong coupling regime is largely enhanced due to the Coulomb interaction especially for half-filling in contrast to the case with the single-orbital periodic Anderson-Holstein model where the softening is suppressed due to the Coulomb interaction.[30–32]

4. Summary and Discussions

In Summary, we have investigated the two-orbital periodic Anderson model coupled with the two-fold degenerate Jahn-Teller phonon by using the dynamical mean-field theory, and have found that the heavy fermion state of nonmagnetic origin is realized due to the cooperative effect of the Coulomb interaction U and the electron-phonon coupling g. The specific features of the heavy fermion state for large U and g are as follows: (1) The local orbital and lattice fluctuations are enhanced, while the local charge (valence) and spin fluctuations are suppressed. (2) The sharp soft phonon mode with a large spectral weight is observed for small U, while the broad soft phonon mode with a small spectral weight is observed for large U. (3) The cooperative effect for half-filling with $n_f = 2$ is more pronounced than that for quarter-filling with $n_f = 1$.

In the absence of g, when U increases, the effective mass increases with increasing spin and orbital fluctuations together with decreasing charge fluctuation. Then, the heavy fermion state of magnetic origin with large (small) spin and orbital (charge) fluctuations is realized for large U due to the strong correlation effect. When we increase g for a fixed value of U, the effective mass further increases with increasing orbital and lattice fluctuations together with decreasing spin and charge fluctuations. Then, the heavy fermion state of nonmagnetic origin with large (small) orbital and lattice (spin and charge) fluctuations is realized for large U and g due to the cooperative effect of the strong correlation and the strong coupling. In this heavy fermion state, the phonon spectral function shows the broad soft phonon mode while the f electron