Crossover from skin-mode to proton-neutron-mode in $E1$ excitations of neutron-rich nuclei

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Character of the low-energy $E1$ excitations is investigated by analyzing transition densities obtained from the RPA calculations in the doubly-magic nuclei. We propose a decomposition method of the $E1$ excitations into the $pn$ mode (i.e. oscillation between protons and neutrons) and the skin mode (i.e. oscillation of the neutron skin against the inner core) via the transition densities, by which their mixing is handled in a straightforward manner. Crossover behavior of the $E1$ excitations is found, from the skin mode at low energy to the $pn$ mode at higher energy. The ratio of the skin-mode strength to the full strength turns out to be insensitive to nuclide and to effective interactions in the energy region of the crossover. Depending on the excitation energy, the observed low-energy $E1$ excitations are not necessarily dominated by the skin mode, as exemplified for $^{90}$Zr.