First mass measurements of neutron-rich calcium isotopes, $^{55-57}$Ca[†]

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The mass of atomic nuclei is a fundamental quantity as it reflects the sum of all interactions within the nucleus, which is a quantum many-body system comprised of two kinds of fermions, protons and neutrons. Changes in the shell structures in nuclei far from stability can be directly probed by mass measurements.

The shell evolution of the neutron $2p_{1/2}$ and $1f_{5/2}$ orbitals in neutron-rich calcium region has attracted considerable attention in recent years. The presence of a large subshell gap at $N = 34$ between the orbitals in the Ca isotopes was theoretically predicted,[1] and the measurement of $E(2_1^+)$ in ^{54}Ca suggested the possible emergence of a sizable subshell closure at $N = 34$.[2] One of the most critical information on the existence of the subshell gap at $N = 34$ is the atomic masses of the calcium isotopes beyond $N = 34$. We performed the first mass measurements of neutron-rich Ca isotopes beyond $N = 34$ to probe the shell evolution of the neutron $2p_{1/2}$ and $1f_{5/2}$ orbitals.

The experiment was performed at the Radioactive Isotope Beam Factory (RIBF) at RIKEN, which is operated by RIKEN Nishina Center and Center for Nuclear Study, University of Tokyo. The masses were measured directly by using the TOF–$B\rho$ technique. Neutron-rich isotopes were produced by fragmentation of a ^{70}Zn primary beam at 345 MeV/nucleon in a ^{9}Be target. The fragments were separated by the BigRIPS separator,[3] and transported in the High-Resolution Beam Line to the SHARAQ spectrometer.[4] Details on the experimental setup and analysis procedure can be found in the previous report.[5]

We discussed the evolution of the empirical δe shell gaps[6] of neutron-rich Ca isotopes from the atomic masses of $^{55-57}$Ca, as shown in Fig. 1. The δe value is identical with $S_{2\mathrm{n}}(N) - S_{2\mathrm{n}}(N+1)$, where $S_{2\mathrm{n}}(N)$ is the two-neutron separation energy of a nucleus with neutron number N, and the empirical energy gaps across the Fermi surface in the nuclei is evaluated. In the figure, the squares represent the experimental δe values determined for the first time, while the circles represent the literature values obtained from AME2016.[7] The solid lines indicate the theoretical predictions by using KB3G,[8] MBPT,[9] IM-SRG,[10] and modified SDPF-MU (SDPF-BR)[11] interactions. The empirical energy gap at $N = 34$ is close to that at $N = 32$, and slightly smaller than that at $N = 28$. Thus, the experimental result indicates a sizable energy gap of subshells in ^{54}Ca, which is comparable to that in ^{52}Ca. However the gap is not as large as recent predictions by SDPF-BR and IM-SRG interactions. We are preparing a physics article to report the shell evolution in neutron-rich Ca isotopes beyond $N = 34$.

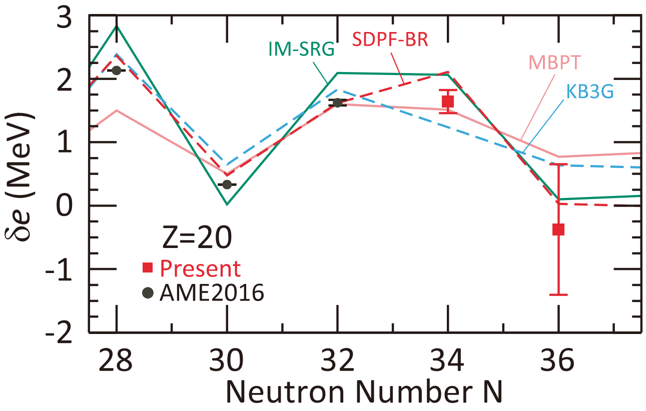

Fig. 1. The empirical δe shell gaps in neutron-rich Ca isotopes. Squares indicate values determined for the first time, and circles are literature values from AME2016.[7] The solid lines show theoretical predictions.[8–11]

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