Probing alpha clusters in the low-density region of the nuclear surface†

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The formation of alpha clusters in the ground state of heavy nuclei has been unclear for many years, both theoretically and experimentally. Although the existence of preformed alpha particles in alpha-decay nuclei is an essential element in the theory of alpha decay,[1)] it was challenging to explain the appearance of alpha clusters with the conventional mean-field models. In recent years, theoretical research based on the generalized density functional made progress and predicted that alpha clusters can exist in the low-density region of the nuclear surface.[2)] It was shown that the formation amplitudes of alpha clusters on the nuclear surface of tin isotopes decrease monotonically with increasing neutron excess, and the formation amplitude of ^{124}Sn is approximately half that of ^{112}Sn.[3)] To directly prove the existence of alpha clusters in the surface of nuclei, the quasi-free alpha knockout reaction is appropriate.

Our group performed an experiment at the Research Center for Nuclear Physics of Osaka University. A proton beam at 392 MeV generated at the cyclotron facility bombarded stable tin targets (^{112}Sn, ^{116}Sn, ^{120}Sn, ^{124}Sn) with an intensity of 100 nA. To achieve the high-precision measurement of knocked-out alpha particles, we used double-arm spectrometers. The experimental setup is shown in Fig. 1. A proton beam impinges on a tin target (red arrow from the left). Following a ^{A}Sn$(p, p\alpha)^{A-4}$Cd reaction (emphasized in the inset), a scattered proton is analyzed by the Grand Raiden spectrometer at an angle of 45.3°. A knocked-out alpha particle is analyzed by the LAS spectrometer at an angle of 60.0°.

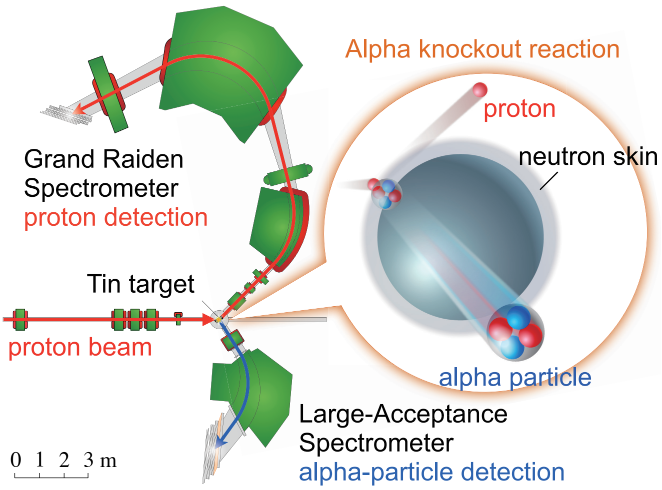

Fig. 1. Schematic illustration of the experimental setup.

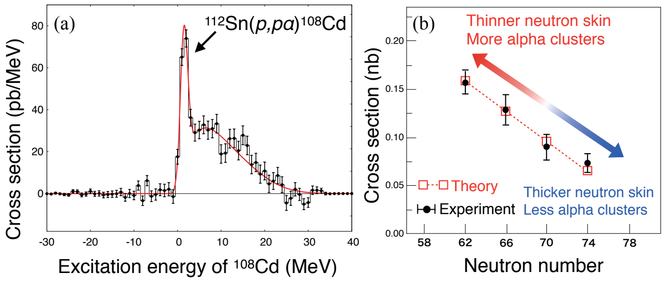

Fig. 2. (a) Missing-mass spectrum of the ^{112}Sn$(p, p\alpha)^{108}$Cd reaction. (b) Neutron-number dependence of the $(p, p\alpha)$ reaction cross sections.

The momenta of scattered protons and knocked-out alpha particles were analyzed with the Grand Raiden spectrometer[4)] and a large acceptance spectrometer, respectively. The missing-mass spectra of Sn$(p, p\alpha)$Cd reactions were constructed from these momenta, and strong transitions from the ground state of Sn to the vicinity of the ground state of Cd were observed. Figure 2 shows (a) the missing-mass spectrum of ^{112}Sn$(p, p\alpha)^{108}$Cd. The peak indicated by the arrow is the transition from the ground state of ^{112}Sn to the vicinity of the ground state of ^{108}Cd. Figure 2(b) shows the isotope dependence of cross sections.[5)] The black filled circles indicate experimental data, and the red open squares indicate theoretical predictions, where the theoretical alpha-cluster formation probabilities were converted to the $(p, p\alpha)$ cross sections using nuclear reaction calculations based on the distorted wave impulse approximation. A good agreement with the theoretical conjecture is observed.

The theoretical study further suggested not only the control of the formation of alpha clusters by neutron skins, but also the suppression of neutron skins by the appearance of alpha clusters. The series of experimental studies of surface alpha clusters have the potential to revise the parameters correlated with the neutron-skin thickness in the nuclear equation of state in the future.

References
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