Formation of α clusters in heavy nuclei probed by the $(p, p\alpha)$ reaction

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Formation of clusters in nuclei is a topic of interest and fundamental significance throughout the history of nuclear physics [1, 2]. In light nuclei, development of cluster structure in states close to the corresponding decay threshold is a well established phenomenon ("Ikeda threshold rule" [3]). Many novel cluster states have been reported in light nuclei—the α-condensate states (e.g., Hoyle state), the molecular states in beryllium isotopes, and the 3-α-linear-chain states in carbon isotopes [1, 2, 4]. In heavy nuclei, on the other hand, the existence of α clusters remains elusive [5]. It has been postulated as a pre-requisite in α decay theories since Gamow's pioneering work in the 1920s, but direct experimental evidence has not been reported so far [5, 6].

Recent generalized relativistic density functional (gRDF) calculations, with cluster formation explicitly taken into account, suggest that α clusters can form at the low-density surface region of heavy nuclei, which could potentially explain the origin of α particles in α decay [8, 9]. This model further predicts a close interplay between surface α-clustering and neutron-skin thickness Δr_{np} in heavy nuclei and as a consequence Δr_{np} gets reduced in comparison to theoretical calculations without considering the α-clustering effect, which will further affect our understanding of the density dependence of the symmetry energy in the nuclear equation of state. As a result of this interplay, the formation of α clusters also gets hindered by the development of a neutron skin in heavy nuclei. According to gRDF calculations, the α-clustering strength (defined as "the effective number of α clusters" in [9]) in tin isotopes decreases monotonically with increase of the mass number [9]. The systematics of the α-clustering strength along the tin isotopic chain can be directly investigated by using quasi-free $(p, p\alpha)$ reaction—a well established experimental probe for α-clustering in the ground state of nuclei [10, 11]. This kind of measurements have been widely used to study α-clustering for decades in light nuclei and has been particularly highlighted in recent years thanks to the significant progress in reaction theories [10, 12, 13].

Therefore, we carried out a quasi-free $(p, p\alpha)$ experiment at RCNP to examine the surface α-clustering strength in ^{112,116,120,124}Sn and its isotopic dependence. The result was recently published in Science [14]. The experiment, as illustrated in Figure 1, was performed with the 392 MeV proton beam at the WS beam line. The scattered protons and α particles after the $(p, p\alpha)$ reaction were detected in coincidence by the Grand Raiden and LAS spectrometers. The experimental setup was designed according to the kinematics of the proton scattering off a preformed α particle and optimized to achieve detection of low-energy α particles (down to $\sim$50 MeV) and high signal-to-noise ratio. In the proof-of-principle measurement with the ^{nat}Li target, we checked that the correlated proton-α particle pair was correctly recorded and the missing-mass spectrum exhibited a prominent peak at $\sim$2.4 MeV, in good agreement with the known α-separation energy of ^{7}Li(2.47 MeV) [15]. This clearly validates our detector setting and analysis method for the quasi-free $(p, p\alpha)$ experiment.

For each of the four tin isotopes, the missing-mass (M_X) spectrum [Figure 2 (left panel)] shows a clear peak located at the known α-separation energy, as expected for the quasi-free knockout of preformed α particles. This result thus provides direct evidence for the preformation of α particles in these tin isotopes. The observed momentum distribution of the α particles further reaffirms that the formation of α particles indeed occurs in the low-density surface region of heavy nuclei as predicted by the gRDF calculation.

The M_X spectra are well fitted with the Gaussians for the ground-state peaks and the simulated line shapes of the continuum. By integrating the ground-state peak, the $(p, p\alpha)$ cross section ($\sigma_{p,p\alpha}$) is deduced for each tin isotope. As shown in the right panel of Figure 2, $\sigma_{p,p\alpha}$ gradually decreases as the mass number increases, with a factor of ∼2 decrease from ^{112} Sn to ^{124}Sn. The observed isotopic systematics of $\sigma_{p,p\alpha}$ is well reproduced by theoretical calculations taking into account the radial density distributions of the α clusters of the gRDF prediction and the reaction mechanism. Further analysis confirms that the observed decline in $\sigma_{p,p\alpha}$ is indeed predominantly caused by the decrease in the α-clustering strength while the effect of the reaction mechanism is minor. Our result thus supports the tight interplay between the surface α-clustering and Δr_{np} in heavy nuclei, which will lead to a reduction of Δr_{np} in comparison to theoretical calculations without considering the α-clustering effect as predicted by the gRDF calculations [9]. A linear correlation between Δr_{np} and the slope parameter L has been predicted by mean-field model calculations [16] and is generally used to constrain L. As a matter of fact, many projects across the world are ongoing to measure the neutron-skin thicknesses of heavy nuclei like ^{208}Pb with sufficient precision. Our result suggests the necessity of considering the effect of nuclear clustering when constraining the EOS parameters from the neutron-skin thickness [14, 17].

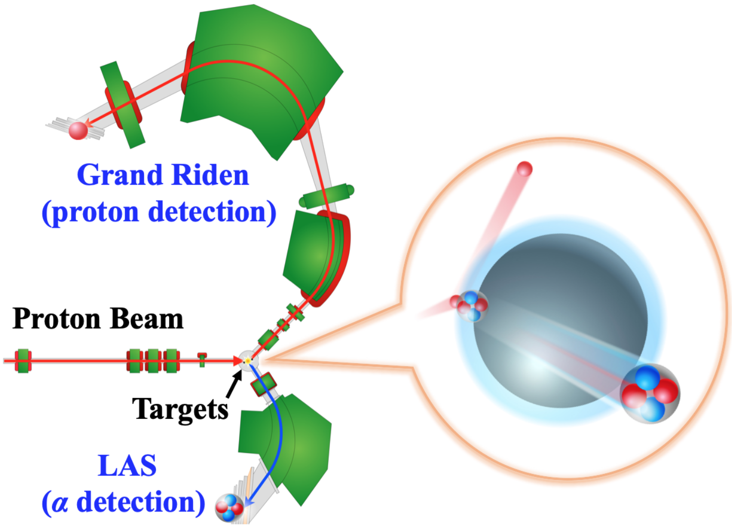

Figure 1: Illustration of the quasi-free $(p, p\alpha)$ experiment based on the Grand Raiden and LAS spectrometers.

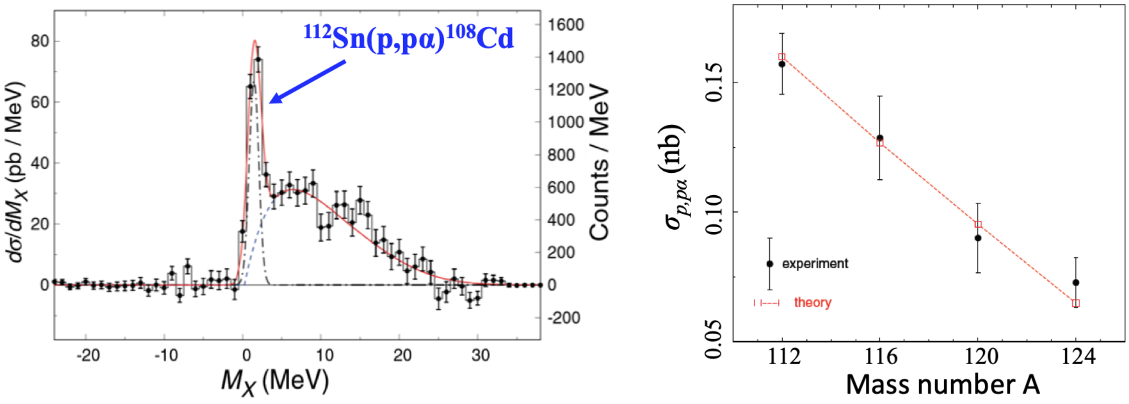

Figure 2: (Left)The measured missing-mass (M_X) spectrum for ^{112}Sn. The red solid line shows the results of the fits with the Gaussians for the ground-state peaks (the black dashed-dotted lines) and the simulated shapes of the continuum (the blue dashed lines). Similar analysis is also performed for the other three tin isotopes ^{116,120,124}Sn. (Right) Isotopic dependence of the $(p, p\alpha)$ cross section ($\sigma_{p,p\alpha}$), as determined experimentally (black points) and theoretically (red line).

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