Clear evidence of $\alpha$ clusters in the ground state of heavy nuclei

Junki Tanaka\textsuperscript{1,2*}, Zaihong Yang\textsuperscript{2,3}, Stefan Typel\textsuperscript{1}
for RCNP Sn($p$, $p\alpha$) collaboration.

\textsuperscript{1}Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany / GSI Helmholtz Center for Heavy Ion Research GmbH, Darmstadt, Germany

\textsuperscript{2}RIKEN Nishina Center for Accelerator-Based Science, Wako, Japan

\textsuperscript{3}Research Center for Nuclear Physics, Osaka University, Ibaraki, Japan

\textsuperscript{*}E-mail: junki.tanaka@riken.jp

We obtained clear evidence of $\alpha$ clustering at the surface of heavy nuclei by measuring the cross sections for quasi-free $\alpha$-knockout reactions along the tin isotopic chain. The $\alpha$-cluster appearance at the nuclear surface could not only be a natural explanation for the $\alpha$-preformation in the $\alpha$-decay theory, but also provides the modification to the relation between neutron-skin thicknesses $\Delta r_{np}$ and a slope parameter $L$ in the nuclear equation of state.

1 Surface $\alpha$ clustering and $\alpha$ decay in h

The formation of $\alpha$ clusters is an essential ingredient in heavy nuclei, pre-requisite to describe the $\alpha$ decay as proposed 90 years ago by G. Gamow - the quantum tunnelling of pre-formed $\alpha$ particles through a Coulomb barrier (1)(Figure 1). However, a consistent description of $\alpha$ clusters and nucleons in one model is challenging from a theoretical perspective. Clusters should get dissolved in the saturated nuclear matter and contribute to the mean-field as independently moving nucleons. This contradictory situation was overcome by decay theoretical studies - $\alpha$ particles exist only in nuclear surface (2, 3), \textit{the dilute nuclear matter}. So far there is no clear evidence of $\alpha$ clustering especially in the ground state of heavy nuclei except for $\alpha$ decay.

![Figure 1: Preformed-$\alpha$ particle decays through a Coulomb barrier.](image)
Recently, the formation of $\alpha$ clusters is described by the generalised relativistic mean-field (gRMF) model with explicit cluster degrees of freedom (5). Figure 2a is the density distribution of the particles as a function of radius, the amplitudes are locally located around the surface, and a significant difference between $^{112}$Sn and $^{124}$Sn is predicted. Figure 2b is the isotopic dependence of the number of particles, which decreases by increasing the mass number.

This trend could be understood by the proton- and neutron-density distributions (Figure 3) (4). Focusing on the dilute nuclear matter region - right insets, $\alpha$ clusters appear below one tenth of the saturation density - $0.016^{-3}$ fm (6). In the case of $^{116}$Sn, a comparable number of protons and neutrons are existing in the surface, while in $^{124}$Sn, the neutron skin is developed, the density of protons are less than that of the neutrons. This unbalanced ratio of densities of protons and neutrons leads to the reduced probability of making $\alpha$ particles, which require two protons and two neutrons.
2 Relation to nuclear equation of state

One important aspect of $\alpha$ clusters in nuclear surface is their relation to the nuclear equation of state (EOS) (7). The knowledge of the nuclear EOS for neutron rich matter is important for nuclear physics as well as for the understanding of properties of cosmic objects like neutron stars. In the nuclear EOS, a parameter $L$ is introduced in the symmetry energy term, which is the derivative of the symmetry energy, and thus called the slope parameter.

![Image](image1.png)

Figure 4: a: Relation between the neutron skin thickness and slope parameter $L$ for $^{208}$Pb (8). b: Mass-dependent neutron-skin thicknesses for thin isotopes (9). Both a and b are the theoretical calculations.

It is known that the neutron skin thickness has a close correlation to the slope parameter $L$ (10). Figure 4 a shows the linear correlation of $L$ and neutron skin thickness for $^{208}$Pb (8). By measuring the neutron-skin thickness one can predict the $L$ parameters by using this relation, which triggered many experimental projects to obtain the neutron-skin thickness. However the theoretical calculations in figure 4 a are based on the conventional mean-field models, which do not take surface $\alpha$ clustering into account. Figure 4 b is the theoretical calculations of neutron skin thickness of tin isotopes (9). The calculations without $\alpha$ clusters(open circles) and with $\alpha$ clusters (filled points) give 15% 44% differences to neutron-skin thicknesses. Thus, the existence of $\alpha$ clusters in nuclear surfaces requires the revision of the theoretical predictions to include $\alpha$ clustering.
3 Quasi-free $\alpha$ knockout - $\text{Sn}(p, p\alpha)$ experiment

The most direct proof to see the amplitude of $\alpha$ clusters in nuclei should be quasi-free alpha knockout reaction.

![Diagram of quasi-free knockout reaction](image)

Figure 5: Initial and final state of the quasi-free knockout $^{\text{A}}\text{Sn}(p, p\alpha)^{\text{A-4}}\text{Cd}$. The angles of the final state are the measured angles in the experiment.

A projectile proton comes from the left side and hits an alpha cluster at the surface of a tin isotope. A proton knocks out an alpha particle and a cadmium isotope remains as a spectator. The scattered

![Diagram of experimental setup](image)

Figure 6: The red arrows are for proton and blue for $\alpha$ particle. A 392 MeV proton beam is injected onto the tin target and scattered protons are measured at 45 degrees and $\alpha$-particles at 60 degrees.
The experiment was performed, at the Research Center for Nuclear Physics in Osaka University using double-arm magnetic spectrometer Grand Raiden spectrometer (GR) (II) and Large acceptance spectrometer (LAS). Scattered protons and α particles are detected with drift chambers and the plastic scintillators at the focal planes.

Figure 7: Position correlation of the proton (x-axis) and α (y-axis) particles at the focal planes.

Considering the energy conservation law,

\[ E_{p_{in}} + E_{Sn} = E_{p_{out}} + E_{\alpha} + E_{Cd}, \]

the missing mass of the residue \( M_X \) is given by

\[ M_X = m_\alpha + m_{Cd} - m_{Sn} \]
\[ = T_\alpha - T_{p_{in}} - T_{p_{out}} - T_{Cd} \]
\[ = T_\alpha - T_{p_{in}} - T_{p_{out}} - \frac{|q|^2}{2m_{Cd}} \]
\[ \sim T_\alpha - T_{p_{out}} - 392, \]

where \( E \) is total energy, \( m \) is mass, \( T \) is kinetic energy, \( T_{p_{in}} \) is the incoming beam energy 392 MeV. Figure 7 shows the positions of coincident protons and alpha particles in GR (x-axis) and LAS (y-axis), respectively. A clear loci is seen, which corresponding to constant \( T_\alpha - T_{p_{out}} \) term in Eq. 2; therefore, the missing mass spectrum will make a peak structure.
4 Result and discussion

Figure 8: Missing mass spectra from $^{A}{\text{Sn}}(p, p'\text{)}^{A-4}\text{Cd}$. The red lines are the fitting results of one gaussian plus three-body phase-space simulations including the experimental conditions.

Figure 8 shows the missing mass spectra from $^{112-124}\text{Sn}(p, p'\text{)}\text{Cd}$ reaction. The x-axis is the missing mass, which corresponding to excitation energy spectrum of Cd isotopes. The strong transition from the ground state of tin to the ground state of cadmium was observed. The fact that $\alpha$ particles from the most outer shells are knocked out in this transition, implies that they are from the surface of the tin nuclei. Furthermore the $(p, p')$ probe is sensitive only to the surface region in this energy because of the absorption effects of $\alpha$ particles inside the nuclei (\textit{12}). Figure 9 is the isotopic dependence of the measured cross sections. We observed the smooth decrease of the cross sections when increasing the mass number. The red open squares are the theoretical calculations; it used the wave functions of alpha particles from gRMF theory and the Distorted-Wave Eikonal Model in Impulse Approximation. It has a good agreement with theoretical prediction. Thus, we confirmed the trend of isotopic dependence of $\alpha$ formation amplitude via $\alpha$ knockout reactions.

Figure 9: Isotopic dependence of measured cross sections (filled points) and theoretical predictions(open squairs) of $^{A}\text{Sn}(p, p'\text{)}$.
5 Summery

- We obtained the clear evidence of $\alpha$ clustering at the surface of heavy nuclei by measuring the cross sections for $\alpha$-knockout reactions along the tin isotopic chain.

- The cross sections along the isotopic chain decrease smoothly but substantially with neutron number, which agrees with the theoretical interpretation by considering the increasing neutron skin along the isotopic chain.

- $\alpha$-cluster appearance at the nuclear surface could be a natural explanation for the $\alpha$-preformation introduced in the theory of $\alpha$-decay.

- The existence of $\alpha$-clusters on the surface needs to be taken into consideration to determine the slope parameter $L$ from the neutron skin thickness $\Delta r_{np}$.

- We plan future experiments with different nuclei including radioactive $\alpha$-emitters.

6 Acknowledgement

We would like to appreciate all the collaborators listed below.
References

1. G. Gamow, *Zeitschrift für Physik* 51, 204 (1928).

2. I. Tonozuka, A. Arima, *Nuclear Physics A* 323, 45 (1979).

3. C. Qi, R. Liotta, R. Wyss, *Progress in Particle and Nuclear Physics* 105, 214 (2019).

4. S. Terashima, *et al.*, *Phys. Rev. C* 77, 024317 (2008).

5. S. Typel, G. Röpke, T. Klähn, D. Blaschke, H. H. Wolter, *Phys. Rev. C* 81, 015803 (2010).

6. K. Hagel, *et al.*, *Phys. Rev. Lett.* 108, 062702 (2012).

7. X. Roca-Maza, N. Paar, *Progress in Particle and Nuclear Physics* 101, 96 (2018).

8. X. Roca-Maza, M. Centelles, X. Vinas, M. Warda, *Physical review letters* 106, 252501 (2011).

9. S. Typel, *Physical Review C* 89, 064321 (2014).

10. B. Alex Brown, *Phys. Rev. Lett.* 85, 5296 (2000).

11. M. Fujiwara, *et al.*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 422, 484 (1999).

12. K. Yoshida, K. Minomo, K. Ogata, *Physical Review C* 94, 044604 (2016).