α-clustering at the surface of heavy nuclei $^{112-124}$Sn probed with $(p, p\alpha)$ reaction

Z. H. Yang[1,2], J. Tanaka[3,4], S. Typel[3,4], T. Aumann[3,4], J. Zenihiro[1], S. Adachi[1], S. Bai[5], P. v. Beek[3], D. Beaumel[6], Y. Fujikawa[7], J. Han[5], S. Heil[3], S. Huang[5], A. Inoue[1], Y. Jiang[5], M. Knösel[3], N. Kobayashi[1], Y. Kubota[2], W. Liu[5], J. Lou[5], Y. Maeda[8], Y. Matsuda[9], K. Miki[10], S. Nakamura[1], K. Ogata[1,11], V. Panin[1], H. Scheit[3], F. Schindler[3], P. Schrock[12], D. Symochko[3], A. Tamii[1], T. Uesaka[2], V. Wagner[3], K. Yoshida[13]
[1]*Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan*
[2]*RIKEN Nishina Center for Accelerator-Based Science, 2-1 Hirosawa, Wako 351-0198, Japan*
[3]*Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[4]*GSI Helmholtz Center for Heavy Ion Research GmbH, 64291 Darmstadt, Germany*
[5]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[6]*Institut de Physique Nucleáire Orsay, 15 Rue, Georges, Clemenceau 91400 Orsay, France*
[7]*Department of Physics, Kyoto University, Kitashirakawa-Oiwake, Sakyo, Kyoto 606-8502, Japan*
[8]*Faculty of Engineering, University of Miyazaki, 1-1 Gakuen, Kibanadai-nishi, Miyazaki 889-2192, Japan*
[9]*Cyclotron and Radioisotope Center, Tohoku University, 6-3 Aoba, Aramaki, Aoba-ku, Sendai 980-8578, Japan*
[10]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[11]*Department of Physics, Osaka University, Osaka 558-8585, Japan*
[12]*Center for Nuclear Study, The University of Tokyo, 2-1 Hirosawa, Wako 351-0198, Japan*
[13]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*

Alpha decay has been known since the very early years of nuclear physics, which is generally described as the quantum tunneling of preformed alpha particles, a semi-classical picture initiated by George Gamow in 1920s [1]. Despite the essential role in understanding the alpha decay process, there is so far no unambiguous experimental evidence reported for the existence of α clusters in heavy nuclei [2, 3]. Recent generalized relativistic density functional (gRDF) calculations, with cluster formation taken into account, suggest that α-clustering occurs at the low-density surface of heavy nuclei, which could explain the origin of α particles in the alpha decay process [4, 5]. According to gRDF calculations, there is close correlation between surface α-clustering and neutron-skin thickness in heavy nuclei and as a consequence the α-clustering strength in tin isotopes decreases monotonically with increase of the neutron number [5]. If confirmed, this will further impact our understanding of the density dependence of the symmetry energy in the nuclear equation of state [4, 5].

The quasi-free $(p, p\alpha)$ reaction has proven to be the most direct probe for α-clustering in the ground state of nuclei [6, 7]. By detecting proton and alpha particle in coincidence, the $(p, p\alpha)$ reaction cross sections can be determined, which is directly related to the α-clustering strength (namely, possibility to find α clusters) in the target. This kind of measurements have been widely used to study α-clustering for decades in light nuclei (e.g. ^{9}Be and ^{12}C), and has been particularly highlighted in recent years thanks to the significant progress in reaction theories by incorporating microscopic optical potentials and microscopic wave functions of the alpha cluster [6, 8, 9].

We have carried out direct measurements on α-clustering strength at the surface of tin isotopes ^{112,116,120,124}Sn by using quasi-free $(p, p\alpha)$ reaction at 392 MeV at the WS beam line of RCNP. The scattered protons and α particles after the $(p, p\alpha)$ reaction were detected in coincidence by the Grand Raiden and LAS spectrometers, which allows to reconstruct the separation energy and intrinsic momentum of the knocked out α particles from the conservation of energy and momentum. The experimental setup was designed according to the quasi-free scattering kinematics of the proton off a preformed alpha particle and optimized to achieve detection of low-energy α particles (down to $\sim$50 MeV) and high signal-to-noise ratio. In particular, we have optimized the working gas and operation high voltage so that the VDC of LAS spectrometer is insensitive to $Z = 1$ particles.

We started the measurement with ^{nat}Li$(p, p\alpha)$ reaction as validation of our detector setting and analysis method. The spectrum of the timing difference between protons in Grand Raiden and coincident α particles in LAS is presented in Figure 1 (left panel) for ^{nat}Li target, where significant enhancement within the $p - \alpha$ "true coincidence" time window corresponding to quasi-free $(p, p\alpha)$ reactions on ^{6,7}Li is evident. In the right panel, the α separation energy (E_{sep}) spectrum for "true coincidence" events (red line) and "random coincidence" events (blue line) were reconstructed from the momenta of proton and alpha particles. Obviously, the E_{sep} spectrum for "true coincidence" is dominated by a peak located at $\sim$2.4 MeV, in good agreement with the realistic separation energy of α particles in ^{7}Li ($E_{\mathrm{sep}} = 2.47$ MeV). The measured E_{sep} spectrum for quasi-free $(p, p\alpha)$ reaction can then be deduced by subtracting the "random coincidence" background, after proper normalization, from the "true coincidence" spectrum. To conclude, the present setup works well for $(p, p\alpha)$ measurements.

In Figure 2, we presented the E_{sep} spectra for ^{112}Sn with the same analysis method as was done for ^{nat}Li target. As shown in the right panel, the physical E_{sep} spectrum, after background subtraction, exhibits a prominent peak at 2 MeV, which is consistent with the expected α-particle separation energy for ^{112}Sn (1.83 MeV, calculated from the masses). Similar analysis has also been done for the other tin isotopes ^{116,120,124}Sn, and the expected E_{sep} peak was also clearly observed for each of them. The E_{sep} spectra were then used to deduce the corresponding $(p, p\alpha)$ cross sections for each isotope, and gradual decrease of the obtained cross sections from ^{112} Sn to ^{124}Sn was found from the preliminary analysis, which is consistent with the gRDF predictions by S. Typel [5].

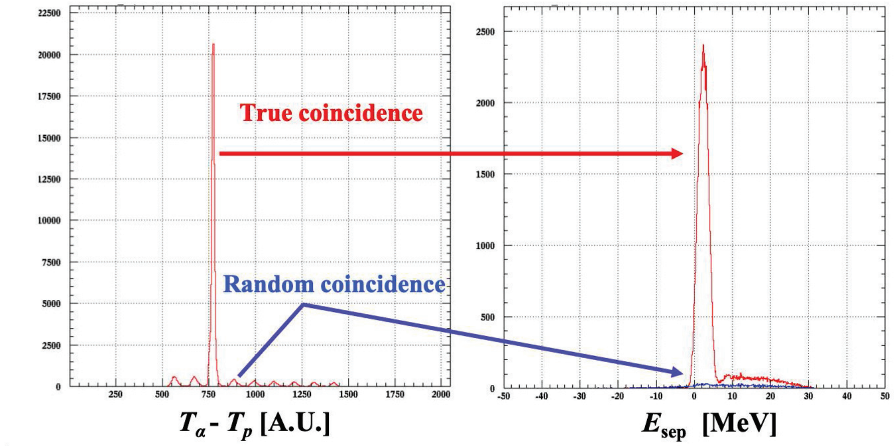

Figure 1: The measured spectra for ^{nat}Li$(p, p\alpha)$ reaction. (left) the timing difference spectrum between protons and coincident alpha particles. (right) the alpha separation energy (E_{sep}) spectrum for "true coincidence" events (red line) and "random coincidence" events (blue line).

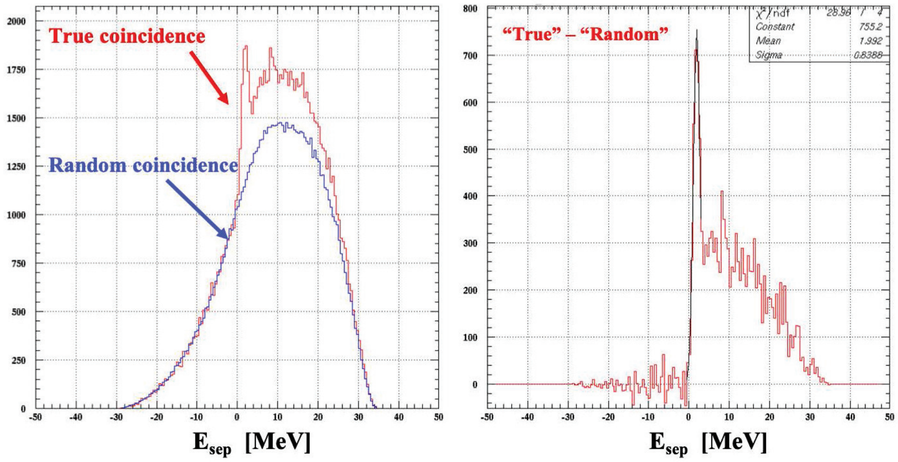

Figure 2: The measured E_{sep} spectra for ^{112}Sn. On the right panel, the "random coincidence" background has been subtracted.

References

[1] G. Gamow, Z. Phys. **51**, 204 (1928).

[2] G. Röpke, Phys. Rev. C **90**, 034304 (2014).

[3] C. Qi, Prog. Part. Nucl. Phys. **105**, 214 (2019).

[4] S. Typel *et al.*, Phys. Rev. C **81**, 015803 (2010).

[5] S. Typel, Phys. Rev. C **89**, 064321 (2014).

[6] P. G. Roos *et al.*, Phys. Rev. C **15**, 69 (1977).

[7] A. Nadasen *et al.*, Phys. Rev. C **40**, 1130 (1989).

[8] K. Yoshida *et al.*, Phys. Rev. C **94**, 044604 (2016).

[9] M. Lyu *et al.*, Phys. Rev. C **97**, 044612 (2018).