Progress report on the RCNP research project
“Research on nuclear clustering by new reaction probes”

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Abstract

In this report, we introduce the RCNP research project “Research on nuclear clustering by new reaction probes” launched from April 2019 for two years. Its goals, outcomes, and highlights in 2019 are presented. We also describe the perspectives of the project.

1 Introduction

The saturation of the energy and density, which is a basic property of atomic nuclei, implies that a nucleus can be decomposed into smaller nuclei (clusters) with small excitation energy [1]. Because of this, there exist many cluster structure in the excited states (and the ground states in some cases) of stable and unstable nuclei [2,3]. The study of nuclear clustering has long history; its beginning [4] is even earlier than the finding of neutron, and it is continuously giving us deeper understanding of the dynamics and correlations of many nucleons. Moreover, it is indispensable for understanding various astrophysical phenomena, as many of the cluster states are closely related to the astrophysical nuclear reactions [5].

Historically, transfer reactions, resonant scattering and fusion reactions have been used as the major experimental tools for studying the nuclear clustering. However, in these years, the α-knockout reactions and α-inelastic scattering have been attracting many interests as novel probe for nuclear clustering [6-12], since they have advantages compared to the conventional methods and provide us unique insights into nuclear clustering. From the α-knockout reactions, we can extract the α-cluster formation probabilities at nuclear surface more accurately, which may provide us, for example, the information on the equation-of-state of neutron star matter [13]. The α-inelastic scattering can easily create the cluster resonances which are rarely populated by the fusion reactions, and hence, makes it possible to investigate the resonance properties of astrophysical interest. Because the cluster resonances such as the ^{12}C + ^{12}C resonance give significant effects to the stellar reactions [14], an accurate knowledge of their properties is essential for understanding various astrophysical phenomena. For these reactions, various experiments have ever been performed and large amount of data has been stored. In particular, RCNP has provided the high-resolution data for various α-inelastic scattering. Therefore, the analysis of these reaction data should have a great impact on nuclear cluster physics and nuclear astrophysics.

To conduct the theoretical analyses of the experimental data of the α-knockout reactions and α-inelastic scattering, the RCNP research project "Research on nuclear clustering by new reaction probes" has been launched from April 2019 for two years. This report describes the project overview, outcomes and perspectives.

2 Project Description

The project has 6 members for the theoretical study, who are the authors of this report, and two members from the experimental side who play a role for the smooth communication with the experimental groups. The project aims to conduct the analyses of the α-knockout reactions and α inelastic scattering data to obtain the information about nuclear clustering, in particular those relevant to the astrophysics. For this purpose, the project has two major themes whose goals, plans, and outcomes in 2019 are explained below.

Theme 1. Analysis of the α-knockout reactions for the study of the α-cluster formation at the nuclear surface

Goals: We investigate the α-cluster formation probabilities at the nuclear surface by analyzing the α-knockout reactions. It reveals how the α cluster is formed under the various environments (various densities and proton/neutron asymmetries). To conduct the analysis, we develop a theoretical framework that quantitatively describes the α-knockout reaction by combining the knockout reaction theory and the cluster structure theory.

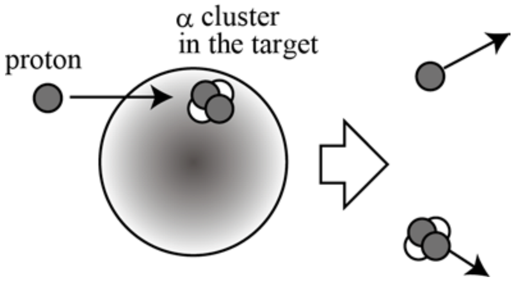

Fig. 1: A schematic figure for the α-knockout reaction. A proton kicks an α cluster in the peripheral region of a target nucleus. When the incident energy is large enough, this reaction process is rather clean and serves as a quantitative probe to the α cluster formation probability.

Plan: The experimental data of the (p, pα) reactions with the Ne and Ti targets are investigated. The α-cluster formation probabilities of Ne and Ti isotopes are calculated by using the antisymmetrized molecular dynamics model (AMD), which can describe cluster formation at the nuclear surface. The calculated cluster formation probabilities are used as an input of the reaction model to obtain the knockout cross section. The validity of the models is verified by comparing the calculated and observed cross-sections. At the same time, we also investigate to what extent the α cluster formation probability can be determined solely from the experimental data.

Outcomes in 2019: The α-knockout reaction with the ^{20}Ne target has been analyzed by combining AMD and the distorted wave impulse approximation (DWIA) framework for the α-knockout reaction [6,15]. It is shown for the first time that the observed cross section [16] can be reproduced without any adjustable parameter by using a reliable α formation probability, p-α cross section, and optical potentials. This success demonstrates that the α-knockout reaction is a reliable and quantitative measure for the α-cluster formation at the nuclear surface. We also performed similar analyses for other stable nuclei, *i.e.*, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca, and ^{48}Ti, and found that the ordinary mean-field approximation for the ground state fails to explain the observed α-formation probability in order of magnitude.

Theme 2. Analysis of the α inelastic scattering for the study of the cluster resonances

Goals: We investigate the properties of the cluster resonances close to the cluster decay thresholds and the Gamow window, which will affect the nuclear reaction rates relevant to the stellar evolution, type Ia supernova and superbursts. We expect that many of such cluster resonances can be populated and observed by the inelastic α scattering as they should have large cross sections due to their enhanced isoscalar monopole and dipole transition strengths. The cluster resonances and their resonance parameters will be identified from the comparison of the magnitude and angular distribution of the cross sections between theory and experiments. The major goals are the following three.

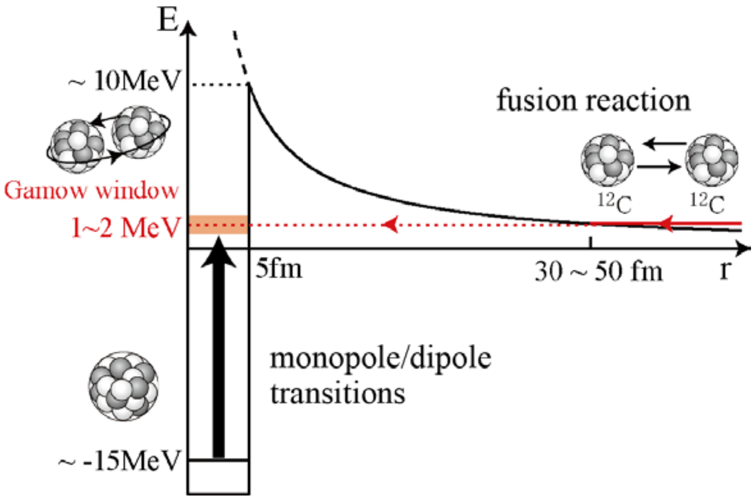

Fig. 2: A schematic figure which shows our strategy. The fusion reaction rarely creates the resonances close to the Gamow window as the tunneling probability is very small. On the other hand, the monopole and dipole transitions can easily produce the resonances as it bypass the Coulomb barrier.

1. Prediction of the energy and decay modes of cluster resonance composed of ^{12}C and ^{16}O nuclei
2. Identification of the cluster resonances consisting of ^{12}C and ^{16}O nuclei from the α inelastic scattering data
3. Provision of the information for future experiments such as optimal incident energies

Plan: To identify the cluster resonances from the cross-section data, we perform the nuclear structure calculations by AMD, and obtain the resonance parameters (energy and widths), the monopole and dipole transition strengths and their transition densities. The transition densities are used as an input of the reaction model to calculate the cross sections. We investigate the inelastic α scattering off the ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si and ^{32}S targets with the theoretical analyses of the reaction data, which have been already measured at RCNP.

Outcomes in 2019: The α inelastic scattering off Z=N nuclei in the A=12−28 region (^{12}C, ^{16}O etc.) has been investigated by the microscopic coupled-channel calculation with the Melbourne *g*-matrix NN interaction and the densities of the target nuclei obtained by AMD [17-20]. The calculation successfully reproduced the observed elastic and inelastic cross-sections to 0^+ and 2^+ states at incident energies of E_α = 100–400 MeV [21]. It is worthwhile to mention that quantitative description of the observed 0^+ cross sections was obtained with no adjustable parameter. This is a great advantage superior to usual phenomenological reaction analyses and enables ones to investigate properties of the isoscalar monopole excitation to cluster states via α inelastic scattering. It was also found that coupled-channel effects give significant contributions to inelastic cross sections even at E_α = 400 MeV except for the first 2^+ and 3^- states.

To study the properties of the cluster resonances relevant to carbon and oxygen burning processes, we investigated the properties of the ^{12}C + ^{16}O and ^{16}O + ^{16}O molecular resonances using the AMD [22]. The calculation reasonably reproduced the energies and moment-of-inertia of the observed ^{12}C + ^{16}O and ^{16}O + ^{16}O cluster resonances. Furthermore, we found that new ^{12}C + ^{16}O resonances exist close to the Gamow window, which should affect the reaction rate. Now we are evaluating the monopole and dipole transition strengths for comparing with the observed data.

3 Project highlights in 2019

In 2019, the outcomes from the project were published as the original 9 papers [15, 17-20, 22-25] in peer-refereed journals and presented in the 9 invited talks at the international symposia. We also issued a joint press release from Osaka Univ., Kagawa college and Hokkaido Univ [26]. One of the project members (K.Y.) won the ASRC director general's award 2019. Here, we briefly introduce these research highlights in 2019.

3.1 Analysis of α-knockout reaction from ^{20}Ne

It has been highly expected that the ground state of ^{20}Ne manifests a strong α+^{16}O clustering as many theoretical and experimental studies have already suggested. However, the α-cluster formation probability (α spectroscopic factor) is difficult to measure, and hence, its absolute magnitude has long been uncertain. For example, it was expected that the proton-induced knockout reaction, ^{20}Ne(p,pα)^{16}O reaction, is a good spectroscopic tool for that, and the first measurement was conducted in 1984 by Carey *et al* [16]. However, the measured α spectroscopic factor disagreed with the theoretical predictions by a factor of two, and this inconsistency remains unresolved until today.

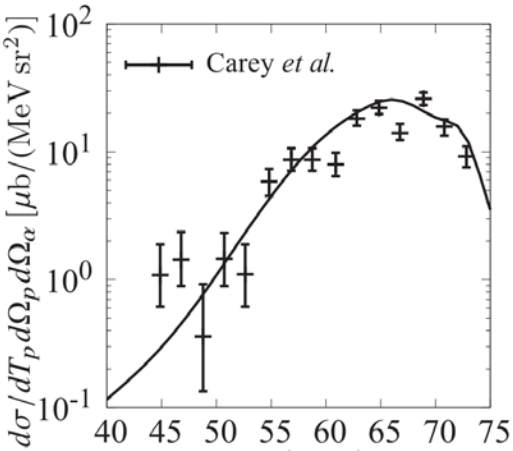

Fig.3: ^{20}Ne(p,pα)^{16}O cross section as a function of the proton emission energy T_p. The experimental data [16] is also shown.

To solve this problem, the α-cluster formation probability calculated by AMD and the distorted-wave impulse approximation (DWIA) framework for the knockout reaction were combined to quantitatively describe the ^{20}Ne(p,pα)^{16}O reaction cross section [6, 15]. As shown in Fig. 3, our analysis successfully reproduced the data without any adjustable parameter for the first time. This success demonstrates that (p,pα) reaction is a quantitative probe for the α amplitude. From this result, we can show that the α spectroscopic factor 0.26 calculated by AMD is reasonable enough to reproduce the data. It was also shown that the use of the reliable p-α effective interaction and the optical potentials for scattering waves are essential for the quantitative description.

3.2 Study of the α inelastic scattering off ^{12}C and ^{16}O

The α inelastic scattering cross sections off ^{12}C were investigated with a *g*-matrix folding model approach [17]. The coupled-channel calculations were performed using α-nucleus potentials which were microscopically derived by folding the Melbourne *g*-matrix NN interaction with the matter and transition densities of ^{12}C obtained by AMD. It is emphasized that our model successfully described the absolute amplitudes of the inelastic cross sections to the second 0^+ states, and hence, it resolved the overshooting problem that had been reported in many phenomenological reaction calculations. The calculation also reproduced the cross sections to the 0_3^+ and 2_2^+ states (see Fig. 4). This success in describing the inelastic cross sections shows the reliability of the E0 and E2 transition strengths calculated by the present structure theory.

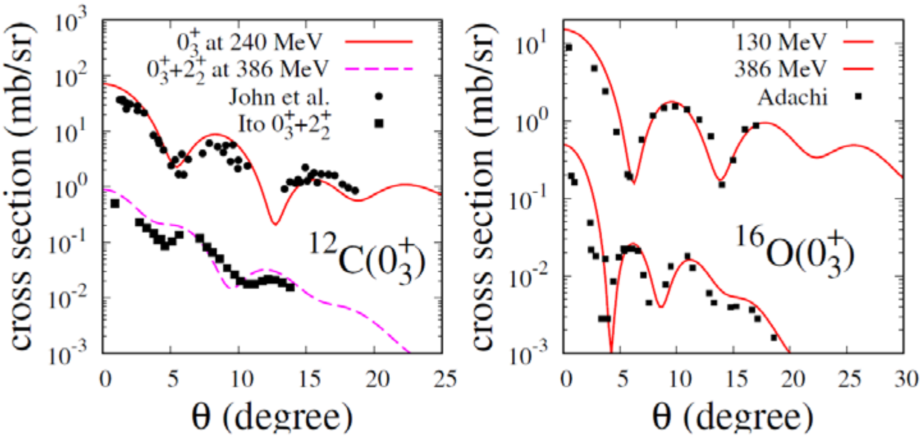

Fig. 4: ^{12}C(α, α') cross sections to the 0_3^+ and 2_2^+ states and ^{16}O(α,α') cross sections to the 0_3^+ state. Figures are from Refs. [17, 18] (replotted).

We also applied the same microscopic coupled-channel (MCC) approach to the α inelastic scattering off ^{16}O [18]. This calculation was the first MCC calculation of the ^{16}O(α, α') reaction based on the α-nucleus potentials microscopically derived from the *g*-matrix NN interaction and the microscopically calculated ^{16}O densities. The calculation reproduced well the $0_{2,3,4}^+$, 2_1^+ , 1_1^-, and 3_1^- cross sections at E_α = 104–386 MeV without the overshooting problem of the 0^+ cross sections. Significant channel-coupling (CC) effects were found in the 0_2^+, 0_5^+, and 1_1^- cross sections due to the strong quadrupole coupling between developed cluster states. This indicates that the scaling law between the α-scattering cross section and B(E0) strength is not necessarily valid for the cluster states and suggests the importance of reliable reaction analysis based on the MCC approach.

3.3 Deep sub-barrier ^{12}C + ^{16}O molecular resonances relevant to nucleosynthesis

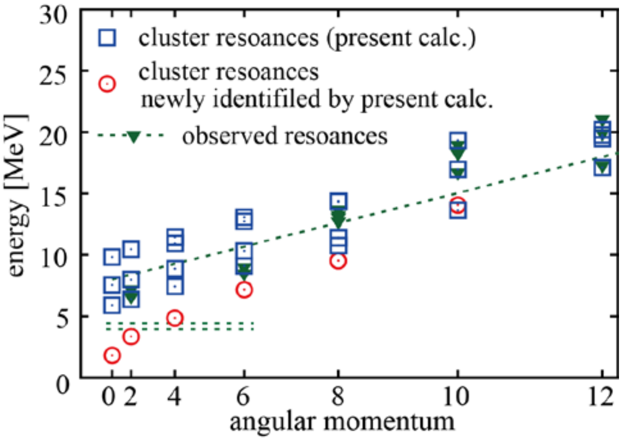

Fig. 5: The energy of the calculated and observed ^{12}C+^{16}O cluster resonances. The red circles show the newly found resonances close to the Gamow window.

The ^{12}C + ^{16}O fusion reaction, which takes place in the supernova explosion, plays an essential role for the nucleosynthesis. However, the measurement of its reaction rate is rather difficult because the Coulomb penetration probability is tiny due to low incident energy for this fusion process. Therefore, a theoretical investigation of the reaction rate is essentially important.

For this purpose, we studied the properties of the ^{12}C + ^{16}O molecular resonances [22], which should considerably affect the reaction rate. In our model, we considered approximately the rotation effect of the ^{12}C cluster in addition to the coupling effect between the ^{12}C + ^{16}O cluster and deformed mean-field configurations. The calculation reasonably reproduced the energies and moment-of-inertia of the observed cluster resonances, which demonstrates the reliability of the present calculation. Furthermore, we predicted new ^{12}C+^{16}O molecular resonances at deep sub-barrier energy close to the Gamow window. Based on these findings, we have pointed out that these molecular resonances will enhance the ^{12}C + ^{16}O fusion reaction rate, which can lead to the large abundance of Mg and Si isotopes.

4 Summary and perspectives

In summary, we have reported the status of the RCNP research project “Research on nuclear clustering by new reaction probes”. The project aims the theoretical analyses of the α-knockout reactions and α-inelastic scattering data, in particular those from RCNP, to understand the cluster states relevant to astrophysics. In the study of the α-knockout reactions, we have analyzed the $^{20}Ne(p,p\alpha)^{16}O$ data and showed that our theoretical framework is accurate enough to achieve the quantitative and reliable discussion of the α cluster formation probability. Similar analyses were also carried out for the ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca and ^{48}Ti targets, which will be summarized and published in 2020. In the study of the α inelastic cross section, the existing data for light targets (^{12}C, ^{16}O, ^{20}Ne etc.) were comprehensively analyzed. It was shown that our calculation successfully describes the absolute amplitudes of the inelastic cross sections, and hence, it resolves the overshooting problem reported in many phenomenological reaction studies. Thus, our theoretical framework is a useful tool for investigating the properties of cluster states from the α inelastic scattering data. We have also investigated the ^{12}C+^{16}O cluster resonances and predicted new resonances very close to the Gamow window, which should strongly affect the reaction rate. In 2020, the analysis of heavier targets (^{24}Mg, ^{28}Si, ^{32}S etc.) will be carried out and the cluster resonances relevant to the carbon-oxygen-burning process (^{12}C+^{12}C, ^{12}C+^{16}O, ^{16}O+^{16}O etc.) will be discussed.

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