α-cluster structure of ^{12}C from first principles†

T. Abe,[*1] T. Otsuka,[*2,*1,*3] T. Yoshida,[*4,*5] Y. Tsunoda,[*4] N. Shimizu,[*4] N. Itagaki,[*6] Y. Utsuno,[*3,*4] J. P. Vary,[*7] P. Maris,[*7] and H. Ueno[*1]

The ^{12}C nucleus is of particular importance in stellar nucleosynthesis. It is produced by triple-α reactions through the second 0^+ state (Hoyle state). However, the properties of the Hoyle state are not fully understood. The Hoyle state is still being studied actively from both sides of experiments and theories. On the theoretical side, *ab initio* approaches for low-energy nuclear structure calculations have been advanced rapidly in recent years, owing to recent computational and methodological developments. Here, we report the low-lying structure of ^{12}C studied by the *ab initio* calculations in the no-core Monte Carlo shell model (MCSM).[1)]

Figure 1 shows the no-core MCSM results compared to the experiments. The calculations were carried out in the basis space of $N_{\rm shell} = 7$ with the harmonic-oscillator energy of $\hbar\omega = 20$ MeV. The Daejeon16 NN interaction[2)] was adopted. In Fig. 1, the excitation energies and transition strengths ($B(E2)$, $M(E0)$) for the ground (0_1^+) and two low-lying (2_1^+, 0_2^+) states are indicated. For the 2_1^+ state, the Q-moment is also depicted in the unit of e fm^2. As seen in Fig. 1, the no-core MCSM calculations ("th" in the figure) provide a reasonable agreement with the experimental values ("exp" in the figure). It is remarkable that the *ab initio* calculations for the low-lying states of the twelve-body system can reproduce the experimental data.

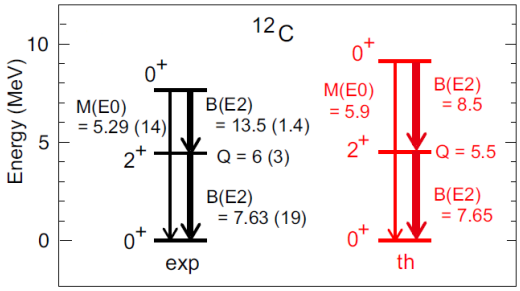

Fig. 1. ^{12}C excitation spectra and the $B(E2)$ ($M(E0)$) values in the unit of e^2 fm^4 (e fm^2) compared to experiments. For more details, see Ref. 1).

The density in the body-fixed frame (intrinsic density) is closely related to the structure of atomic nuclei. It is, however, still difficult to observe the intrinsic density experimentally. Thus, the theoretical approaches are indispensable to investigate the intrinsic density of atomic nuclei. Figure 2 displays the density distributions of the ground (0_1^+) and Hoyle (0_2^+) states in comparison with the α-particle (^{4}He) density. For the ground state, three α-like clusters are closely lying one another, being closer to the quantum liquid (*i.e.*, normal nuclear matter). The Hoyle state appears rather clearly separated three α-like clusters compared to the ground state. It is noteworthy that *ab initio* calculations in the twelve-body system exhibit three-α-like cluster structure of ^{12}C without any *a priori* assumptions of α particles.

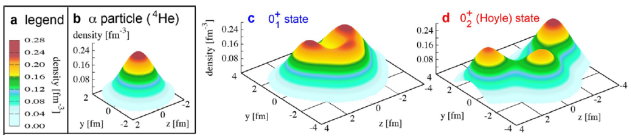

Fig. 2. (a) Color code of density. (b) Density of the ground state of the α-particle. (c) Density of the ground state of ^{12}C. (d) Density of the Hoyle state of ^{12}C. See the details in Ref. 1).

From the T-plot analysis,[3)] it is found that the ground state is composed of the quantum liquid (normal nuclear matter) with ∼94% probability and the α-like clusters with ∼6% probability, while the Hoyle state comprises the quantum liquid with ∼33% probability and the α-like clusters with ∼61% probability. Therefore, the structure of ^{12}C can be viewed as a crossover of the quantum liquid and clustering in terms of the critical phenomena in quantum many-bod systems. Note that this feature obtained by the T-plot analysis is verified by the hierarchical cluster analysis with dendrogram, that is one of the techniques employed in the machine learning.

Now, we can describe the low-lying structure (static property) of ^{12}C. From future perspective, we would like to apply the no-core MCSM wave functions obtained here to the calculations for triple-α reactions (dynamics) so that we can fully understand the process of the ^{12}C production in stars from first principles.

† Condensed from the article in Nat. Commun. **13**, 2234 (2022)

*1 RIKEN Nishina Center
*2 Department of Physics, University of Tokyo
*3 Advanced Science Research Center, Japan Atomic Energy Agency
*4 Center for Nuclear Study, University of Tokyo
*5 Research Organization for Information Science and Technology
*6 Yukawa Institute for Theoretical Physics, Kyoto University
*7 Department of Physics and Astronomy, Iowa State University

References

1) T. Otsuka *et al.*, Nat. Commun. **13**, 2234 (2022).
2) A. M. Shirokov *et al.*, Phys. Lett. B **761**, 87 (2016).
3) Y. Tsunoda *et al.*, Phys. Rev. C **89**, 031301(R) (2014).