Structure of ^{12}C studied by the no-core Monte-Carlo shell model

T. Abe,[*1] P. Maris,[*2] T. Otsuka,[*1,*3] N. Shimizu,[*4] Y. Utsuno,[*5,*4] and J. P. Vary[*2]

Carbon-12 is of particular importance in our life. This nucleus is produced by the triple-α reactions through the second 0^+ state known as the Hoyle state. The properties of this state are still being investigated actively both in the experimental and theoretical ways. On the theoretical side, *ab initio* approaches for low-energy nuclear structure calculations have been developed rapidly in recent years, owing to recent computational and methodological developments. Here, we report the low-lying states of ^{12}C examined by the *ab initio* calculations in the no-core Monte Carlo shell model (MCSM).[1)]

We have performed the large-scale calculations in the no-core shell-model (NCSM) method,[2)] applying the MCSM technique for conventional shell-model calculations.[3–5)] The no-core MCSM calculations have been done with 100 basis states in the basis space of $N_{\rm shell} = 7$ with the harmonic-oscillator energy of $\hbar\omega = 20$ MeV. We have adopted the Daejeon16 NN interaction,[6)] which is based on an NN interaction from chiral effective field theory (χEFT).

Figure 1 shows preliminary results of the no-core MCSM calculations in comparison with the experimental data.[7)] In Fig. 1, the absolute energies and transition strengths for three low-lying states are shown. The no-core MCSM results with the Daejeon16 interaction provide a reasonable agreement with the experimental data for the ground 0^+ and the first-excited 2^+ states. The experimental ground-state energy is -92.16 MeV, while our result is -91.9 MeV and well reproduces the no-core full-configuration (NCFC, one of the other NCSM approaches) result with the same interaction of $-92.9(1)$ MeV.[6)] The point-proton radius for the ground state is $\sim$2.29 fm both in the no-core MCSM and the NCFC methods, corresponding to the experimental value of 2.33 fm. The excitation energy of the first-excited 2^+ state is 5.01 MeV in the no-core MCSM and 4.57(15) MeV in the NCFC. These energies are also comparable with the experimental value of 4.44 MeV. The electric quadrupole and monopole transition strengths are also in reasonable agreement with the experimental values.

The excitation energy of the second 0^+ state, however, is higher than the experimental value by $\sim$3 MeV and the point-proton radius is 2.60 fm, which is smaller than the values by the phenomenological calculations, typically larger than 3 fm (see, for example, Ref. 8) and references therein). It is because the Hoyle state is believed to have the loosely-bound three-α-cluster structure and is challenging to be described in the harmonic-oscillator basis at least with the basis space employed here. It is awaited to extrapolate our results obtained in the finite basis-space size into the infinite basis-space-size limit so as to compare with the experimental values and also the other theoretical calculations in more detail. Based on our preliminary calculations, the investigation of the intrinsic structure of ^{12}C is currently underway, aiming to elucidate the α-cluster structure in light-mass nuclear systems from first principles.

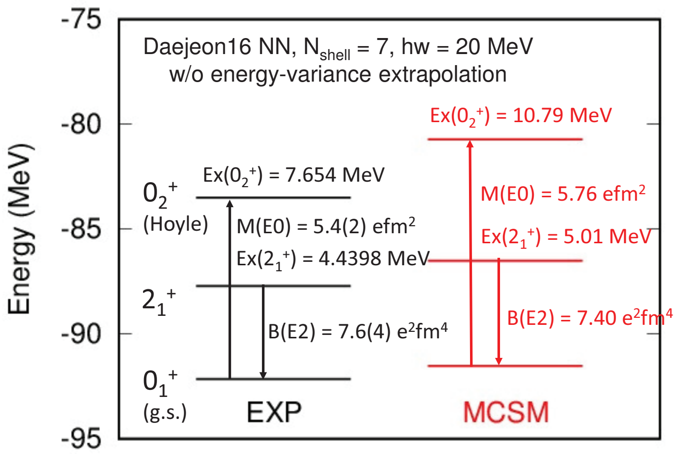

Fig. 1. Excitation spectra of ^{12}C. The right (left) side in the figure shows no-core MCSM results (experimental data) with the red (black) color. The energy levels of three low-lying states are shown by horizontal bars. The electric quadrupole and monopole transition strengths are denoted by arrows. The experimental data are taken from Ref. 7).

References

1) T. Abe, P. Maris, T. Otsuka, N. Shimizu, Y. Utsuno, J. P. Vary, Phys. Rev. C **86**, 054301 (2012).
2) B. R. Barrett, P. Navrátil, J. P. Vary, Prog. Part. Nucl. Phys. **69**, 131 (2013).
3) T. Otsuka, M. Honma, T. Mizusaki, N. Shimizu, Y. Utsuno, Prog. Part. Nucl. Phys. **47**, 319 (2001).
4) N. Shimizu, T. Abe, Y. Tsunoda, Y. Utsuno, T. Yoshida, T. Mizusaki, M. Honma, T. Otsuka, Prog. Theor. Exp. Phys. **2012**, 01A205 (2012).
5) N. Shimizu, T. Abe, M. Honma, T. Otsuka, T. Togashi, Y. Tsunoda, Y. Utsuno, T. Yoshida, Phys. Scr. **92**, 063001 (2017).
6) A. M. Shirokov, I. J. Shin, Y. Kim, M. Sosonkina, P. Maris, J. P. Vary, Phys. Lett. B**761**, 87 (2016).
7) F. Ajzenberg-Selove, Nucl. Phys. A **506**, 1 (1990).
8) M. Chernykh, H. Feldmeier, T. Neff, P. von Neumann-Cosel, A. Richter, Phys. Rev. Lett. **98**, 032501 (2007).

*1 RIKEN Nishina Center
*2 Department of Physics and Astronomy, Iowa State University
*3 Department of Physics, the University of Tokyo
*4 Center for Nuclear Study, the University of Tokyo
*5 Advanced Science Research Center, Japan Atomic Energy Agency