Search for α condensed states in ^{13}C using α inelastic scattering

Kento Inaba

α condensation in atomic nuclei is of great interest in the modern nuclear physics. In α condensates, all α clusters are condensed into the same lowest-energy orbit like the atomic Bose-Einstein condensation. Since they have a very narrow momentum distribution around zero, their density becomes much lower than the saturation density. Very recently, it was proposed that the α condensation reduces the internal energy of cold dilute nuclear matter. Because it is inferred that the energy gain due to the α condensation is suppressed in the asymmetric nuclear matter, the α condensation induces the strong isospin dependence of the equation of state of the dilute nuclear matter. However, it is not trivial that the α condensation really occur in the dilute nuclear matter, therefore it must be confirmed by experiments.

Although we cannot directly investigate infinite nuclear matter in the laboratory, we can get some clues to the α condensation in dilute nuclear matter through experimental searches for α condensates in finite nuclei (α condensed states) over a wide range of the mass number and isospin. If the α condensed states universally exist in various nuclei, it will demonstrate that the α condensate is a trivial conformation in dilute nuclear many-body systems. Many theoretical and experimental efforts have been devoted to establish the α condensed states and to reveal their nature. However, the scope of these studies has been limited to self-conjugated $A = 4k$ nuclei. Few studies have discussed the α condensation in $A \neq 4k$ nuclei with non-zero isospin, so far.

In the present work, we searched for the α condensed state in ^{13}C as the first step for the systematic exploration into non-self-conjugated $A \neq 4k$ nuclei. Since the $IS0$ and $IS1$ transitions can induce density change of nuclei, these transitions are suitable to excite the α condensed state with dilute density from the ground state. Therefore, we measured the angular distribution of the cross section for the ^{13}C(α, α') reaction at $E_{\alpha} = 388$ MeV at forward angles including 0° where the cross sections for the $IS0$ and $IS1$ transitions are large in order to precisely measure the strengths of these transitions. The measured cross sections were analyzed by employing the DWBA calculation with the single-folding potentials to determine the isoscalar transition strengths in ^{13}C. The measured angular distributions of the cross sections for the observed discrete states were reasonably well reproduced by the DWBA calculations. This result demonstrated the reliability of the present DWBA analysis.

We found a bump structure around $E_x = 12.5$ MeV in ^{13}C mainly excited in the $IS0$ transition. The peak-fit analysis suggested that this bump consisted of several $1/2^-$ states. We performed the multipole-decomposition analysis in order to determine the strength distributions for the isoscalar

ΔL = 0–3 transitions. The known discrete states were correctly observed in the corresponding ΔL strength distributions. We found the two bumps at E_x = 14.5 and 16.1 MeV in the ΔL = 1 strength distribution. The spins and parities of these states were assigned to be $1/2^+$ or $3/2^+$.

We compared the experimental level diagram and the *IS*0 and *IS*1 strengths for the $1/2^-$ and $1/2^+$ states with those predicted by the shell model with the SFO interaction [1], OCM [2], and AMD [3]. The shell-model calculation best reproduces the experimental level diagram of the $1/2^-$ states among these calculations, but it cannot explain the observed sizable *IS*0 strengths. On the other hand, the OCM and AMD calculations, which incorporate the clustering degrees of freedom, can reproduce the sizable *IS*0 strengths. This fact shows that clustering degrees of freedom are crucial to account for the sizable *IS*0 strengths for these states. Therefore, the theoretical calculations covering both the cluster-model and shell-model configuration spaces are necessary to well describe these $1/2^-$ states.

The small bump observed around E_x = 13.5 MeV in ^{13}N, which is the possible mirror states of the $1/2^-$ states around E_x = 12.5 MeV near the 3α + *n* decay threshold in ^{13}C, dominantly decays to the 0^+_2 state in ^{12}C [4]. This fact implies that the $1/2^-$ states around E_x = 12.5 MeV are the candidates for the α condensed state with a dilute density in which a $p_{1/2}$ neutron couples to the ^{12}C(0^+_2) core. The OCM calculation suggests that the predicted $1/2^-_4$ and $1/2^-_5$ states mainly decay to the 0^+_2 state and they are dilute cluster states having larger radii than that of the ground state. However, the calculation proposes that the wave functions of the $1/2^-$ states in ^{13}C are dominated by the ^{9}Be + α configuration due to the attractive odd-parity α-*n* force. Therefore, the α condensed state is unlikely to emerge as the negative parity states in ^{13}C.

It is expected that the excitation energy of a state having a dilute structure in Z > N nuclei is smaller than that of the mirror state due to a reduction of the energy difference by the Coulomb interaction. However, the energy difference of the 13.5-MeV state in ^{13}N and the 12.5-MeV state in ^{13}C contradicts this speculation. Further theoretical investigation of the Coulomb shift between these mirror states is required.

The experimental level diagram for the $1/2^+$ states populated by the *IS*1 transitions is reasonably well reproduced by the shell-model and OCM calculations if we assume the spins and parities of both the 14.5-MeV and 16.1-MeV states to be $1/2^+$. On the other hand, the excitation energies of the $1/2^+_2$ and $1/2^+_3$ states predicted in the AMD calculation are much larger than those in the shell-model and the OCM calculations. We suggest that the AMD calculation misses the $1/2^+_{2,3,4}$ states predicted by the OCM calculation. All the calculations reasonably well reproduce the measured *IS*1 strength for the $1/2^+_1$ state, which is suggested to have a shell-model-like structure in these calculations. We propose that the 16.1-MeV state is a possible candidate for the α condensed state predicted by the OCM and AMD calculations on the basis of the good correspondence between the experimental and calculated level structures. However, the measured

*IS*1 strength for the 16.1-MeV state is much larger than the theoretical predictions. This discrepancy in the *IS*1 strength raises a doubt about the identification of the α condensed state.

We need further experimental information to establish the α condensed state in ^{13}C. The spins of the 14.5-MeV and 16.1-MeV states should be determined. The decay modes of these states should be also investigated since the α condensed state is expected to decay by emitting a neutron via the 0^+_2 state in ^{12}C. A new experiment measuring the decay neutrons from the 14.5-MeV and 16.1-MeV states in coincidence with inelastically scattered α particles is highly desired.

[1] Toshio Suzuki, Rintaro Fujimoto, and Takaharu Otsuka, Phys. Rev. C **67**, 044302 (2003).

[2] Taiichi Yamada and Yasuro Funaki, Phys. Rev. C **92**, 034326 (2015).

[3] Y. Chiba and M. Kimura, Phys. Rev. C **101**, 024317 (2020).

[4] H. Fujimura et al., Phys. Rev. C **69**, 064327 (2004).