Hoyle band and α condensation in ^{12}C

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The Hoyle state, the second $J^\pi = 0^+$ state at 7.65 MeV in ^{12}C, is a typical example of cluster states and had a long history since it was predicted by F. Hoyle and subsequently observed by Cook *et al.* as a key state in the synthesis of ^{12}C in stellar evolution. In the last decade, the aspects of the α condensate, in which α clusters occupy an identical S-orbit, has attracted great interest since the so-called Tohsaki-Horiuchi-Schuck-Röpke (THSR) wave function[1)], which has the 3α condensate character, was shown to be equivalent to the Hoyle state wave function obtained by solving the equations of the full 3α resonating group method (RGM) or generator coordinate method (GCM)[2)]. In addition to the Hoyle state, the nature of the other positive-parity excited states were recently highlighted by many experiments[3–6)].

In this report, we investigate the structures of the positive parity excited states above the 3α threshold by using an extended version of the THSR wave function, which includes the 3α condensate and ^{8}Be $+ \alpha$ asymptotic configurations, with a treatment of resonances[7)]. In particular, we focus on the structures of the "Hoyle band" states as well as the 2_2^+[3–5)] and 4_2^+[6)] states, which were recently observed above the Hoyle state, in addition to the structures of the 0_3^+ and 0_4^+ states, which were also quite recently identified in experiment[3)].

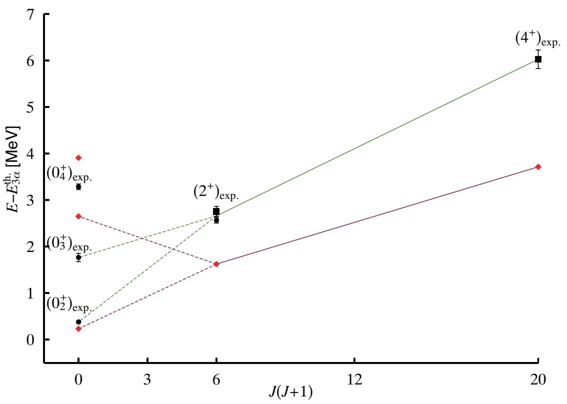

Fig. 1. The observed energy levels for the 0_3^+, 0_4^+, and 2_2^+ states in Ref.[3)], and the 2_2^+[5)] and 4_2^+[6)] states are denoted by black circles and black squares, respectively. The calculated energy levels for the five states are denoted by red diamonds.

In Fig. 1, the calculated energy levels are plotted as a function of $J(J+1)$, together with the experimental data. We can observe that the 0_2^+, 2_2^+, and 4_2^+ states roughly follow a $J(J+1)$ trajectory both in theory and experiment, which gives a support to the rotational picture. In fact, we found the very strong $E2$ transitions inside the Hoyle band $B(E2; 4_2^+ \to 2_2^+) = 591$ e^2fm^4 and $B(E2; 2_2^+ \to 0_2^+) = 295$ e^2fm^4.

On the other hand, the $J^\pi = 0^+$ band head in experiment seems to be fragmented into the Hoyle state and the 0_3^+ state, and the calculated levels also have a similar tendency concerning the $B(E2)$ transition from the 2_2^+ state, the Hoyle state being located slightly below and the 0_3^+ state slightly above the $J(J+1)$ line. Accordingly, the transition between the 2_2^+ and 0_3^+ states is also very strong $B(E2; 2_2^+ \to 0_3^+) = 104$ e^2fm^4.

This suggests that the Hoyle band, especially in what concerns the 0^+ band-head state, cannot be considered a simple rotational band. This results from the fact that the 3α condensate structure in the Hoyle state is not the same as the usual ^{8}Be$(0^+) + \alpha$ rotation, in which the remaining α cluster orbits outside the ^{8}Be core. Namely, in the Hoyle state, the remaining α cluster also orbits inside the ^{8}Be core, and independent 3α-cluster motion in an identical $0S$-orbit is realized. Consequently, the Hoyle state gains extra binding energy, and hence its energy position is considered to be pushed below the $J(J+1)$ line, as shown in Fig. 1. The same effect is also argued to occur in the study of ^{16}O[8,9)], in which the 4α condensate is identified as a "complete condensate" and the ^{12}C$(0_2^+) + \alpha$ state as a "local condensate". Because of the existence of the "complete condensate", a higher 0^+ excited state, which is shown to have a prominent ^{8}Be$(0^+) + \alpha$ structure[7,10)] with the remaining α cluster orbiting outside the ^{8}Be core, appears as a higher nodal state, the 0_3^+ state excited from the Hoyle state with a very strong monopole transition strength calculated to be $M(E0; 0_2^+ \to 0_3^+) = 35$ fm^2.

References

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