Excited states above the Hoyle state

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In ^{12}C, there exists besides the Hoyle state (the second 0^+ state of ^{12}C) a number of other α gas states above the Hoyle state that one can qualify as excited states of the Hoyle state. For a description of those states, it is useful to adopt a generalized THSR wave function[1)], as the so-called THSR wave function[2,3)] is known to be the best to describe the Hoyle state[4)]. The part of the 3α THSR wave function that contains the c.o.m. motion of the α particles contains two Jacobi coordinates $\boldsymbol{\xi}_1$ and $\boldsymbol{\xi}_2$. As a natural extension of the original THSR wave function, it is possible to associate two different width parameters B_1, B_2 with the two Jacobi coordinates. In this case the translationally invariant THSR wave function has the following form:

$$\Psi_{3\alpha}^{\rm thsr} = \mathcal{A}\left[\exp\left(-\frac{4}{3B_1^2}\boldsymbol{\xi}_1^2 - \frac{1}{B_2^2}\boldsymbol{\xi}_2^2\right)\phi_1\phi_2\phi_3\right]. \quad (1)$$

With this type of generalized THSR wave function, one can get a much richer spectrum of ^{12}C. Axial symmetry has been assumed and the four B parameters are taken as Hill-Wheeler coordinates. In Fig. 1, the calculated energy spectrum is shown. One can see that besides the ground state band, there are many J^π states obtained above the Hoyle state. All these states turn out to have large rms radii (3.7 ∼ 4.7 fm), and therefore can be considered as excitations of the Hoyle state. The Hoyle state can thus be considered as the "ground state" of a new class of excited states in ^{12}C. In particular, the nature of the series of states $(0_2^+, 2_2^+, 4_2^+)$ and the 0_3^+ and 0_4^+ states have recently been widely discussed from the experimental side[5–9)].

In Fig. 1, the $E2$ transition strengths between J and $J \pm 2$ states and monopole transitions between 0^+ states are shown with corresponding arrows. We note the very strong $E2$ transitions inside the Hoyle band, $B(E2; 4_2^+ \to 2_2^+) = 591$ e^{2}fm^4 and $B(E2; 2_2^+ \to 0_2^+) = 295$ e^{2}fm^4. The transition between the 2_2^+ and 0_3^+ states is also very large, $B(E2; 2_2^+ \to 0_3^+) = 104$ e^{2}fm^4. There have been attempts to interpret the Hoyle band as a rotational band of a spinning triangle as this was successfully done for the ground state band[10)]. However, the situation may not be as straightforward as it seems[11)]. Since the two transitions $2_2^+ \to 0_2^+$ and $2_2^+ \to 0_3^+$ are of similar magnitude, no clear band head can be identified. Whether they can be qualified as members of a rotational band or of a vibrational band or a mixture of both is an open question. One should also realize that the 0_3^+ state is strongly excited from the Hoyle state by monopole transition whose strength is obtained from the extended THSR calculation to be $M(E0; 0_3^+ \to 0_2^+) = 35$ fm^2. Therefore, the 0_3^+ state seems to be a state where one α particle has been lifted out of the condensate to the next higher S level with a node. This is confirmed by the S^2 factor, which is calculted to be close to unity for the ^{12}C$(0_1^+)+\alpha(S)$ channel. We can also conclude that the 2_3^+ and 4_3^+ states, together with the 0_3^+ state, form the higher nodal rotational band, from the Reduced Width Amplitude analysis. On the other hand, the 0_4^+, 2_4^+ and 4_4^+ states all have the largest contribution from the ^{8}Be$(2^+)+\alpha(D)$ channel, indicating that these states are built out of an α particle orbiting in a D-wave around a (correlated) two α pair, also in a relative $0D$ state.

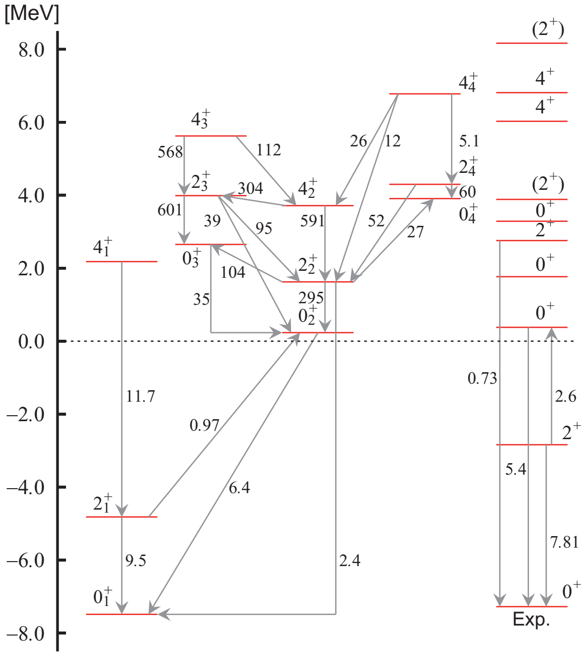

Fig. 1. Spectrum of ^{12}C obtained from the extended THSR approach in comparison with experiment.

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