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Cluster and molecular structures observed in reactions of light nuclei

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Abstract. The experimental evidence for existence of nuclear molecular structures has been reviewed, starting with the simplest two-centre symmetric systems (^{9}Be and A=10 nuclei), then discussing the possibility of three-centre molecular states in carbon isotopes ^{13,14}C and finally giving experimental results for asymmetric cluster and molecular structures in oxygen isotopes $^{17-20}$O.

1. Introduction

The ^{8}Be nucleus in its three lowest lying states is a classical case of a clusterised system [1, 2] - its properties are completely consistent with configuration of two touching α-particles. Such a deformed structure has a simple experimental signature, *i.e.* a rotational band given in Fig. 1. ^{9}Be, with an additional neutron, also has a two-centre structure, with the neutron resembling the behaviour of the valence electrons in molecular physics. Two rotational bands (also given in Fig. 1) have been experimentally identified - one (K=3/2$^-$, based on the ground state) can be connected to a configuration in which the valence neutron is filling the molecular π-orbit, while the other (K=1/2$^+$, based on the state at E_x= 1.68 MeV) resembles the molecular configuration with the extra neutron in the molecular σ-orbit. As seen in Fig. 1, the K=1/2$^+$ band shows a "staggering" behaviour of the excitation energies, which is characteristic of the Coriolis decoupling.

The ^{9}Be nucleus thus seems to be a perfect example of a *nuclear molecule*, a two centre system which is given an extra binding through exchange of a valence particle (neutron). Several open questions remain to be answered to establish this picture - the most important one definitely being a clear identification of the K=1/2$^+$ band-head in the analog nucleus, ^{9}B. A number of experiments has recently been performed in that direction [3, 4, 5], so the final theoretical test of the consistency of molecular picture is to be expected soon. Another important unresolved problem is the question of the 9/2$^-$ member of the ground state rotational band - there is a long debate (see *e.g.* [6]) if the state seen in several experiments at $E_x\approx$ 11.3 MeV was indeed the missing member of the K=3/2$^-$ band.

2. Spectroscopy of A=10 nuclei

With the molecular structure of ^{9}Be almost established, the next step is an addition of further (valence) nucleon and systematic study of the A=10 nuclei. The best studied nucleus of the A=10 triplet is ^{10}Be - the rotational band associated with the α+α+n+n molecular structure

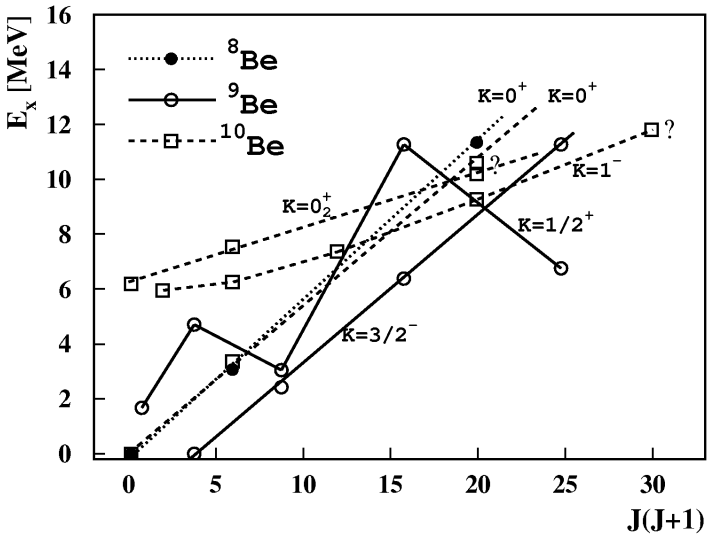

Figure 1. Rotational bands in ^{8}Be (full circles), ^{9}Be (open circles) and ^{10}Be (open squares).

has been clearly identified after a series of experiments with both stable and radioactive beams [7, 8, 9, 10, 11]. Three members of the band have been found: 0^+ at E_x= 6.18 MeV, 2^+ at E_x= 7.54 MeV and 4^+ at E_x= 10.15 MeV (given, together with the g.s. band in Fig. 1) - the deformation of the states seems to be one of the highest among all known states of all nuclei (and much larger than the deformation of the classic cluster example, ground state of ^{8}Be). This result is supported with a number of theoretical papers, *e.g.* [12, 13, 14], and it now seems to be well established.

A number of questions remain to be answered regarding the A=10 nuclei spectroscopy. First of all, although *all* experimentally seen states of ^{10}Be has been given a consistent theoretical explanation, theory predicts a number of states not yet seen in the experiment. Further experiments are needed to look for higher members of the molecular and g.s. rotational band [15], for states of the "atomic" ^{6}He+α character [16], for states with the α+t+t structure [17], and finally for states with the α+α+dineutron structure with an α-halo configuration [18].

Essential next step in establishing molecular picture as the important one for light nuclei would be the identification of states in ^{10}B and ^{10}C that are analog to the above mentioned members of the ^{10}Be molecular rotational band. Some experimental results in that direction have recently been published [19, 20, 21, 22, 23] and will be given in the following, but a clear picture is yet to be found.

For ^{10}B, results are obtained for different decay modes of the excited states, including proton, deuteron and α-particle emission. The α-decay is particularly interesting, when it leads to the excited states of ^{6}Li, especially the second one (0^+ T=1 at E_x= 3.56 MeV, denoted as ^{6}Li**), which is an analogue to the ^{6}He ground state. The ^{10}B states analogue to the two lowest members of the ^{10}Be molecular band are for long time known to be the ones at E_x= 7.56 and 8.89 MeV. The position of the 4^+ state is crucial for a complete understanding of the molecular configurations in A=10 nuclei, so several experiments have been performed to identify it. Results from the ^{11}B(^{3}He,^{6}Li** α)^{4}He measurements [19, 23] suggest that the 4^+ state is at $E_x\approx$ 11.5 MeV. It is clear that further work (*i.e.* clear spin and parity assignments) is definitely needed, especially because the analogue of the 9.56 MeV 2^+ state in ^{10}Be is also expected in this energy region (and the observed state at 11.5 MeV may actually be connected to it). The 9.56 MeV state in ^{10}Be (and its analogs in ^{10}B and ^{10}C) is interesting by itself, because that is the only

^{10}Be state with significant and comparable decay strengths for both ^{9}Be+n and ^{6}He+α channels [7, 10], which makes it rather important for decay properties of high-lying cluster states in ^{11}Be [24, 25].

The experimental data for ^{10}C [20, 21] is still incomplete; nevertheless, good arguments [26] point to existence of the 0^+ state at E_x= 5.29 MeV, and 2^+ state at E_x= 6.57 MeV, both being relatively narrow and having the α+^{6}Be cluster structure. This suggestion is consistent with recent analysis within the shell-model picture [27, 28], but has to be checked in further experiments; our preliminary analysis of the ^{7}Be+^{6}Li measurement seems to confirm it, too. Crucial point is again the identification of the 4^+ member of the band, the analogue of the 10.15 MeV state in ^{10}Be.

The final recognition of the analogue states in ^{10}Be, ^{10}B and ^{10}C will allow direct insight in their structure by comparison of Coulomb effects. This will not at all be a trivial task, as witnessed by the fact that $B(E2)$ values measured for the $2^+_1 \rightarrow 0^+_1$ transition for the three isobars [29, 30] fail to have a simple interpretation and to agree with theory. Nevertheless, such result will definitely provide stringent tests for both *ab initio* and cluster calculations.

For systems with one nucleon more (*i.e.* the A=11 nuclei), measurements of the ^{4}He(^{7}Be,α)^{7}Be and ^{4}He(^{7}Be,p)^{10}B reactions [31] have been recently performed. A comparison of that experimental data with the one from the ^{7}Li+α resonant elastic scattering [32], reveals states of significant alpha partial widths in ^{11}B and ^{11}C, making them good candidates for being members of the deformed cluster rotational bands.

3. Clustering in ^{13}C and ^{14}C

Having in mind the three alpha-particle structure of the Hoyle state in ^{12}C, one may wonder what would happen when extra neutrons are added. Initial suggestion [33] of very deformed prolate structure in ^{13}C stabilised by valence neutron, seems to be too simple - subsequent measurements [34, 35, 36] have shown that some of the proposed members in the corresponding rotational band have properties that does not fit the suggested systematics. Further experimental work is needed to clarify the issue - in particular, one should try to identify ^{13}C states decaying to the Hoyle state by neutron emission. Equivalent study has been performed for the ^{13}N nucleus [37] and several states were found to have a significant branching ratio for decay by proton emission to the Hoyle state. Fully consistent picture of ^{13}C structure at E_x>10 MeV, and relation to theoretical predicted states in that energy region [38, 39], is yet to be found.

The situation seems to be a bit better for ^{14}C, where both oblate and prolate states were identified [40] starting with the 0^+ states at E_x= 6.59 and 9.75 MeV, respectively. Details of the proposed rotational bands yet has to be checked by measuring sequential decay reactions (*e.g.* [41]) or ^{10}Be+α resonant elastic scattering [42]. Theoretical interpretation in terms of three-centre α+α+α+n+n molecular structure and / or ^{10}Be+α cluster structure is also being built [43, 44].

A rather detailed experimental spectroscopy of states in ^{16}C [45] and ^{17}C [46] has been performed recently up to excitation energies of ≈16 MeV, with no clear signs of cluster and molecular states; further work is to be expected because calculations predict [47] that ^{16}C (at high excitation energies) should have the clearest signature of linear three-centre molecular structure stabilised by valence neutrons.

4. Cluster and molecular states of oxygen isotopes

Clustering in excited states of ^{16}O (starting already with the first excited state at E_x= 6.05 MeV) is another historical example - the rotational bands of both positive and negative parity states have been identified [48] long time ago and interpreted as parity splitting doublet due to the asymmetric ^{12}C+α cluster structure [49]. Again, one may wonder what happens when

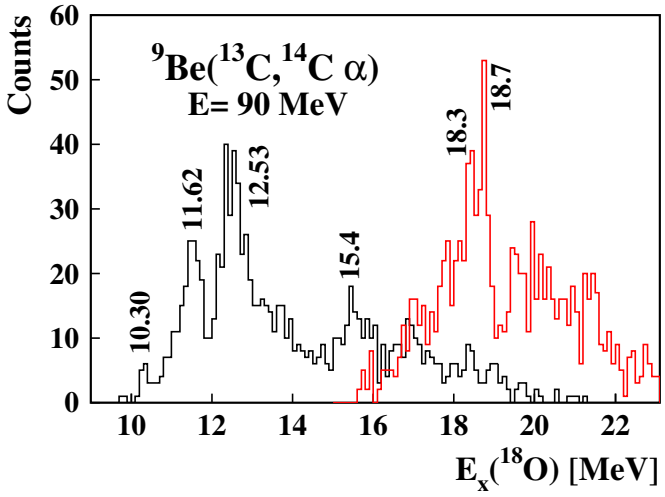

Figure 2. ^{18}O excitation energy spectrum reconstructed from the the $^{14}C_{g.s.}+\alpha$ coincidences. Two shown lines correspond to different combinations of detectors.

extra neutrons are added to such structure, and that question has been discussed in a number of recent papers [50, 51, 52, 53] for isotopes $^{17-20}$O.

Although with many unclear details, it seems that several cluster and molecular rotational bands can be found in these oxygen isotopes, compared in Table 1 (another classical example, the inversion doublet in ^{20}Ne, has been added for comparison).

nucleus	band-head	$\pi=+$ $\hbar^2/2\theta$ (keV)	$\pi=-$ $\hbar^2/2\theta$ (keV)	energy splitting (MeV)
^{16}O	0^+_2	230	210	2.9
^{18}O	0^+_2	200	200	4.0
^{18}O	0^+_4	110	110	2.4
^{19}O	$3/2^+_2$	200	200	3.8
^{20}O	0^+_2	160	150	5.2
^{20}O	0^+_4	90	100	1.7
^{20}Ne	0^+_1	170	190	4.8

Table 1. Cluster and molecular rotational bands in some oxygen isotopes. The slope parameters ($\hbar^2/2\theta$) are given for both positive and negative parity bands of a given structure. Last column gives the energy splitting ($2\cdot\delta_E$) of the parity doublets.

From Table 1 it is evident that in both ^{18}O and ^{20}O the bands at higher excitation energies have also higher moments of inertia (*i.e.* lower slope parameters) and smaller energy splittings. For lighter well-studied systems, ^{10}Be [54] and ^{12}Be [55, 56], it was theoretically suggested that their higher-lying bands have more "ionic" character, while the lower-lying bands show molecular nature (*i.e.* with shared neutrons between two clusters), because the delocalisation of neutrons reduces significantly the excitation energy. Similar claims were made for ^{22}Ne [57] and finally for ^{20}O [58], where the lower-lying band was suggested to have mixed ^{14}C+^{6}He and ^{12}C+4n+α configurations, while the higher-lying one is suggested to correspond to the ^{16}C+α "ionic" structure.

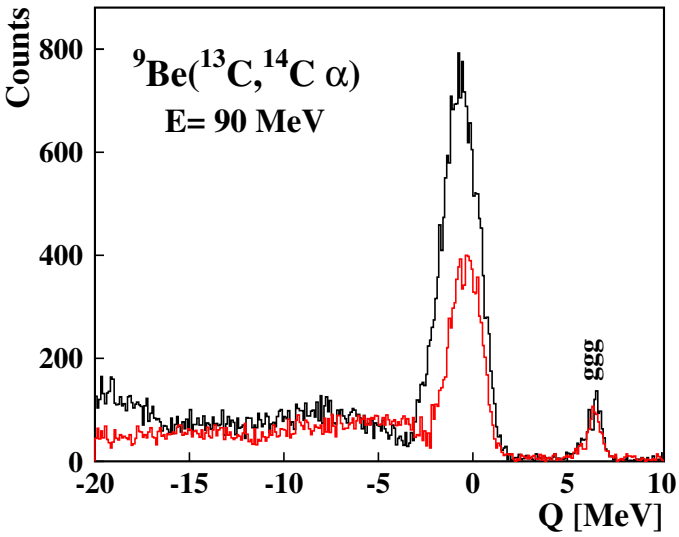

Figure 3. Q-value spectrum for the ^{14}C+α coincidences. Two shown lines correspond to different combinations of detectors. Gating on the peak at Q= 6.60 MeV gives the spectrum at Fig. 2.

Studies of decay modes of the observed states, (like the one performed for ^{17}O in Ref. [50] and for ^{18}O in Ref. [59]), should be done to give clear picture on the structure of high-lying states in oxygen isotopes. Figure 2 gives one such spectrum (previously unpublished). It is obtained measuring the ^{9}Be(^{13}C,^{14}C α) reaction with the E= 90 MeV beam. The details of the experimental set-up can be found in Ref. [50], which also discusses the results obtained in the same measurement for the ^{17}O nucleus.

Though statistics is rather low (especially when compared to the similar ^{17}O spectrum [50]), several peaks are clearly seen in the ^{18}O excitation energy spectrum reconstructed from the the ^{14}C$_{g.s.}$+α coincidences. Some of these peaks correspond to the states previously strongly populated in the ^{12}C(^{18}O,^{14}Cα) reaction at E= 82 MeV [60, 61], and clearly populated in the ^{14}C(^{6}Li,d) reaction at 34 MeV [62, 63] They are also strong in the ^{14}C(^{18}O,^{14}Cα)^{14}C reaction [59] and already there suggested to be members of the deformed cluster rotational band. The state at $E_x\approx$ 10.30 MeV is also the strongest state seen in the ^{12}C(^{7}Li,p) reactions, and as such suggested to have 6p-4h configuration [64, 65].

Similar discussion can be made for every state seen in Fig. 2; obviously the studied sequential decay reaction selectively populates the states with large alpha-strengths. Those states were, along with others, grouped into rotational bands in Ref. [51]. The measurement of the ^{14}C+α coincidences actually showed two strong peaks in the Q-value spectrum (Fig. 3). The peak marked with "ggg" and corresponding to the ^{14}C(g.s.)+2α exit channel is indeed clearly seen (Q= 6.60 MeV). There is another strong and broad structure at $Q\approx -0.5$ MeV; it corresponds to the ^{14}C nucleus left in its excited (unresolved) states at E_x= 6-8 MeV. Gating on the latter, the corresponding ^{18}O excitation energy spectrum shows only one strong (and broad) peak, at $E_x\approx$ 18.5 MeV.

Nevertheless, a measurement with better resolution is needed to resolve the ^{14}C states in the broad bump at $Q\approx -0.5$ MeV in Fig. 3 and thus study a decay of the ^{18}O states into different ^{14}C states (some of which have well developed cluster structure, like the 0^+ state at 6.59 MeV). A better statistics is also needed, as well as the detector set-up which will allow the clear identification of the particles, thus enabling a study of other decay channels, like ^{6}He emission

(to be expected for states with molecular character). We have performed such a measurement recently at the Orsay accelerator facility, so new experimental results for ^{18}O and other oxygen isotopes are to be expected soon.

5. Summary

Recent experimental results regarding cluster and molecular states in the A=10 nuclei, ^{13,14}C and $^{17-20}$O, have been reviewed and corresponding open problems listed. The A=10 isobars are suggested to provide the best test of consistency of molecular picture, in which two clusters are additionally bound through exchange of valence nucleons. The possible existence of three-centre structures in ^{13,14}C and asymmetric configurations in $^{17-20}$O is also discussed, and current knowledge on them reviewed. The Zagreb group has recently performed a number of experiments studying all the three discussed topics, so new results are to be expected soon.

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