Journal of Physics: Conference Series **436** (2013) 012014 doi:10.1088/1742-6596/436/1/012014

# Clustering effects in reactions induced by light nuclei

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**Abstract.** Since the pioneering discovery of $^{12}$C+$^{12}$C molecular resonances half a century ago, a great deal of research work has been undertaken in the $\alpha$-clustering study. Our knowledge on the physics of nuclear molecules has increased considerably and nuclear clustering remained one of the most fruitful domains of nuclear physics, facing some of the greatest challenges and opportunities in the years ahead. In this work, the occurrence of "exotic" shapes in light $N$=$Z$ $\alpha$-like nuclei is investigated. Various approaches of the superdeformed and hyperdeformed bands associated with quasimolecular resonant structures are presented. Clustering aspects are also briefly discussed for light nuclei with neutron excess trough very recent results on neutron-rich Oxygen isotopes.

## 1. Introduction

The search for resonant structures in the excitation functions for various combinations of light $\alpha$-cluster ($N$=$Z$) nuclei in the energy regime from the Coulomb barrier up to regions with excitation energies of $E_x$=20−50 MeV remains a subject of contemporary debate [1, 2]. These resonances have been interpreted in terms of nuclear molecules [1]. The question of how quasimolecular resonances may reflect continuous transitions from scattering states in the ion-ion potential to true cluster states in the compound systems is still unresolved [1, 2]. In many cases, these resonant structures have been associated with strongly-deformed shapes and with alpha-clustering phenomena [3, 4], predicted from the Nilsson-Strutinsky approach, the cranked $\alpha$-cluster model [3], or other mean-field calculations [4, 5]. In light $\alpha$-like nuclei clustering is observed as a general phenomenon at high excitation energy close to the $\alpha$-decay thresholds [3, 6]. This exotic behavior has been perfectly illustrated by the famous "Ikeda"-diagram for $N$=$Z$ nuclei in 1968 [7], which has been recently extended by von Oertzen [8] for neutron-rich nuclei, as shown in the left panel of Fig.1. Clustering is a general phenomenon [9] not only observed in light neutron-rich nuclei [10], but also in halo nuclei such as $^{11}$Li [11] or $^{14}$Be, for instance [12]. The problem of cluster formation has also been treated extensively for very heavy systems by R.G. Gupta [5] and by Zagrebaev and W. Greiner [13] where giant molecules and the collinear ternary fission may exist [14].

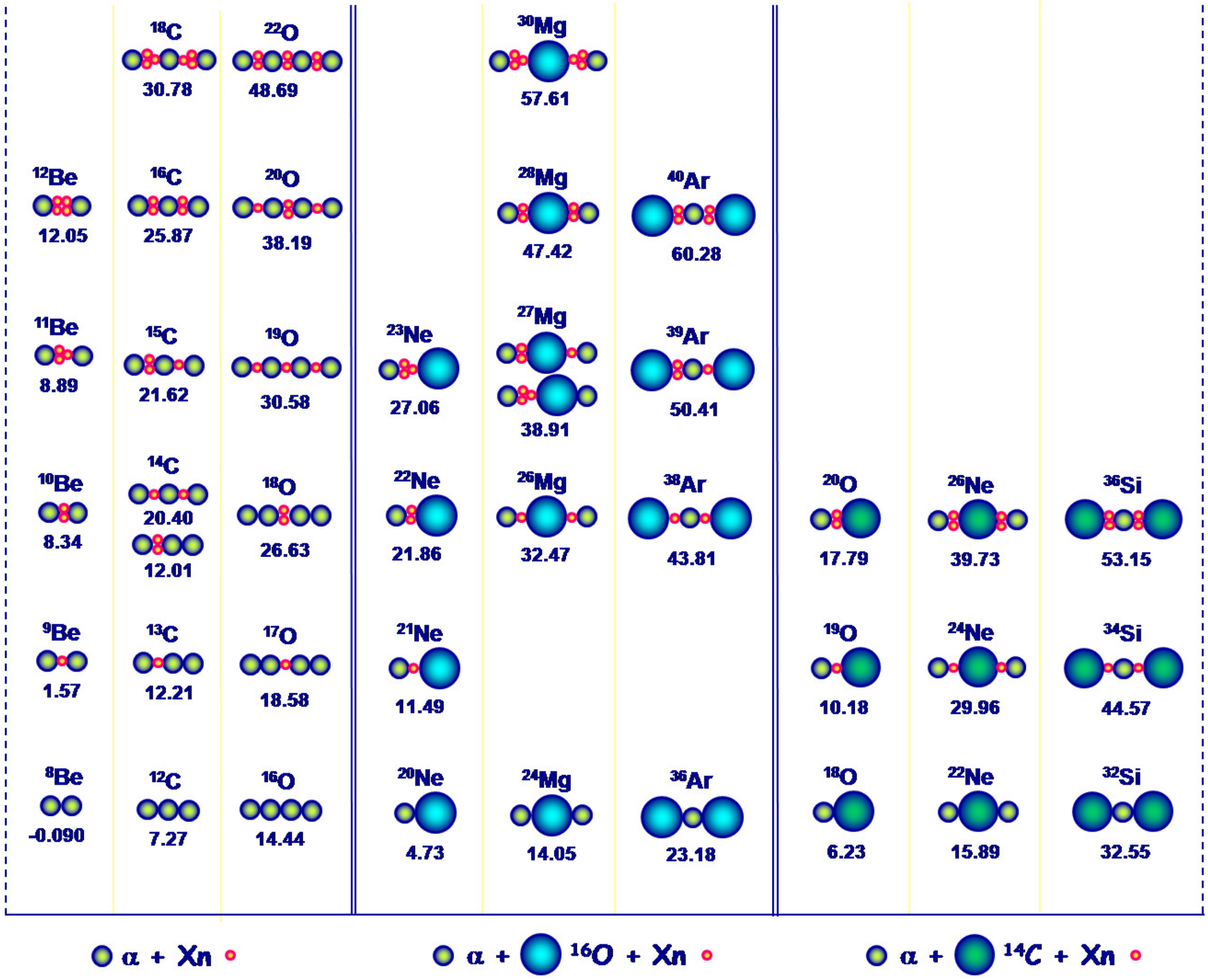


**Figure 1.** Schematic illustration of the structures of molecular shape isomers in light neutron-rich isotopes of nuclei consisting of $\alpha$-particles, $^{16}$O- and $^{14}$C-clusters plus some covalently bound neutrons (Xn means X neutrons) [9]. The so called "Extended Ikeda-Diagram" [8] with $\alpha$-particles (left panel) and $^{16}$O-cores (middle panel) can be generalized to $^{14}$C-cluster cores (right panel). The lowest line of each configuration corresponds to parts of the original Ikeda diagram [7]. However, because of its deformation, the $^{12}$C nucleus is not included, as it was earlier [7]. Threshold energies (in MeV) are given for the relevant decompositions.

## 2. Alpha clustering, deformations and alpha condensates

The real link between superdeformation (SD), nuclear molecules and alpha clustering [4, 15, 16, 17] is of particular interest, since nuclear shapes with major-to-minor axis ratios of 2:1 have the typical ellipsoidal elongation for light nuclei (with quadrupole deformation parameter $\beta_2 \approx 0.6$). Furthermore, the structure of possible octupole-unstable 3:1 nuclear shapes (hyperdeformation (HD) with $\beta_2 \approx 1.0$) has also been discussed for actinide nuclei [17] in terms of clustering phenomena. Typical examples for possible relationship between quasimolecular bands and extremely deformed (SD/HD) shapes have been widely discussed in the literature for $A = 20-60$ $\alpha$-conjugate $N{=}Z$ nuclei, such as $^{28}$Si [18, 19, 20, 21, 22], $^{32}$S [4, 23, 24, 25, 19], $^{36}$Ar [17, 26, 27, 28, 29], $^{40}$Ca [30, 31, 32, 33], $^{44}$Ti [4, 34, 35], $^{48}$Cr [36] and $^{56}$Ni [37, 38, 39, 40].

In fact, highly deformed shapes and SD rotational bands have been discovered in several light $\alpha$-conjugate ($N{=}Z$) nuclei, such as $^{36}$Ar and $^{40}$Ca by using $\gamma$-ray spectroscopy techniques [27, 30]. In particular, the extremely deformed rotational bands in $^{36}$Ar [27] (shown as crosses in Fig. 2) might be comparable in shape to the quasimolecular bands observed in both $^{12}$C+$^{24}$Mg [28, 41, 42, 43] (shown as open triangles in Fig. 2) and $^{16}$O+$^{20}$Ne [44, 45] (shown as full rectangles) reactions. Ternary clusterizations are also predicted theoretically, but were not found experimentally in $^{36}$Ar so far [29]. On the other hand, ternary fission of $^{56}$Ni – related to its hyperdeformed shapes – was identified from out-of-plane angular correlations measured in the $^{32}$S+$^{24}$Mg reaction with the Binary Reaction Spectrometer (BRS) at the Vivitron Tandem facility of the IPHC, Strasbourg [46]. This finding [46] is not limited to light $N{=}Z$ compound nuclei, true ternary fission [13, 14, 48] can also occur for very heavy [14, 48] and superheavy [47] nuclei.

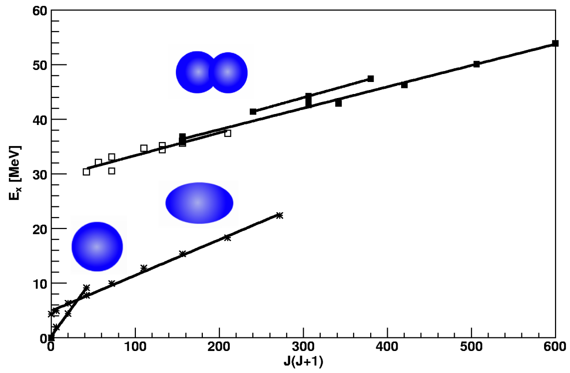


**Figure 2.** Rotational bands and deformed shapes in $^{36}$Ar. Excitation energies of the ground state (spherical shape) and SD (ellipsoidal shape) bands [27], respectively, and the energies of HD (dinuclear shape) band from the quasimolecular resonances observed in the $^{12}$C+$^{24}$Mg (open rectangles) [28, 41, 42, 43] and $^{16}$O+$^{20}$Ne (full rectangles) [44, 45] reactions are plotted as a function of J(J+1). This figure has been adapted from Refs. [26, 28].

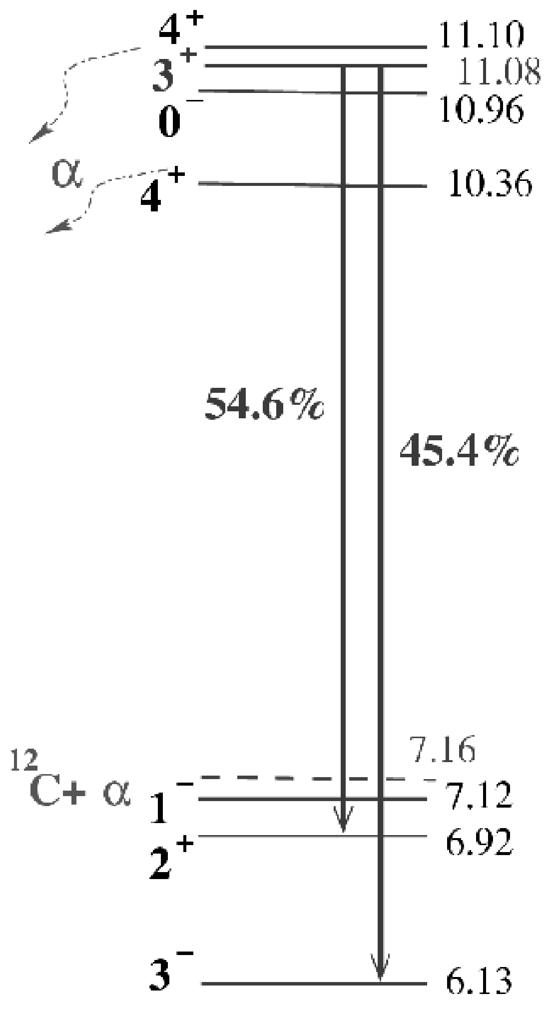


**Figure 3.** New partial (high-energy) level scheme of $^{16}$O corresponding to $\gamma$-ray transitions observed in the $^{12}$C($^{24}$Mg,$^{20}$Ne)$^{16}$O$^*$ $\alpha$-transfer reactions. This figure has been adapted from Ref. [29].

There is a renewed interest in the spectroscopy of the $^{16}$O nucleus at high excitation energy [29]. Exclusive data were collected on $^{16}$O in the inverse kinematics reaction $^{24}$Mg+$^{12}$C studied at $E_{lab}(^{24}Mg)$ = 130 MeV with the BRS in coincidence with the EUROBALL IV installed at the VIVITRON facility [29]. From the $\alpha$-transfer reactions (both direct transfer and deep-inelastic orbiting collisions [49]), new information has been deduced on branching ratios of the decay of the $3^+$ state of $^{16}$O at 11.085 MeV ± 3 keV. The high-energy level scheme of $^{16}$O shown in Fig. 3 indicates that this state does not $\alpha$-decay because of its non-natural parity (in contrast to the two neighbouring $4^+$ states at 10.36 MeV and 11.10 MeV), but it $\gamma$ decays to the $2^+$ state at 6.92 MeV (54.6 ± 2 %) and to the $3^-$ state at 6.13 MeV (45.4%). By considering all the four possible transition types of the decay of the $3^+$ state (*i.e.* E1 and M2 for the $3^+ \rightarrow 3^-$ transition and, M1 and E2 for the $3^+ \rightarrow 2^+$ transition), our calculations yield the conclusion that $\Gamma_{3^+} < 0.23$ eV, a value fifty times lower than known previously, which is an important result for the well studied $^{16}$O nucleus [29]. Clustering effects in the light neutron-rich oxygen isotopes $^{17,18,19,20}$O will be discussed in Section 3.

In the study of the Bose-Einstein Condensation (BEC) the $\alpha$-particle states in light $N{=}Z$ nuclei [50, 51, 52], are of great importance. At present, the search for an experimental signature of BEC in $^{16}$O is of highest priority. A state with the structure of the "Hoyle" state [53] in $^{12}$C coupled to an $\alpha$ particle is predicted in $^{16}$O at about 15.1 MeV (the $0_6^+$ state), the energy of which is $\approx$ 700 keV above the 4$\alpha$-particle breakup threshold [54]. However, any state in $^{16}$O equivalent to the so-called "Hoyle" state [53] in $^{12}$C is most certainly going to decay by particle emission with very small, probably un-measurable, $\gamma$-decay branches, thus, very efficient particle-detection techniques will have to be used in the near future to search for them. BEC states are expected to decay by alpha emission to the "Hoyle" state and could be found among the resonances in $\alpha$-particle inelastic scattering on $^{12}$C decaying to that state (an early attempt to excite these states by $\alpha$ inelastic scattering was presented in Ref. [55]), or could be observed in an $\alpha$-particle transfer channel leading to the $^{8}$Be–$^{8}$Be final state. Another possibility might be to perform Coulomb excitation measurements with intense $^{16}$O beams at intermediate energies.

## 3. Clustering in light neutron-rich nuclei

As discussed previously, clustering is a general phenomenon observed also in nuclei with extra neutrons as it is presented in an extended "Ikeda"-diagram [7] proposed by von Oertzen [8] (see the left panel of Fig. 1). With additional neutrons, specific molecular structures appear with binding effects based on covalent molecular neutron orbitals. In these diagrams $\alpha$-clusters and $^{16}$O-clusters (as shown by the middle panel of the diagram of Fig. 1) are the main ingredients. Actually, the $^{14}$C nucleus may play similar role in clusterization as the $^{16}$O one since it has similar properties as a cluster: i) it has closed neutron p-shells, ii) first excited states are well above $E^*$ = 6 MeV, and iii) it has high binding energies for $\alpha$-particles.

A general picture of clustering and molecular configurations in light nuclei can be drawn from a detailed investigation of the light oxygen isotopes with A $\geq$ 17. Here we will only present recent results on the even-even oxygen isotopes: $^{18}$O [56] and $^{20}$O [57]. But very striking cluster states have also been found in odd-even oxygen isotopes such as: $^{17}$O [58] and $^{19}$O [59].

Fig. 4 gives an overview of all bands in $^{18}$O as a plot of excitation energies as a function of J(J+1) together with their respective moments of inertia. In the assignment of the bands both the dependence of excitation energies on J(J+1) and the dependence of measured cross sections on 2J+1 [56] were considered. Slope parameters obtained in a linear fit to the excitation energies [56] indicate the moment of inertia of the rotational bands given in Fig. 4. The intrinsic structure of the cluster bands is reflection asymmetric, the parity projection gives an energy splitting between the partner bands. The assignment of the experimental molecular bands are supported by either generator-coordinate-method [60] or Antisymmetrized Molecular Dynamics (AMD) calculations [61].

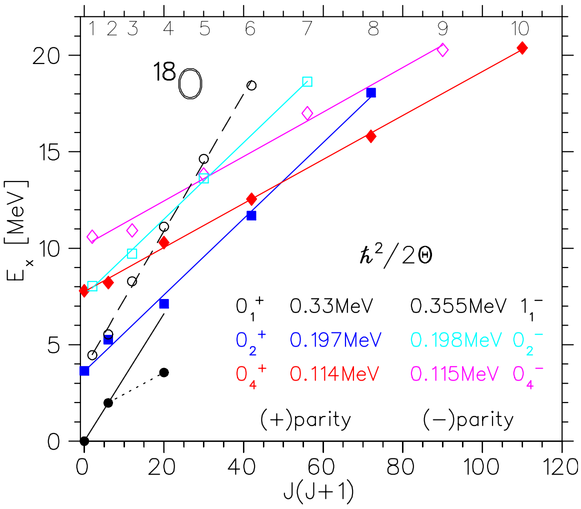


**Figure 4.** Overview of six rotational band structures observed in $^{18}$O. Excitation energy systematics for the members of the rotational bands forming inversion doublets with K=0 are plotted as a function of J(J+1). The curves are drawn to guide the eye for the slopes. The indicated slope parameters contain information on the moments of inertia. Square symbols correspond to cluster bands, whereas diamonds symbols correspond to molecular bands. This figure is adapted from [56].

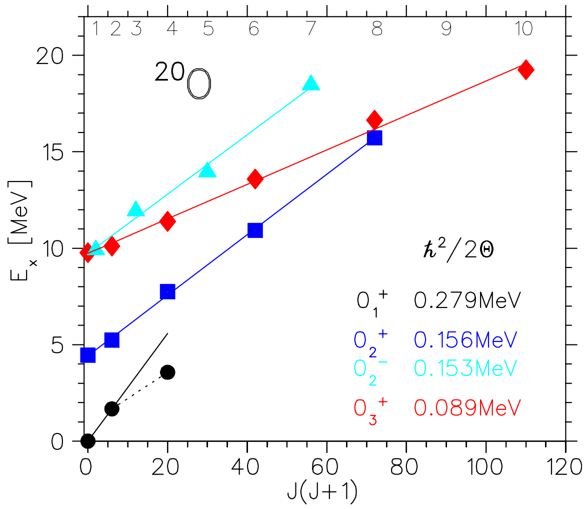


**Figure 5.** Overview of four rotational band structures observed in $^{20}$O. Excitation energy systematics for the members of the rotational bands forming inversion doublets with K=0 are plotted as a function of J(J+1). The curves are drawn to guide the eye for the slopes. The indicated slope parameters contain information on the moments of inertia. Square and triangle symbols correspond to cluster bands, whereas diamonds symbols correspond to molecular bands.This figure is adapted from [57]

We can compare the bands of $^{20}$O [57] shown in Fig. 5 with those of $^{18}$O displayed in Fig. 4. The first doublet (K=$0_2^{\pm}$) has a slightly larger moment of inertia (smaller slope parameter) in $^{20}$O, which is consistent with its interpretation as $^{14}$C–$^{6}$He or $^{16}$C–$^{4}$He molecular structures (they start well below the thresholds of 16.8 MeV and 12.32 MeV, respectively). The second band, for which the negative parity partner is yet to be determined, has a slope parameter slightly smaller than in $^{18}$O. This is consistent with the study of the bands in $^{20}$O by Furutachi et al [61], which clearly establishes parity inversion doublets predicted by AMD calculations for the $^{14}$C–$^{6}$He cluster and $^{14}$C-2n-$\alpha$ molecular structures. The corresponding moments of inertia given in Fig. 4 and Fig. 5 are strongly suggesting large deformations for the cluster structures. We may conclude that the reduction of the moments of inertia of the lowest bands of $^{18,20}$O is consistent with the assumption that the strongly bound $^{14}$C nucleus having equivalent properties to $^{16}$O, has a similar role as $^{16}$O in relevant, less neutron rich nuclei. Therefore, the Ikeda-diagram [7] and the "extended Ikeda-diagram" consisting of $^{16}$O cluster cores with covalently bound neutrons [8] must be further extended to include also the $^{14}$C cluster cores as illustrated in Fig. 1.

## 4. Summary, conclusions and outlook

The connection of $\alpha$-clustering, quasimolecular resonances, orbiting phenomena and extreme deformations (SD, HD, ...) has been discussed in this work by using $\gamma$-ray spectroscopy of coincident binary fragments from either inelastic excitations and direct transfers (with small energy damping and spin transfer) or from orbiting (fully damped) processes [49] in the $^{24}$Mg+$^{12}$C reaction. From a careful analysis of the $^{16}$O+$^{20}$Ne $\alpha$-transfer exit-channel (strongly populated by orbiting) new information has been deduced on branching ratios of the decay of the $3^+$ state of $^{16}$O at 11.089 MeV. This result is encouraging for a complete $\gamma$-ray spectroscopy of the $^{16}$O nucleus at high excitation energy. In addition, we have presented new results on neutron-rich oxygen isotopes displaying very well defined molecular bands in agreement with AMD predictions. Consequently, the extended Ikeda diagram has been further extended for light neutron-rich nuclei by inclusion of the $^{14}$C cluster, similarly to the $^{16}$O one. Of particular interest is the quest for the $4\alpha$ states of $^{16}$O near the $^8$Be+$^8$Be and $^{12}$C+$\alpha$ decay thresholds, which correspond to the so-called "Hoyle" state. The search for extremely elongated configurations (HD) in rapidly rotating medium-mass nuclei, which has been pursued by $\gamma$-ray spectroscopy measurements, will have to be performed in conjunction with charged-particle techniques in the near future since such states are most certainly going to decay by particle emission (see [46, 62, 63]).

## Acknowledgments

We thank the VIVITRON staff and the EUROBALL group of Strasbourg for their excellent support. C.B. would like to acknowledge Christian Caron (Springer) for initiating the new series of three volumes of *Lecture Notes in Physics* dedicated to "Clusters in Nuclei".

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Journal of Physics: Conference Series **436** (2013) 012014 doi:10.1088/1742-6596/436/1/012014

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