CLUSTERS IN LIGHT NUCLEI*

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A great deal of research work has been undertaken in the α-clustering study since the pioneering discovery, half a century ago, of $^{12}C + {}^{12}C$ molecular resonances. Our knowledge in the physics of nuclear molecules has increased considerably and nuclear clustering remains 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 occurence of "exotic" shapes in light $N = Z$ α-like nuclei is investigated. Various approaches of superdeformed and hyperdeformed bands associated with quasimolecular resonant structures are presented. Results on clustering aspects are also discussed for light neutron-rich oxygen isotopes.

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1. Introduction

The observation of resonant structures in the excitation functions for various combinations of light α-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 contiuous 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 phe-

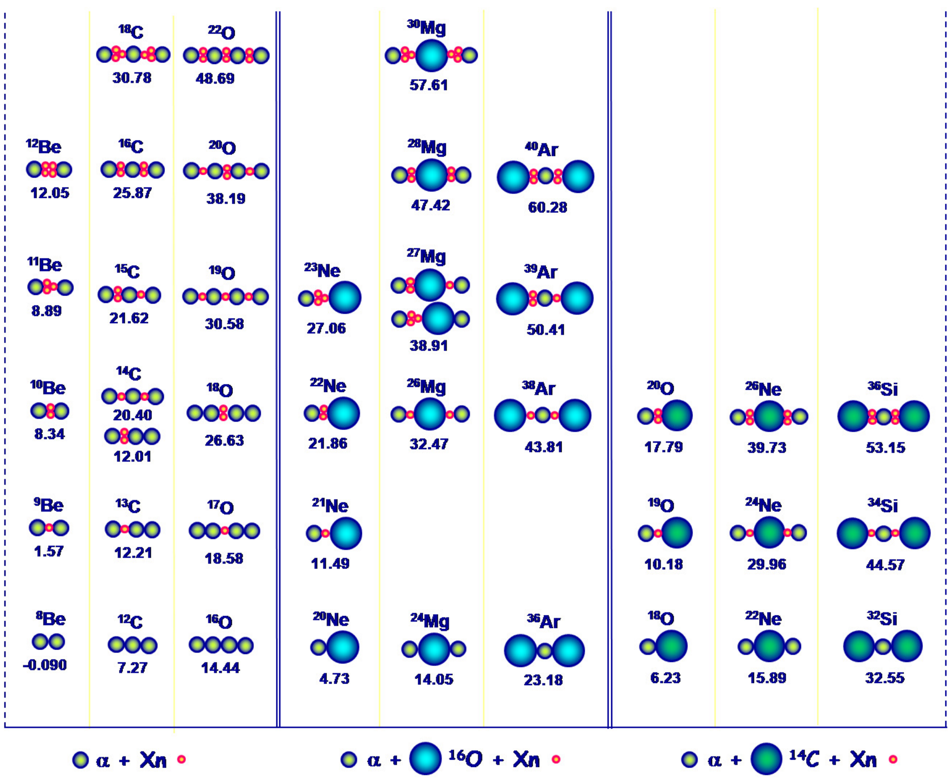

Fig. 1. (Color online) Schematic illustration of the structures of molecular shape isomers in light neutron-rich isotopes of nuclei consisting of α-particles, ^{16}O- and ^{14}C-clusters plus some covalently bound neutrons (Xn means X neutrons). The so-called "Extended Ikeda-Diagram" [8] with α-particles (left panel) and ^{16}O-cores (middle panel) can be generalized to ^{14}C-clusters cores (right panel). Threshold energies (in MeV) are given for the relevant decompositions.

nomena [3,4], predicted from the Nilsson–Strutinsky approach, the cranked α-cluster model [3], or other mean-field calculations [4,5]. In light α-like nuclei clustering is observed as a general phenomenon at high excitation energy close to the α-decay thresholds [3,6]. This exotic behavior has been perfectly well illustrated by the famous "Ikeda"-diagram for $N = Z$ nuclei in 1968 [7] that 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 not only observed in light neutron-rich nuclei [9] but also in halo nuclei such as ^{11}Li [10] or in very heavy systems where giant molecules can exist [11].

2. Alpha clustering, deformations and alpha condensates

The relationship between superdeformation (SD), nuclear molecules and alpha clustering [4, 12, 13, 14] is of particular interest, since nuclear shapes with major-to-minor axis ratios of 2:1 have the typical ellipsoidal elongation (with quadrupole deformation parameter $\beta_2 \approx 0.6$) for light nuclei. Furthermore, the structure of possible octupole-unstable 3:1 nuclear shapes (with $\beta_2 \approx 1.0$) — hyperdeformation (HD) — for actinide nuclei has also been widely discussed [14] in terms of clustering phenomena. Typical examples of a possible link between quasimolecular bands and extremely deformed (SD/HD) shapes have been widely discussed in the literature for light $N = Z$ nuclei, for $A = 20$–60, such as ^{28}Si [15], ^{32}S [4, 16, 17, 18], ^{36}Ar [14, 19, 20, 21, 22], ^{40}Ca [23, 24, 25, 26], ^{44}Ti [4, 27, 28], ^{48}Cr [29] and ^{56}Ni [30, 31, 32, 33].

In fact, highly deformed shapes and SD rotational bands have been recently discovered in several such $N = Z$ nuclei, such as ^{36}Ar and ^{40}Ca by using γ-ray spectroscopy techniques [20, 23]. In particular, the extremely deformed rotational bands in ^{36}Ar [20] (shown as crosses in Fig. 2) might be comparable in shape to the quasimolecular bands in both $^{12}\mathrm{C} + {}^{24}\mathrm{Mg}$ [21, 34, 35, 36] (shown as open triangles in Fig. 2) and $^{16}\mathrm{O} + {}^{20}\mathrm{Ne}$ reactions [37, 38] (shown as full rectangles), and their related ternary clusterizations are also predicted theoretically but were not found experimentally in ^{36}Ar so far [22]. On the other hand, ternary fission related to hyperdeformed shapes of ^{56}Ni was identified from out-of-plane angular correlations measured in the $^{32}\mathrm{S} + {}^{24}\mathrm{Mg}$ reaction with the Binary Reaction spectrometer (BRS) at the VIVITRON Tandem facility of the IPHC Strasbourg [39]. This finding [39] is not limited to light $N = Z$ compound nuclei but true ternary fission [11, 41] can also occur for very heavy [41] and superheavy [40] nuclei.

There is a renewed interest in the spectroscopy of the ^{16}O nucleus at high excitation energy [22]. Exclusive data were collected with the inverse kinematics reaction $^{24}\mathrm{Mg} + {}^{12}\mathrm{C}$ studied at $E_{\mathrm{lab}}(^{24}\mathrm{Mg}) = 130$ MeV with the BRS in coincidence with the EUROBALL IV installed at the VIVITRON facility [22]. From the α-transfer reactions (both direct trans-

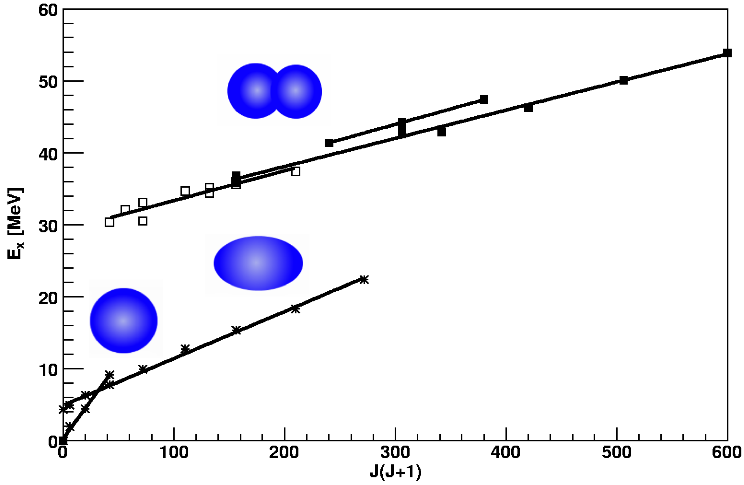

Fig. 2. Rotational bands and deformed shapes in ^{36}Ar. Excitation energies of the g.s. (spherical shape) and SD bands [20] (ellipsoidal shape), respectively, and the energies of HD band from the quasimolecular resonances observed in the ^{12}C + ^{24}Mg (open rectangles) [21, 34, 35, 36] and ^{16}O+^{20}Ne (full rectangles) [37, 38] reactions (dinuclear shape) are plotted as a function of $J(J+1)$. This figure has been adapted from Refs. [19, 21].

fer and deep-inelastic orbiting collisions [42]), 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 indicates in Fig. 3 that this state does not α-decay because of non-natural parity (in contrast to the two neighbouring 4^+ states at 10.36 MeV and 11.10 MeV, respectively), but it γ decays to the 2^+ state at 6.92 MeV ($54.6 \pm 2\%$). By considering all the four possibilities of transitions types of the 3^+ state (*i.e.* E_1 and M_2 for the $3^+ \to 3^-$ transition and, M_1 and E_2 for the $3^+ \to 2^+$ transition), our calculations yield the conclusion that a value for the decay width Γ_γ is fifty times lower than known previously, it means $\Gamma_{3^+} < 0.23$ eV. This result is important as it is the last known γ-decay level for the well studied ^{16}O nucleus [22]. In Sec. 3 we will dicuss clustering effects in the other light neutron-rich oxygen isotopes: ^{17,18,19,20}O.

In the framework of the study of Bose–Einstein Condensation (BEC) the α-particle state [43, 44] in light $N = Z$ nuclei, an experimental signature of BEC in ^{16}O, is at present of highest priority. A state with the structure of "Hoyle" state [45] in ^{12}C coupled with an α particle is predicted to be the 0^+_6 state of ^{16}O at about 15.1 MeV, which energy is just lying (*i.e.* ≈ 700 keV) above the 4α-particle breakup threshold [46]. However, any state in ^{16}O equivalent to the so-called "Hoyle" state [45] in ^{12}C is most

Fig. 3. New partial (high-energy) level scheme of ^{16}O corresponding to γ-ray transitions observed in the ^{12}C(^{24}Mg,^{20}Ne)^{16}O* α-transfer reactions. This figure has been adapted from Ref. [22].

certainly going to decay by particle emission with very small, probably unmeasurable, γ-decay branches. Very efficient particle-detection techniques will have to be used in the near future as such BEC states will be expected to decay by alpha emission to the "Hoyle" state, and could be associated with resonances in α-particle inelastic scattering on ^{12}C leading to that state (an early attempt to excite these states by α inelastic scattering was presented in Ref. [47]), or be observed in α-particle transfer 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 also observed for nuclei with extra neutrons in an extended "Ikeda"-diagram [7] as 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 diagram α-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 has equivalent properties as a cluster, as the ^{16}O nucleus: *(i)* closed neutron p-shells, *(ii)* first excited states well above $E^* = 6$ MeV, and *(iii)* high binding energies for α-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 of the even–even oxygen isotopes: ^{18}O [48] and ^{20}O [49]. But very striking cluster states have also been found in odd–even oxygen isotopes such as: ^{17}O [50] and ^{19}O [51].

Fig. 4 gives an overview of all bands in ^{18}O as a plot of excitation energies in dependence of $J(J+1)$ together with their respective moment of inertia. In the construction of the bands both the excitation energy systematics of the $J(J+1)$ dependence and the measured cross-sections [48] dependence on $(2J+1)$ were used. The experimental molecular bands are supported by either generator-coordinate-method [52] or Antisymmetrized Molecular Dynamics (AMD) calculations [53]. Slope parameters obtained in a linear fit to the excitation energies data [48] 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.

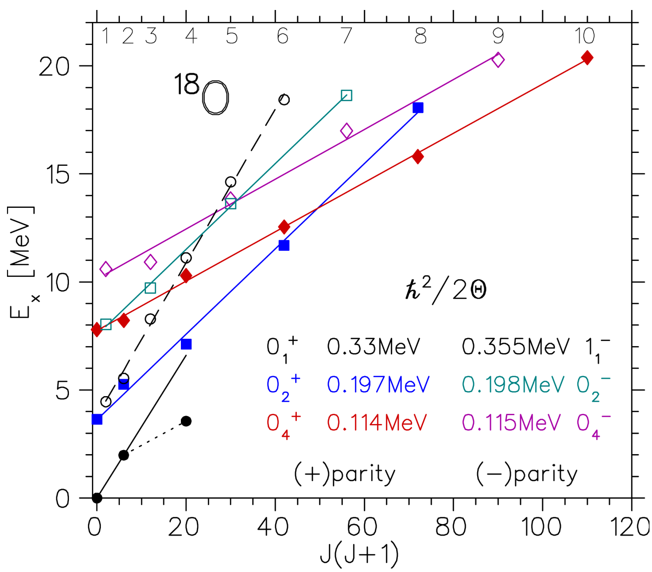

Fig. 4. (Color online) Overview of six rotational band structures observed in ^{18}O. Excitation energy systematics for the members of the rotational bands forming inversion doublets with $K=0$ are plotted as a function of $J(J+1)$. The indicated slope parameters contain information on the moments of inertia. Square symbols correspond to cluster bands, whereas diamonds symbols correspond to molecular bands. This figure is adapted from [48].

For ^{20}O [49], we can compare the bands of Fig. 5 with those of ^{18}O (displayed in Fig. 4). The first doublet ($K = 0_2^{\pm}$) has a moment of inertia which is slightly larger (smaller slope parameter), consistent with the 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 as compared to ^{18}O. This is consistent with the study of bands in ^{20}O by Furutachi *et al.* [53] that clearly establishes parity inversion doublets predicted by AMD calculations for the ^{14}C–^{6}He cluster and ^{14}C–2n–α molecular structures.

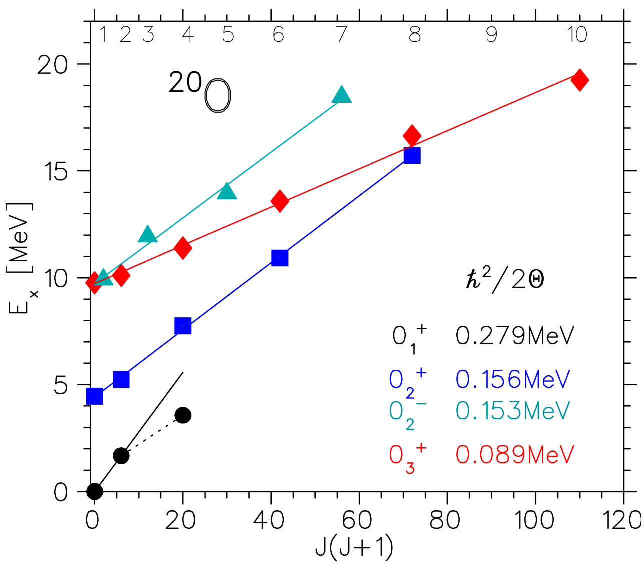

Fig. 5. Overview of four rotational band structures observed in ^{20}O. Excitation energy systematics for the members of the rotational bands forming inversion doublets with $K = 0$ are plotted as a function of $J(J + 1)$. The indicated slope parameters contain information on the moments of inertia. Square and triangle symbols correspond to cluster bands, whereas diamonds symbols correspond to molecular bands. This figure is adapted from [49].

The corresponding momenta of inertia values given in Fig. 4 and Fig. 5 are highly suggesting large deformations of the clusters structures. We may also conclude that the strongly bound ^{14}C nucleus has equivalent properties as an ^{16}O cluster; the reduction of the moment of inertia of the lowest bands of ^{18,20}O is consistent with the argument of ^{14}C being a core as ^{16} in relevant nucli. Therefore, the Ikeda-diagram [7] and the "extended Ikeda-diagram" consisting of ^{16}O clusters cores with covalently bound neutrons [8] must be revised to include also the ^{14}C clusters cores as illustrated by Fig. 1.

4. Summary and conclusions

The connection of α-clustering, quasimolecular resonances, orbiting phenomena and extreme deformations (SD, HD, ...) has been discussed in this work by using γ-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 [42] in the ^{24}Mg + ^{12}C reaction system. From a careful analysis of the ^{16}O + ^{20}Ne α-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 γ-ray spectroscopy of the ^{16}O nucleus at high excitation energy. Of particular interest is the quest for the corresponding 4α states near the ^{8}Be + ^{8}Be and ^{12}C + α decay thresholds. The search for extremely elongated configurations (HD) in rapidly rotating medium-mass nuclei, which has been pursued by γ-ray spectroscopy measurements, will have to be performed in conjunction with charged-particle techniques in the near future (see [39, 54]). In addition, we have presented new results of neutron-rich oxygen isotopes displaying very well defined molecular bands in agreement with AMD predictions. Consequently, the extended Ikeda diagram has been revised for light neutron-rich nuclei to include the ^{14}C cluster, similarly to the ^{16}O cluster.

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