Since the pioneering discovery of molecular resonances in the $^{12}\text{C}+^{12}\text{C}$ reaction more than half a century ago a great deal of research work has been undertaken in alpha clustering. Our knowledge on 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. The occurrence of “exotic” shapes and Bose-Einstein alpha condensates in light $N=Z$ alpha-conjugate nuclei is investigated. Various approaches of the superdeformed and hyperdeformed bands associated with quasimolecular resonant structures are presented. Evolution of clustering from stability to the drip-lines is examined: clustering aspects are, in particular, discussed for light exotic nuclei with large neutron excess such as neutron-rich Oxygen isotopes with their complete spectroscopy.

1. Introduction

In the last decades, one of the greatest challenges in nuclear science is the understanding of the clustered structure of nuclei from both the experimental and theoretical perspectives [1, 2, 3, 4, 5, 6, 7]. Our knowledge on 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. Besides the well known series of Cluster Conferences [8, 9, 10], a series of workshops on the state of the art in nuclear cluster physics was started. The first one was held in Strasbourg in 2008 [11], the second one in Brussels [12] in 2010 and the last one in Yokohama [13] in 2014. Figure 1 (taken from the cover of Ref. [13]) summarizes the different types of clustering discussed during the
last two or three decades [14, 15]. Most of these structures were investigated in an experimental context by using either some new approaches or developments of older methods [16]. Starting in the 1960s 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]. 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 was still unresolved in the 1990s [1]. In many cases, these resonant structures have been associated with strongly-deformed shapes and with $\alpha$-clustering phenomena [18, 19, 20], predicted from the Nilsson-Strutinsky approach, the cranked $\alpha$-cluster model [18, 19], or other mean-field calculations [20, 21]. In light $\alpha$-like nuclei clustering is observed as a general phenomenon at high excitation energy close to the $\alpha$-decay thresholds [18, 19, 22]. This exotic behavior has been perfectly
illustrated by the famous "Ikeda-diagram" for \(N=Z\) nuclei in 1968 [23], which has been recently modified and extended by von Oertzen [24, 25] for neutron-rich nuclei, as shown in the left panel of Fig.2. Despite the early inception of cluster studies, it is only recently that radioactive ion beams experiments, with great helps from advanced theoretical works, enabled new generation of studies, in which data with variable excess neutron numbers or decay thresholds are compared to predictions with least or no assumptions of cluster cores. Some of the predicted but elusive phenomena, such as molecular orbitals or linear chain structures, are now gradually coming to light.

Clustering is a general feature [26] not only observed in light neutron-rich nuclei [27, 28, 29, 30], but also in halo nuclei [31, 32] such as \(^{11}\text{Li}\) [33] or \(^{14}\text{Be}\) [34], for instance. The problem of cluster formation has also been treated extensively for very heavy systems by R.G. Gupta [21], by D. Poenaru, V. Zagrebaev and W. Greiner [36, 35] and by C. Simenel [37] where giant molecules and collinear ternary fission may co-exist [38]. Finally, signatures of alpha clustering have also been predicted and/or discovered in light nuclei surviving from intermediate-energy [39] to ultrarelativistic-energy [40, 41] nuclear collisions. The topic of clustering in nuclei benefits of intense theoretical activity where new experimental information has come to light very recently. Several status reports were already given in conferences and their written contributions can be found in their proceedings [15, 42, 43].

In this short review article, only few selected topics will be presented, I will limit myself first to the light \(^{12}\text{C}, \ ^{16}\text{O}, \ ^{20}\text{Ne} \text{ and } \ ^{24}\text{Mg}\) \(\alpha\)-like nuclei in Section 2, then to alpha clustering, nuclear molecules and large deformations for heavier light nuclei in Section 3. The search for electromagnetic transitions and alpha condensates in heavier \(\alpha\)-like nuclei will be discussed in Sections 4 and 5, respectively, and, finally, clustering effects in light neutron-rich nuclei (oxygen isotopes) will be presented in Section 6 before the summary, conclusions and outlook of Section 7 are briefly proposed.

### 2. Renewed interest in the spectroscopy of \(^{12}\text{C}, \ ^{16}\text{O}, \ ^{20}\text{Ne} \text{ and } \ ^{24}\text{Mg}\) \(\alpha\)-like nuclei

The ground state of \(^{8}\text{Be}\) is the most simple and convincing example of \(\alpha\)-clustering in light nuclei as suggested by several theoretical models and appears naturally in \textit{ab initio} calculations [44, 45]. The picture of the \(^{8}\text{Be}\) nucleus predicted by the No Core Shell model [44] as being a dumbbell-shaped configuration of two alpha particles closely resembles the superdeformed (SD) shapes known to arise in heavier nuclei in the actinide mass region. This dumbbell-like structure gives rise to a rotational band, from which the moment of inertia is found to be commensurate with an axial
Fig. 2. Schematic illustration of the structures of molecular shape isomers in light neutron-rich isotopes of nuclei consisting of $\alpha$-particles, $^{16}\text{O}$- and $^{14}\text{C}$-clusters plus some covalently bound neutrons (Xn means X neutrons) [26]. The so called "Extended Ikeda-Diagram" with $\alpha$-particles (left panel) and $^{16}\text{O}$-cores (middle panel) can be generalized to $^{14}\text{C}$-cluster cores (right panel. The lowest line of each configuration corresponds to parts of the original Ikeda diagram. However, because of its deformation, the $^{12}\text{C}$ nucleus is not included, as it was earlier. The numbers represent the threshold energy dissociating the ground state into the respective cluster configuration. Threshold energies are given in MeV. This figure has been adapted courtesy from W. von Oertzen [26].

deformation of 2:1. The possible of large deformation of light $\alpha$-conjugate nuclei with SD, hyperdeformed (HD) and linear-chain configurations will be discussed in following Sections.

2.1. $^{12}\text{C}$ nucleus "Hoyle" state

The renewed interest in $^{12}\text{C}$ was mainly focused to a better understanding of the nature of the so called "Hoyle" state [46, 47, 48], the excited $0^+$
state at 7.654 MeV that can be described in terms of a bosonic condensate, a cluster state and/or a \( \alpha \)-particle gas \[49, 50, 51\]. The resonant “Hoyle” state \[46\] (without it carbon would not exist as proved in 1957 by an experimental group at Caltech \[47\]) is regarded as the prototypical alpha-cluster state whose existence is of great importance for the nucleosynthesis of \( {^{12}}C \) within stars. The structure of this state has been thoroughly investigated with theoretically modelled with both \emph{ab initio} \[44, 45, 52, 53, 54, 55, 56, 57\] and cluster models \[58, 59, 60\]. Much experimental progress has been achieved recently as far as the spectroscopy of \( {^{12}}C \) near and above the \( \alpha \)-decay threshold is concerned \[61, 62, 63, 64, 65, 66\]. More particularly, the \( 2_2^+ \) “Hoyle” rotational excitation in \( {^{12}}C \) has been observed by several experimental groups \[61, 63\].

The most convincing experimental result comes from measurements of the \( {^{12}}C(\gamma, \alpha) {^{8}}Be \) reaction performed at the HIGS facility \[63\]. The measured angular distributions of the alpha particles are consistent with an \( L=2 \) pattern including a dominant \( 2^+ \) component. This \( 2_2^+ \) state that appears at around 10 MeV is considered to be the \( 2^+ \) excitation of the ”Hoyle” state (in agreement with the previous experimental investigation of Itoh et al. \[61\]) according to the \( \alpha \) cluster \[67\] and \( \alpha \) condensation models \[49\]. On the other hand, the experiment \( {^{12}}C(\alpha, \alpha) {^{12}}C^* \) carried out at the Birmingham cyclotron \[65\], UK, populates a new state compatible with an equilateral triangle configuration of three \( \alpha \) particles. Still, the structure of the ”Hoyle” state remains controversial as experimental results of its direct decay into three \( \alpha \) particles are found to be in disagreement \[68, 69, 70, 71, 72, 73, 74\].

2.2. \( {^{16}}O \) nucleus

In the study of Bose-Einstein Condensation (BEC), that will be presented in more detail in Section 5, the \( \alpha \)-particle states in light \( N=Z \) nuclei \[49, 50, 51\], are of great importance. At present, the search for an experimental signature of BEC in \( {^{16}}O \) is of highest priority. Furthermore, \emph{ab initio} calculations \[75\] predict that nucleons are arranged in a tetrahedral configuration of alpha clusters. A state with the structure of the ”Hoyle” state \[46\] 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 \[76\]. However, any state in \( {^{16}}O \) equivalent to the ”Hoyle” state \[46\] in \( {^{12}}C \) is most certainly going to decay exclusively by particle emission with very small \( \gamma \)-decay branches, thus, very efficient particle-\( \gamma \) coincidence 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. In 1967 Chevallier et al. \[77\] could excite these
states in the $\alpha$-particle transfer channel leading to the $^8$Be-$^8$Be final state and proposed that a structure corresponding to a rigidly rotating linear arrangement of four alpha particles may exist in $^{16}$O. At this time this experimental observation was considered as the equivalent of the three alpha chain states postulated by Morinaga for the $^{12}$C nucleus [78]. However, very recently, a more sophisticated experimental setup was used at Notre Dame [79]: although the excitation function is generally in good agreement with the previous results [77] a phase shift analysis of the angular distributions does not provide evidence to support the reported hypothesis of a 4$\alpha$-chain state configuration.

2.3. $^{20}$Ne and $^{24}$Mg nuclei

Experimental investigations are still underway to understand the nuclear structure of high spin states of both $^{16}$O and $^{20}$Ne nuclei for instance at Notre Dame and/or iThemba Labs [80] facilities. Another possibility might be to perform Coulomb excitation measurements with intense $^{16}$O and $^{20}$Ne beams at intermediate energies. The nucleus viewed as a collection of $\alpha$-particles has been discussed all over the mass table since a long time and it was only recently shown that clear deviations from statistical models in the decay of excited $^{24}$Mg exist [39, 81, 82, 83]. As far as the theory is concerned, a diversity of cluster/symmetry models (cluster models, ab initio calculations, BEC etc ...) which make concrete predictions in terms of alpha clustering in light nuclei is available on the market. What is presently missing is a clearly defined procedure for relating these abstract predictions to the observed level schemes and clear criteria for what constitutes discriminating evidence for a particular model. A more detailed discussion of BEC will be proposed in one of the forthcoming sections (Section 5).

The search for exotic chain-like structures in light $\alpha$-conjugate nuclei remains an exciting prospect. Experiments reporting tentative evidence of $\alpha$-chains in $^{12}$C [78], $^{16}$O [77, 79, 80], $^{20}$Ne [80] and $^{24}$Mg [84] have been largely unsubstantiated, and the view is that such structure have not yet been definitively observed experimentally.

3. Alpha clustering, nuclear molecules and large deformations

The real link between superdeformation/hyperdemormation (SD/HD), nuclear molecules and alpha clustering [20, 85, 86] is of particular interest, since nuclear shapes with major-to-minor axis ratios of 2:1 have the typical ellipsoidal elongation for light nuclei i.e. with quadrupole deformation parameter $\beta_2 \approx 0.6$. Furthermore, the structure of possible octupole-unstable 3:1 nuclear shapes - hyperdeformation with $\beta_2 \approx 1.0$ - has also been discussed for actinide nuclei [86] 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 $^{28}\text{Si}$ [87, 88, 89, 90, 91, 92], $^{32}\text{S}$ [20, 88, 89, 94, 95], $^{36}\text{Ar}$ [86, 96, 97, 98, 99, 100, 101], $^{40}\text{Ca}$ [102, 103, 104, 105, 106], $^{44}\text{Ti}$ [20, 107, 108], $^{48}\text{Cr}$ [109, 110] and $^{56}\text{Ni}$ [111, 112, 113, 114].

Excitation functions have been measured over a wide range energies for many reactions. Norrby discussed a study of $^{32}\text{S}$ via the $^{28}\text{Si} + \alpha$ reaction [94] that revealed 30 new level assignments spanning 132 resonances in total.

In fact, highly deformed shapes and SD rotational bands have been discovered in several light $\alpha$-conjugate nuclei, such as $^{36}\text{Ar}$ and $^{40}\text{Ca}$ by using $\gamma$-ray spectroscopy techniques [96, 97, 102]. In particular, the extremely deformed rotational bands in $^{36}\text{Ar}$ (shown as crosses in Fig. 3) might be comparable in shape to the quasimolecular bands observed in both $^{12}\text{C} + ^{24}\text{Mg}$ (shown as open triangles) and $^{16}\text{O} + ^{20}\text{Ne}$ (shown as full rectangles) reac-

Fig. 3. Rotational bands and deformed shapes in $^{36}\text{Ar}$. Excitation energies of the ground state (spherical shape) and SD (ellipsoidal shape) bands [97], respectively, and the energies of HD (dynamical shape) band from the quasimolecular resonances observed in the $^{12}\text{C} + ^{24}\text{Mg}$ (open rectangles) [98, 113, 116, 117] and $^{16}\text{O} + ^{20}\text{Ne}$ (full rectangles) [118, 119] reactions are plotted as a function of $J(J+1)$. This figure has been adapted from Refs. [96, 98, 101].
tions. These resonances belong to a rotational band, with a moment of inertia close to that of a HD band provided by both the cranked $\alpha$-cluster model [19] and the Nilsson-Strutinsky calculations. The fact that similar quasi-molecular states observed in the two reactions fall on the same rotational band gives further support to our interpretation of the $^{36}\text{Ar}$ composite system resonances. An identical conclusion was reached for the $^{40}\text{Ca}$ composite system where SD bands have been discovered [96]. Therefore, similar investigations are underway for heavier $\alpha$-like composite systems such as $^{44}\text{Ti}$ [20], $^{48}\text{Cr}$ [109] and $^{56}\text{Ni}$ [111, 114].

Ternary clusterizations in light $\alpha$-like composite systems are also predicted theoretically, but were not found experimentally in $^{36}\text{Ar}$ so far [96]. On the other hand, ternary fission of $^{56}\text{Ni}$ – related to its HD shapes – was identified from out-of-plane angular correlations measured in the $^{32}\text{S}+^{24}\text{Mg}$ reaction with the Binary Reaction Spectrometer (BRS) at the VIVITRON Tandem facility of the IPHC, Strasbourg [120]. This finding [120] is not limited to light $N=Z$ compound nuclei, true ternary fission [35, 38, 121] can also occur for very heavy [38, 121] and superheavy [122] nuclei.

4. Electromagnetic transitions as a probe of quasimolecular states and clustering in light nuclei

Clustering in light nuclei is traditionally explored through reaction studies, but observation of electromagnetic transitions can be of high value in establishing, for example, that highly-excited states with candidate cluster structure do indeed form rotational sequences.

4.1. $^{16}\text{O}$ nucleus

There is a renewed interest in the spectroscopy of the $^{16}\text{O}$ nucleus at high excitation energy [96, 99]. Exclusive data were collected on $^{16}\text{O}$ in the inverse kinematics reaction $^{24}\text{Mg}+^{12}\text{C}$ studied at $E_{\text{lab}}(^{24}\text{Mg}) = 130$ MeV with the BRS in coincidence with the EUROBALL IV installed at the VIVITRON facility [96, 99]. From the $\alpha$-transfer reactions (both direct transfer and deep-inelastic orbiting collisions [123]), new information has been deduced on branching ratios of the decay of the $3^+$ state of $^{16}\text{O}$ at 11.085 MeV $\pm 3$ keV. The high-energy level scheme of $^{16}\text{O}$ shown in Ref. [96, 99] indicated 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 $\pm 2\%$) 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 [96, 99]. Clustering effects in the light neutron-rich oxygen isotopes $^{17,18,19,20}$O will also be discussed in Section 5.

Alpha clustering plays an important role in the description of the ground state and excited states of light nuclei in the $p$ shell. For heavier nuclei, in the $sd$-shell, cluster configurations may be based on heavier substructures like $^{12}$C, $^{14}$C and $^{16}$O as shown by the ”Extended Ikeda-diagram” proposed in Fig. 2. This was already well discussed to appear in $^{24}$Mg($^{12}$C-$^{12}$C) and $^{28}$Si($^{12}$C-$^{16}$O) both theoretically and experimentally.

4.2. $^{28}$Si nucleus

The case of the mid-$sd$-shell nucleus $^{28}$Si is of particular interest as it shows the coexistence of deformed and cluster states at rather low energies [89, 90]. Its ground state is oblate, with a partial $\alpha$-$^{24}$Mg structure, two prolate normal deformed bands are found, one built on the $0^+_2$ state at 4.98 MeV and on the $0^+_3$ state at 6.69 MeV. The SD band candidate with a pronounced $\alpha$-$^{24}$Mg structure is suggested [89]. In this band, the $2^+_2$ (9.8 MeV), $4^+_2$ and $6^+_2$ members are well identified as can be clearly observed in Fig. 4.

In the following we will briefly discuss a resonant cluster band which is predicted to start close to the Coulomb barrier of the $^{12}$C+$^{16}$O collision, i.e. around 25 MeV excitation energy in $^{28}$Si. We have studied the $^{12}$C($^{16}$O,$\gamma$)$^{28}$Si radiative capture reaction at five resonant energies around the Coulomb barrier by using the zero degree DRAGON spectrometer installed at Triumf, Vancouver [124, 125]. Details about the setup, that has been optimized for the $^{12}$C($^{12}$C,$\gamma$)$^{24}$Mg radiative capture reaction in our of previous DRAGON experiments, can be found in Ref. [126]. The $^{12}$C($^{16}$O,$\gamma$)$^{28}$Si data clearly show [124, 125] the direct feeding of the prolate $4^+_2$ state at 9.16 MeV and the octupole deformed $3^-$ at 6.88 MeV. This state is the band head of an octupole band which mainly decays to the $^{28}$Si oblate ground state with a strong $E3$ transition. Our results are very similar to what has been measured for the $^{12}$C+$^{12}$C radiative capture reaction above the Coulomb barrier in the first DRAGON experiment [126] where the enhanced feeding of the $^{24}$Mg prolate band has been measured for a $4^+-2^+$ resonance at $E_{c.m.} = 8.0$ MeV near the Coulomb barrier.

At the lowest energy of $^{12}$C+$^{16}$O radiative capture reaction, an enhanced feeding from the resonance $J^\pi = 2^+$ and $1^+$ T=1 states around 11 MeV is observed in $^{28}$Si. Again this is consistent with $^{12}$C+$^{12}$O radiative capture reaction data where $J^\pi = 2^+$ has been assigned to the entrance resonance and an enhanced decay has been measured via intermediate $1^+$ T=1 states.
around 11 MeV in $^{24}$Mg. A definitive scenario for the decay of the resonances at these low bombarding energies in both systems will come from the measurement of the $\gamma$ decay spectra with a $\gamma$-spectrometer with better resolution than BGO but still rather good efficiency such as LaBr$_3$ (lanthanum) crystals (see also the forthcoming Subsection).
Fig. 5. Reaction Q-value of the $^{12}$C($^{12}$C,$^{12}$C)$^{12}$C reaction at $E_{\text{lab}} = 32.9$ MeV versus $\gamma$-ray energies. The spectrum has been obtained with fragment-fragment-$\gamma$ coincidence condition and a $\gamma$ multiplicity $M = 1$ as explained in the text (see also Ref. [127] for more details). This figure has been adapted from Ref. [127].

4.3. $^{12}$C+$^{12}$C resonances

A further area where electromagnetic transitions would be of great interest in support of cluster models is in the case of the quasi-molecular resonances observed in the $^{12}$C+$^{12}$C reaction [1]. The width of these resonances were $\approx 100$ keV, indicating the formation of a $^{24}$Mg intermediate system with a lifetime significantly longer than the nuclear crossing time. These resonances were subsequently interpreted as $^{12}$C+$^{12}$C cluster states.

There has been only one valient attempt to directly observe transitions in this reaction by Haas et al. [127] focussing on transitions between $10^+$
and $8^+$ resonant states at a bombarding energy $E(^{12}\text{C}) = 32 \text{ MeV}$ chosen to populate a known and isolated $10^+$ resonance. Position Sensitive Detectors (PSD) were mounted on either side of the beam axis at the center of the Chateau de Cristal array of 74 barium fluoride detectors. Triple $\gamma$-$^{12}\text{C}$-$^{12}\text{C}$ coincidences were recorded and it was possible to observe a few events in the expected energy window corresponding to the $10^+ \rightarrow 8^+$ transitions as shown by Fig. 5. However, the data were not sufficiently clean to rule out these events as due to the experimental background. The measurement reported only an upper limit (for the radiative partial width of $1.2 \pm 10^{-5}$) given the extreme challenges of eliminating all background displayed in Fig. 5.

It will be very interesting to revisit this earlier experiment taking advantage of new experimental techniques and developments in detector technology for the detection of gamma rays and/or fragments. For example, novel scintillator materials like lanthanum bromide offer superior resolution for the gamma ray of interest while improved silicon detector performance and solid angle coverage could lead to significant improvements both in sensitivity and in statistics.

![Fig. 6. Schematic illustration of the clustering arrangement of five alpha particles in the nucleus $^{20}\text{Ne}$.](image-url)
5. Condensation of $\alpha$ clusters in light nuclei

In principle the nucleus is a quasi-homogeneous collection of protons and neutrons, which adopts a spherical configuration i.e. a spherical droplet of nuclear matter. For light nuclei the nucleons are capable to arrange themselves into clusters of a bosonic character. The very stable $\alpha$-particle is the most favorable light nucleus for quarteting - $\alpha$ clustering - to occur in dense nuclear matter. These cluster structures have indeed a crucial role in the synthesis of elements in stars. The so called "Hoyle" state \cite{46, 48}, the main portal through which $^{12}\text{C}$ is created in nucleosynthesis with a pronounced three-$\alpha$-cluster structure, is the best example of $\alpha$ clustering in light nuclei. In $\alpha$ clustering a geometric picture can be proposed in the framework of point group symmetries \cite{41}. For instance, in $^8\text{Be}$ the two $\alpha$ clusters are separated by as much as $\approx 2\text{fm}$, $^{12}\text{C}$ exhibits a triangle arrangement of the three $\alpha$ particles $\approx 3\text{fm}$ apart, $^{16}\text{O}$ forms a tetrahedron, etc. Evidence for tetrahedral symmetries in $^{16}\text{O}$ was given by the algebraic cluster model \cite{128}. Such kind of symmetries are rather well illustrated by the schematic picture of the $^{20}\text{Ne}$ nucleus proposed in Fig. 6. More realistic is the density plot for $^{20}\text{Ne}$ nucleus calculated as an arrangement of two $\alpha$ particles with a $^{12}\text{C}$ core which is displayed in Fig. 7 to illustrate the enhancement of the symmetries of the $\alpha$ clustering.

In the study of the Bose-Einstein Condensation (BEC) the $\alpha$-particle states were first described for $^{12}\text{C}$ and $^{16}\text{O}$ \cite{49, 129} and later on generalized to heavier light $N=Z$ nuclei \cite{50, 51, 130, 131}. The structure of the "Hoyle" state and the properties of its assumed rotational band have been studied very carefully from measurements of the $^{12}\text{C}(\gamma,3\alpha)$ reaction performed at the HIGS facility, TUNL \cite{63}. At present, the search for an experimental signature of BEC in $^{16}\text{O}$ is of highest priority. A state with the structure of the "Hoyle" state in $^{12}\text{C}$ coupled to an $\alpha$ particle is predicted in $^{16}\text{O}$ at about 15.1 MeV (the $0_6^+$ state), the energy of which is $\approx 700$ keV above the $4\alpha$-particle breakup threshold \cite{76, 132, 133}; in other words, this $0_6^+$ state might be a good candidate for the dilute $4\alpha$ gas state. However, any state in $^{16}\text{O}$ equivalent to the "Hoyle" state in $^{12}\text{C}$ 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 $^{12}\text{C}$ decaying to that state or could be observed in an $\alpha$-particle transfer channel leading to the $^8\text{Be}-^8\text{Be}$ final state. The attempts to excite these states by $\alpha$ inelastic scattering \cite{61} was confirmed recently \cite{134}. Another possibility, that has not been yet explored, might be to perform Coulomb
Fig. 7. Self-consistent ground-state densities of the nucleus $^{20}\text{Ne}$ as calculated with EDF (see text for details). Densities (in units of fm$^{-3}$) are plotted in the intrinsic frame of reference that coincides with the principal axes of the nucleus. This figure has been adapted from Ref. [130] courtesy from E. Kahn and J.-P. Ebran.

excitation measurements with intense $^{16}\text{O}$ beams at intermediate energies.

Clustering of $^{20}\text{Ne}$ has also been described within the energy density functional theory [130] (EDF) as illustrated by Fig. 7 that displays axially and reflection symmetric self-consistent equilibrium nucleon density distributions. We note the well known quasimolecular $\alpha$-$^{12}\text{C}$-$\alpha$ structure although clustering effects are less pronounced than the ones (schematically displayed in Fig. 5) predicted by Nilsson-Strutinsky calculations and even by mean-field calculations (including Hartree-Fock and/or Hartree-Fock-Bogoliubov calculations) [19, 20, 21, 131].

The most recent work of Girod and Schuck [131] validates several possible scenarios for the influence of clustering effects as a function of the neutron richness that will trigger more experimental works. We describe in the following (i.e. in Section 6) recent experimental investigations on the Oxygen isotopes chain.
6. 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” [23] proposed by von Oertzen [24] (see the left panel of Fig. 2). With additional neutrons, specific molecular structures appear with binding effects based on covalent molecular neutron orbitals. In these diagrams $\alpha$-clusters and $^{16}\text{O}$-clusters (as shown by the middle panel of the diagram of Fig. 2) are the main ingredients. Actually, the $^{14}\text{C}$ nucleus may play similar role in clusterization as the $^{16}\text{O}$ 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.

The possibility of extending molecular structures from dimers (beryllium isotopes) [135] to trimers [136] has been investigated in detail for carbon isotopes [137, 138, 141]. Here the neutrons would be exchanged between the three centers (alpha particles). It is possible that the three $\alpha$-particle configuration can align themselves in a linear fashion, or alternative collapse into a triangle arrangement - in either case the neutrons being localised across the three centers. At present experimental evidence for such structures have been found in $^{13}\text{C}$ [137] and $^{14}\text{C}$ [141]. Possibly the best case for the linear arrangement - from a theoretical perspective [139, 140] - is $^{16}\text{C}$ [138].

A general picture of clustering and molecular configurations in light nuclei can also 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: $^{18}\text{O}$ [142] and $^{20}\text{O}$ [143]. But very striking cluster states have also been found in odd-even oxygen isotopes such as: $^{17}\text{O}$ [144] and $^{19}\text{O}$ [145].

Figs. 8 and 9 give an overview of all bands in $^{18}\text{O}$ and $^{20}\text{O}$, respectively, as plots 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 $2J+1$ [143] were considered. Slope parameters obtained in a linear fit to the excitation energies [143] indicate the moment of inertia of the rotational bands given in the respective figures. The intrinsic structure of the cluster bands is reflection asymmetric, the parity projection gives an energy splitting between the partner bands. The assignments of the experimental molecular bands of $^{18}\text{O}$ are supported by both the Generator-Coordinate-Method [146] and the Antisymmetrized Molecular Dynamics (AMD) calculations [147].

We can compare the bands of $^{20}\text{O}$ [143] shown in Fig. 9 with the ones of $^{18}\text{O}$ in Fig. 8. The first doublet ($K=0^+_2$) has a slightly larger moment of inertia (smaller slope parameter) in $^{20}\text{O}$, which is consistent with its
Fig. 8. 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 has been adapted from Ref. [142] courtesy from W. von Oertzen.

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. [147], which clearly establishes parity inversion doublets predicted by AMD calculations for the $^{14}$C-$^{6}$He cluster and $^{14}$C-$2n$-α molecular structures. The corresponding moments of inertia given in 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 $^{20}$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 [23] and the "extended Ikeda-diagram" consisting of $^{16}$O cluster cores with covalently bound neutrons [24] must be further extended
Fig. 9. 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 has been adapted from Ref. [143] courtesy from W. von Oertzen.

to include also the $^{14}$C cluster cores as illustrated in Fig. 2.

7. Summary, conclusions and outlook

The link of alpha clustering, quasimolecular resonances, orbiting phenomena and extreme deformations (SD, HD, ...) has been discussed in this review article. Several examples emphasize the general connexion between molecular structure and deformation effects within the shell model, or rather the Nilsson model. However, we have also presented the BEC picture of light (and medium-light) $\alpha$-like nuclei that appears to be an alternate way of understanding most of properties of nuclear clusters. New results regarding cluster and molecular states in neutron-rich oxygen isotopes in agreement with AMD predictions are finally summarized. Consequently, the "Extended Ikeda-diagram" has been further modified 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 [16, 120]). Marked progress has been made in many traditional and novel subjects of nuclear cluster physics. The developments in these subjects show the importance of clustering among the basic modes of motion of nuclear many-body systems. All these open questions will require precise coincidence measurements [16] coupled with state-of-the-art theory.

8. Dedication and acknowledgments

This review article is dedicated to the memory of my friends Alex Szanto de Toledo and Valery Zagrebaev who unexpectedly passed away in early 2015. I am very pleased to first acknowledge Walter Greiner (who celebrated his 80th birthday on October 29th, 2015) for his continuous support of the cluster physics [1, 11, 35, 36, 148]. I would like also to thank Christian Caron (Springer) for initiating in 2008 the series of the three volumes of Lecture Notes in Physics entitled "Clusters in Nuclei" and edited between 2010 and 2014 [3, 4, 5]. All the authors of the 19 chapters of these volumes are warmly thanked for their fruitful collaboration during the course of the project which is still in progress.
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