Present status of nuclear cluster physics and experimental perspectives

C Beck
Département de Recherches Subatomiques, Institut Pluridisciplinaire Hubert Curien,
IN2P3-CNRS and Université de Strasbourg - 23, rue du Loess BP 28, F-67037 Strasbourg Cedex 2, France
E-mail: christian.beck@iphe.cnrs.fr

Abstract.
Knowledge on nuclear cluster physics has increased considerably as 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 in light \( N/Z \) \( \alpha \)-like nuclei and the evolution of clustering from stability to the drip-lines are being investigated more and more accurately both theoretically and experimentally. Experimental progresses in understanding these questions were recently examined and will be further revisited in this introductory talk: clustering aspects are, in particular, discussed for light exotic nuclei with a large neutron excess such as neutron-rich Oxygen isotopes with their complete spectroscopy.

1. Introduction
One of the greatest challenges in nuclear science is understanding the structure of light nuclei from both experimental and theoretical perspectives. Figure 1 was used by Catford to summarize the different types of clustering discussed during the last Cluster Conference in Debrecen [1]. Most of these structures were investigated in an experimental context by using either some new approaches or developments of older methods [2]. 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 [3, 4]. These resonances [4] have been interpreted in terms of nuclear molecules [3]. 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 [3, 4]. In many cases, these resonant structures have been associated with strongly-deformed shapes and with \( \alpha \)-clustering phenomena [5, 6], predicted from the Nilsson-Strutinsky approach, the cranked \( \alpha \)-cluster model [5], or other mean-field calculations [6, 7]. In light \( \alpha \)-like nuclei, clustering is observed as a general phenomenon at high excitation energy close to the \( \alpha \)-decay thresholds [5, 8]. This exotic behavior has been perfectly illustrated by the famous “Ikeda-Diagram” for \( N=Z \) nuclei in 1968 [9], which has been modified and extended by von Oertzen [10] for neutron-rich nuclei more than 10 years ago, as shown in the left panel of figure 2. Clustering is a general feature [11] not only observed in typical light neutron-rich nuclei [12], but also in less common systems such as the neutron halo \(^{11}\text{Li} \) [13] and/or \(^{14}\text{Be} \) nuclei, for instance [14]. The problem of cluster formation has also been treated extensively for very heavy systems by Gupta [7], by
Figure 1. Different types of clustering in nuclei that have been discussed at this workshop. (Figure adapted from Ref.[1] courtesy from Catford).

Zagrebaev and Greiner [15] and by Simenel [16] where giant molecules and collinear ternary fission may co-exist [17]. Finally, signatures of $\alpha$ clustering have also been discovered in light nuclei undergoing from ultrarelativistic nuclear collisions [18, 19]. In this introductory talk, I will limit myself first to the light $^{12}$C and $^{16}$O $\alpha$-like nuclei in Section 2, then to $\alpha$ clustering, deformations and $\alpha$ condensates in heavier $\alpha$-like nuclei in Section 3, and, finally, to clustering in light neutron-rich nuclei in Section 4.

2. Renewed interest in the spectroscopy of $^{12}$C and $^{16}$O $\alpha$-like nuclei

The renewed interest in $^{12}$C was mainly focused to a better understanding of the nature of the so called ”Hoyle” state [20] that can be described in terms of a bosonic condensate, a cluster state and/or a $\alpha$-particle gas [21, 22, 23]. Much experimental progress has been achieved recently as far as the spectroscopy of $^{12}$C near and above the $\alpha$-decay threshold is concerned [24, 25, 26, 27, 28, 29]. More particularly, the $2^+$ ”Hoyle” rotational excitation in $^{12}$C has been observed by several experimental groups [24, 26, 27]. The most convincing experimental result, displayed in figure 3, comes from measurements of the $^{12}$C($\gamma,\alpha$)$^{8}$Be reaction performed at the HIGS facility [27]. The angular distributions of the alpha particles in the region of 9-10 MeV are consistent with an $L=2$ pattern, including a dominant $2^+$ component. This $2^+$ 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. [24]) according to the $\alpha$ cluster [30] and $\alpha$ condensation models [21, 23]. On the other hand, the experiment $^{12}$C($\alpha,\alpha$)$^{12}$C* carried out at the Birmingham cyclotron [29], 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 [31, 32, 33, 34, 35, 36].
Figure 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 ($X_n$ means $X$ neutrons). The so called "Extended Ikeda-Diagram" [10] 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" [9]. However, because of its deformation, the $^{12}\text{C}$ nucleus is not included, as it was earlier [9]. Decay threshold energies (in MeV) are given for the relevant decompositions of clusters. (Figure adapted from Ref.[11] courtesy from von Oertzen).

In the study of Bose-Einstein Condensation (BEC), the $\alpha$-particle states in light $N=Z$ nuclei [21, 22, 23], are of great importance. 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 [20] 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 [37]. However, any state in $^{16}\text{O}$ equivalent to the "Hoyle" state [20] in $^{12}\text{C}$ 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 $^{12}\text{C}$ decaying to that state. In 1967 Chevallier et al. [38, 39] could excite these states in an $\alpha$-particle transfer channel leading to the $^{8}\text{Be}$-$^{8}\text{Be}$ final state and proposed
that a structure corresponding to a rigidly rotating linear arrangement of four alpha particles may exist in $^{16}\text{O}$. Very recently, a more sophisticated experimental setup was used at Notre Dame [40]: although the excitation function is generally in good agreement with the previous results [38, 39] a phase shift analysis of the angular distributions does not provide evidence to support the reported hypothesis of a $4\alpha$-chain state configuration. Experimental investigations are still underway to understand the nuclear structure of high spin states of both $^{16}\text{O}$ and $^{20}\text{Ne}$ nuclei for instance at Notre Dame [41] and/or iThemba Labs [42] facilities. Another possibility might be to perform Coulomb excitation measurements with intense $^{16}\text{O}$ and $^{20}\text{Ne}$ beams at intermediate energies.

3. Alpha clustering, deformations and alpha condensates in heavier nuclei

The real link between superdeformation (SD), nuclear molecules and alpha clustering [6, 43, 44, 45, 46] is of particular interest, since nuclear shapes with major-to-minor axis ratios of 2:1 are typical ellipsoidal elongations for light nuclei (corresponding to a 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 [45] in terms of clustering phenomena. Typical examples for the 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 $^{28}\text{Si}$ [47, 48, 49, 50, 51], $^{32}\text{S}$ [6, 48, 52, 53, 54], $^{36}\text{Ar}$ [45, 46, 55, 56, 57, 58, 59], $^{40}\text{Ca}$ [60, 61, 62, 63], $^{44}\text{Ti}$ [6, 64, 65], $^{48}\text{Cr}$ [66] and $^{56}\text{Ni}$ [67, 68, 69, 70, 71, 72].

Highly deformed shapes and SD rotational bands have been discovered in several light $\alpha$-conjugate ($N=Z$) nuclei, such as $^{36}\text{Ar}$ and $^{40}\text{Ca}$ by using $\gamma$-ray spectroscopy techniques [55, 60].
In particular, the extremely deformed rotational bands in $^{36}$Ar [55] (shown as crosses in figure 4) might be comparable in shape to the quasimolecular bands observed in both $^{12}$C+$^{24}$Mg (shown as open rectangles in figure 4) and $^{16}$O+$^{20}$Ne (shown as full rectangles in figure 4) reactions. Ternary clusterizations are also predicted theoretically, but were not found experimentally in $^{36}$Ar so far [57]. On the other hand, ternary fission of $^{56}$Ni – related to its hyperdeformed (HD) shapes – was claimed to be identifiable 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 [71], though this remains to be confirmed [72]. This possibility [71] is not limited to light $N=Z$ compound nuclei, true ternary fission [15, 17, 73] can also occur for very heavy [17, 73] and superheavy [74] nuclei.

The next natural question to be addressed is whether dilute-gas-like structures (i.e. BEC) [21, 22, 23] also exist in medium-mass $\alpha$-conjugate nuclei as predicted by several theoretical investigations [75, 76, 77]. Several recent undergoing experiments indicate that it might be the case at least for $^{24}$Mg [78, 79], $^{36}$Ar [80] and $^{56}$Ni [81] and much work is in progress in this field [22].

4. 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" [9] proposed by von Oertzen [10] (see
the left and middle panels of figure 2). With additional neutrons, specific molecular structures appear with binding effects based on covalent molecular neutron orbitals. In these diagrams \( ^{16}\text{O} \)-clusters are the main ingredients. Actually, the \( ^{14}\text{C} \) nucleus may play a similar role in clusterisation as the \( ^{16}\text{O} \) nucleus does. Both of them have similar properties as a cluster: i) closed neutron \( p \)-shells, ii) first excited states are well above \( E^* = 6 \text{ MeV} \), and iii) 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 oxygen isotopes with \( A \geq 17 \). Here I will only present recent results on the even-even oxygen isotopes: \( ^{18}\text{O} \) [82] and \( ^{20}\text{O} \) [83]. But very striking cluster states have also been found in odd-even oxygen isotopes such as: \( ^{17}\text{O} \) [84] and \( ^{19}\text{O} \) [85].

Figure 5 gives an overview of all bands in \( ^{18}\text{O} \) 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 \( 2J+1 \) [82] were considered. Slope parameters obtained in a linear fit to the excitation energies [82] indicate the moment of inertia of the rotational bands given in figure 5. 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 [86] or Antisymmetrized Molecular Dynamics (AMD) calculations [87].

The bands of \( ^{20}\text{O} \) [83] shown in figure 6 can be compared with those of \( ^{18}\text{O} \) displayed in figure 5. The first doublet (\( K=0^\pm \)) has a slightly larger moment of inertia (smaller slope parameter) in \( ^{20}\text{O} \), which is consistent with its interpretation as \( ^{14}\text{C}–^6\text{He} \) or \( ^{16}\text{C}–^4\text{He} \) 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 has yet to be determined, has a slope parameter slightly smaller than in \( ^{18}\text{O} \). This is consistent with the study of the bands in \( ^{20}\text{O} \) by Furutachi et al. [87], which clearly establishes parity inversion doublets predicted by AMD calculations for the \( ^{14}\text{C}–^6\text{He} \) quasimolecular (cluster) and \( ^{14}\text{C}–2n–\alpha \) molecular structures. The corresponding moments of inertia illustrated in figure 4 and figure 5 are strongly suggesting large deformations for the cluster structures. It may be concluded that the reduction of the moments of inertia of the lowest bands of \( ^{18,20}\text{O} \) is consistent with the assumption that the strongly bound \( ^{14}\text{C} \) nucleus have equivalent properties to \( ^{16}\text{O} \). It is interesting to note that the Quantum Mechanical Fragmentation Theory (QMFT) of Gupta [7] reaches to the same conclusion on the possibility of \( ^{14}\text{C} \) clustering [88]. Therefore, the "Ikeda-Diagram" [9] and the "Extended Ikeda-Diagram" consisting of \( ^{18}\text{O} \) cluster cores with covalently bound neutron [10] must be further extended to include also the \( ^{14}\text{C} \) cluster cores as illustrated in right panel of figure 2.

5. Summary and outlook
The connection of \( \alpha \)-clustering, quasimolecular resonances, \( \alpha \) condensates in very light nuclei and extreme deformations (SD, HD, ...) in heavier nuclei as investigated by more and more sophisticated experimental devices, has been discussed in this introductory talk. In particular, high-precision spectroscopy techniques help us to uncover important parts of the complete spectroscopy of the so called "Hoyle" state in \( ^{12}\text{C} \). The origin of carbon for life is likely to be understood in the very near future with answer to the question of the "Hoyle" state structure. Similarly the quest for the 4\( \alpha \) states of \( ^{16}\text{O} \) near the \( ^{8}\text{Be}+^8\text{Be} \) and \( ^{12}\text{C}+\alpha \) decay thresholds, which correspond to the "Hoyle" state. Results have also been presented on neutron-rich oxygen isotopes displaying very well defined quasimolecular bands in agreement with AMD predictions. Consequently, the "Extended Ikeda-Diagram" has been further extended for light neutron-rich nuclei by inclusion of the \( ^{14}\text{C} \) cluster as a core, similarly to the \( ^{16}\text{O} \) one. 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 likely going to decay by particle emission (see [2, 71, 72]).

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References

[1] Catford W 2012, *J. Phys.: Conferences Series* **436** 012095
[2] Papka P and Beck C 2012 Clusters in Nuclei - Vol.2 ed. Beck C, *Lecture Notes in Physics* **848** 299
[3] Greiner W, Park Y Jae, and Scheid W 1995 *Nuclear Molecules*, (Singapore: World Scientific)
[4] Beck C et al. 1994 *Phys. Rev. C* **49** 2618
[5] Freer M 2007 *Rep. Prog. Phys.* **70** 2149
[6] Horiuchi H 2010 Clusters in Nuclei - Vol.1, ed. Beck C, *Lecture Notes in Physics* **818** 57
[7] Gupta R K 2010 Clusters in Nuclei - Vol.1, ed. Beck C, *Lecture Notes in Physics* **818** 232
[8] von Oertzen W, Freer M, and Kanada-En’yo Y 2006 *Phys. Rep.* **432** 43
[9] Horiiuchi H and Ikeda K 1968 *Prog. Theor. Phys.* **40** 277
[10] von Oertzen W 2001 *Eur. Phys. J. A* **11** 403
[11] von Oertzen W and Milin M, 2014 Clusters in Nuclei - Vol.3, ed. Beck C, *Lecture Notes in Physics* **875** 147
[12] Kanada-En’yo Y et al. 2010 Clusters in Nuclei - Vol.1, ed. Beck C, *Lecture Notes in Physics* **818** 129
[13] Ikeda K et al. 2010 Clusters in Nuclei - Vol.1, ed. C. Beck, *Lecture Notes in Physics* **818** 165
[14] Nakamura N and Kondo Y 2012 Clusters in Nuclei - Vol.2, ed. Beck C, *Lecture Notes in Physics* **848** 67
[15] Zagrebaev V and Greiner W 2010 Clusters in Nuclei - Vol.1, ed. Beck C, *Lecture Notes in Physics* **818** 267
[16] Sinened C 2014 Clusters in Nuclei - Vol.3, ed. Beck C, *Lecture Notes in Physics* **875** 95
[17] Kamin D V and Pyatkov Y 2014 Clusters in Nuclei - Vol.3, ed. Beck C, *Lecture Notes in Physics* **875** 183
[18] Zarubin P L 2014 Clusters in Nuclei - Vol.3, ed. Beck C, *Lecture Notes in Physics* **875** 51
[19] Broniowski W and Ruiz Arriola E 2014 *Phys. Rev. Lett.* **112** 112501
[20] Hoyle F 1954 *Astrophys. J. Suppl. Ser.* **1** 121
[21] Kohsaka A, et al. 2001 *Phys. Rev. Lett.* **87** 192501
[22] von Oertzen W 2010 Clusters in Nuclei - Vol.1, ed. Beck C, *Lecture Notes in Physics* **818** 102
[23] Yamada T et al. 2012 Clusters in Nuclei - Vol.2, ed. Beck C, *Lecture Notes in Physics* **848** 229
[24] Isho I et al. 2004 *Nucl. Phys. A* **738** 268
[25] Freer M et al. 2011 *Phys. Rev. C* **83** 034314
[26] Isho M et al. 2011 *Phys. Rev. C* **84** 054308
[27] Zimmerman W R et al. 2014 *Phys. Rev. Lett.* **110** 152502
[28] Kokalova Tz et al. 2013 *Phys. Rev. C* **87** 057307
[29] Marin-Lamb cardi D J et al. 2014 *Phys. Rev. Lett.* **113** 012502
[30] Uegaki E et al. 1977 *Prog. Theor. Phys.* **57** 1262
[31] Freer M et al. 1994 *Phys. Rev. C* **49** R1751
[32] Raduta A D et al. 2011 *Phys. Lett. B* **705** 65
[33] Manfredi J et al. 2012 *Phys. Rev. C* **85** 037603
[34] Kirseborn O S et al. 2012 *Phys. Rev. Lett.* **108** 202501
[35] Rana T K et al. 2013 *Phys. Rev. C* **88** 021601(R)
[36] Itoh et al. 2014 *Phys. Rev. Lett.* submitted
[37] Funaki Y et al. 2008 *Phys. Rev. Lett.* **101** 082502
[38] Chevallier P et al. 1967 *Phys. Rev.* **160** 827
[39] Brachard F et al. 1976 *Phys. Rev. C* **13** 967
[40] Curtis N et al. 2013 *Phys. Rev. C* **88** 064309
[41] Kokalova Tz et al. 2013 *Phys. Rev. C* **87** 057309
[42] Papka P and Kokalova Tz 2014 (private communications)
[43] Beck C 2004 *Nucl. Phys. A* **738** 24
[44] Beck C 2004 *Int. J. Mod. Phys. E* **13** 9
[45] Cseh J et al. 2009 *Phys. Rev. C* **80** 034320
[46] Beck C et al. 2011 *Acta Physica Polonica B* **42** 747
[47] Taniguchi Y et al. 2009 *Phys. Rev. C* **80** 044316
