Recent Experimental Results on Nuclear Cluster Physics

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Abstract. Knowledge on nuclear cluster physics has increased considerably since the pioneering discovery of $^{12}\text{C}+^{12}\text{C}$ resonances half a century ago 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/or Bose-Einstein $\alpha$ condensates in light $N=Z$ $\alpha$-conjugate nuclei is investigated. Evolution of clustering from stability to the drip-lines examined with clustering aspects persisting in light neutron-rich nuclei is consistent with the extension of the "Ikeda-diagram" to non $\alpha$-conjugate nuclei.

1. Introduction
Among the greatest challenges in nuclear science was the understanding of the clustered structure of nuclei from both the experimental and theoretical perspectives [1, 2, 3, 4, 5, 6, 7, 8]. Progress in physics of nuclear molecules and nuclear clustering were facing some of the greatest challenges and opportunities in the years ahead. Besides the well known series of Cluster conferences [9, 10, 11], a series of workshops on the State-Of-The-Art in Nuclear Cluster Physics was started citeStrasbourg,Brussels,Yokohama. The first one was held in Strasbourg in 2008 [12], the second one in Brussels in 2010 [13] and the last one in Yokohama in 2014 [14]. Fig. 1 (taken from the cover of Ref. [14]) summarizes the different types of clustering that were discussed during the last two or three decades [8, 15]. Most of these exotic 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 $\alpha$-conjugate ($N=Z$) nuclei in the energy regime from the Coulomb barrier up to regions with high excitation energies ($E_x=20–50$ MeV) remains a subject of contemporary debate [1, 8]. These resonances were 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 were associated with strongly-deformed shapes and with $\alpha$-clustering phenomena [6, 8, 17, 18], predicted from the Nilsson-Strutinsky approach, the cranked $\alpha$-cluster model [6, 17], or other mean-field calculations [18, 19]. In light $\alpha$-like nuclei clustering is observed as a general phenomenon not only at high excitation energies close to the $\alpha$-decay thresholds [6, 8, 17, 20] but may also play a key role at low excitation
energies and for the ground states. This exotic behavior was perfectly illustrated by the famous "Ikeda-diagram" for $N=Z$ nuclei in 1968 [21], which was modified and recently extended by von Oertzen [22, 23] for neutron-rich nuclei, as shown in the right panel of Fig. 2. Despite the early inception of cluster studies, it is only recently that radioactive ion beams experiments, with great help 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. For instance, new experimental approaches for the tetraneutron system at RIKEN [24] challenge the most advanced theoretical models [25, 26]. On the other hand, predicted but elusive phenomena, such as molecular orbitals or linear chain structures, are now gradually coming to light from experimental data [6, 8].

Clustering is a general feature [6, 8, 23] not only observed in light neutron-rich nuclei [27], but also in halo nuclei such as $^{11}$Li [28] or $^{14}$Be [29], for instance. The problem of cluster formation has also been treated extensively for very heavy systems by R.G. Gupta [19], by D. Poenaru, V. Zagrebaev and W. Greiner [30, 31] and by C. Simenel [32] suggesting that giant molecules and collinear ternary fission may co-exist [33]. Finally, signatures of $\alpha$-clustering have also been predicted and/or discovered in light nuclei surviving from intermediate-energy [34] to ultrarelativistic-energy [35] nuclear collisions. The topic of nuclear clusters benefits of intense theoretical activity [7] where new experimental information has come to light very recently [6, 8]. Several status reports were given in conferences and their written contributions can be found in their respective proceedings [15, 36, 37].

2. Renewed interest in the spectroscopy of light $\alpha$-like nuclei: $\alpha$ condensates?

The renewed interest in the $^{12}$C nucleus [38] was mainly focused to a better understanding of the nature of the so called "Hoyle" state [39] that can be described in terms of a bosonic
condensate, a cluster state and/or a $\alpha$-particle gas [40, 41, 42]. Much experimental progress has been achieved recently as far as the spectroscopy of $^{12}$C near and above the $\alpha$-decay threshold is concerned [38, 43, 44]. More particularly, the $2^+ \rightarrow$ "Hoyle" rotational excitation in $^{12}$C has been observed [43]. The $^{12}$C($\alpha,\alpha$)$^{12}$C* reaction [44] 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 [38, 45].

In the study of Bose-Einstein Condensation (BEC), the $\alpha$-particle states in light $N=Z$ nuclei [40, 41, 42], 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 [39] 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 [46]. However, any state in $^{16}$O equivalent to the "Hoyle" state [39] 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. [47] could excite these states in an $\alpha$-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. A more sophisticated experimental setup was used recently [48]: although the excitation function is generally in good agreement with the previous results [47] a phase shift analysis of the angular distributions does not provide evidence to support the reported hypothesis of a 4$\alpha$-chain state configuration. Tetrahedral symmetries are predicted to occur in $^{16}$O [49]. Experimental investigations are still underway to understand the nuclear structure of high-spin states of $^{16}$O, $^{20}$Ne and heavier nuclei [50, 51]. The search for exotic chain-like structures remains an exciting prospect but, up to now, tentative evidence of chain states have been unsubstantiated and the view is that such structure have not yet been definitively observed.

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

The relationship between $\alpha$-clustering, nuclear molecules and superdeformation (SD) [8, 18, 52, 53] 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 in terms of clustering phenomena [8]. Typical examples for the link between quasimolecular bands and extremely deformed (SD/HD) shapes can be found in the literature for $A = 20 - 60$ $\alpha$-conjugate $N=Z$ nuclei [8, 18, 36, 52, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67]. Highly deformed shapes and SD rotational bands have been discovered in several light $\alpha$-like nuclei, such as $^{36}$Ar and $^{40}$Ca by using $\gamma$-ray spectroscopy techniques [57, 59]. In particular, the extremely deformed rotational SD band in $^{36}$Ar [57] is comparable in shape to the quasimolecular bands observed in both $^{12}$C+$^{24}$Mg and $^{16}$O+$^{20}$Ne reactions [8, 58, 64]. Ternary clusterizations are also predicted theoretically, but were not found experimentally in $^{36}$Ar so far [8, 58]. On the other hand, ternary fission of $^{56}$Ni, related to its HD shapes, was identified from out-of-plane angular correlations measured in the $^{32}$S+$^{24}$Mg reaction with the Binary Reaction Spectrometer at the VIVITRON Tandem facility [67]. This possibility [8, 67] is not limited to light $N=Z$ compound nuclei, true ternary fission [31, 33, 68] can also occur for very heavy [33, 68] and superheavy [69] nuclei. The next natural question to be addressed is whether dilute-gas-like BEC structures [40, 41, 42] also exist in medium-mass $\alpha$-conjugate nuclei as predicted by several theoretical investigations [70, 71, 72]. Several recent undergoing experiments indicate that it might be the case at least for $^{24}$Mg [73], and much work is in progress in this field [8, 41].
4. Clustering in light neutron-rich nuclei

Clustering is a general phenomenon [8] observed also in nuclei with extra neutrons as illustrated in Fig. 2 by the "Ikeda-Diagram" [21] modified and extended by von Oertzen [22]. With additional neutrons, specific molecular structures appear with binding effects based on covalent molecular neutron orbitals. In these diagrams α-clusters and 16O-clusters are the main ingredients. Actually, the 14C nucleus may play a similar role in clusterisation as the 16O nucleus does. Both of them have similar properties as a cluster: 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 investigation of the oxygen isotopes with A ≥ 17. Recent results on the even-even oxygen isotopes i.e. 18O [74, 75] and 20O [23] as well as very striking cluster states found in odd-even oxygen isotopes such as 17O [76] and 19O [23] have been obtained. Therefore, the "Ikeda-Diagram" [21] and the "Extended Ikeda-Diagram" consisting of 16O cluster cores with covalently bound neutrons [22] is being further revised to include also the 14C cluster cores as illustrated in Fig. 2 (right panel).
5. Concluding remarks
Marked progress is being accomplished in many traditional or novel subjects of nuclear cluster physics. High-precision spectroscopy techniques enable us to uncover important parts of the complete spectroscopy of the "Hoyle" state in $^{12}$C. Thus, 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. The connection of $\alpha$-clustering and quasimolecular resonances with $\alpha$ condensates in very light nuclei and with extreme deformations (SD, HD, ...) in heavier nuclei as investigated by more and more sophisticated experimental devices is discussed in this introductory talk. Some neutron-rich nuclei displaying very well defined quasimolecular bands in agreement with theoretical predictions justify the "Extended Ikeda-Diagram" to be generalized by the inclusion of the $^{14}$C cluster as a core, similarly to the $^{16}$O one. The developments in these selected subjects of nuclear clusters physics show the importance of clustering among the basic modes of motion of nuclear many-body systems.

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