Clustering phenomena: perspectives from iThemba LABS

R. Neveling
iThemba Laboratory for Accelerator Based Sciences, Somerset West 7129, South Africa
E-mail: neveling@tlabs.ac.za

Abstract. Aspects of alpha-clustering in nuclei were studied at iThemba LABS over the past twenty years by means of quasi-free scattering, inelastic scattering and transfer reactions and through particle decay spectroscopy. An overview of relevant work is provided, which highlights the unique opportunities at iThemba LABS, specifically with the K600 zero degree facility and recently commissioned ancillary detection systems.

1. Introduction
The study of clustering phenomena in nuclei, in particular alpha-clustering, is almost as old as the field of nuclear physics itself, and essentially started when Rutherford first distinguished between α and β rays in the radiation emitted from uranium and its compounds [1]. These rays were later identified as particles, specifically the core of the 4He atom (or α particles) and electrons. The α-rays Rutherford observed were α-particles undergoing quantum-mechanical tunneling from inside the decaying nucleus. The question whether these α particles could be considered as pre-formed inside the nucleus ushered in a research topic on clustering that is still of interest today.

Various aspects of clustering phenomena have been under investigation at the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS), South Africa. The majority of these exploit the capabilities of the K600 magnetic spectrometer at iThemba LABS, a high resolution kinematically corrected quadrupole dipole dipole magnetic spectrometer for light ions. In recent years the capability to measure inelastically scattered particles and reactions at extreme forward angles that includes zero degrees was successfully developed [2], making it one of only two facilities worldwide (the other being at RCNP, Japan [3]) where high energy resolution is combined with zero degree measurements at medium beam energies. The advantage of such measurements is the selectivity it provides to excitations with low angular momentum transfer. For this reason it represents a valuable experimental tool for research into E0 and E1 resonance strengths [4, 5, 6] but crucially also in finding and identifying ΔL=0 cluster states. The recent addition of coincident particle and gamma detection capabilities [7] further enhances the selectivity of such a facility, which opens up a host of new opportunities to be explored.

2. Clustering in the ground state
The focus of studies into alpha clustering phenomena is commonly in relation to the appearance of cluster structures at and beyond excitation energies equivalent to alpha particle decay
thresholds. This state of affairs follows from the definition for the emergence of clustering phenomena as developed by Ikeda et al. [8]. According to this picture the $^8$Be nucleus is the only example whereby it would be reasonable to expect alpha clusters appearing in the ground state, as all states in $^8$Be lies above the alpha decay threshold. However, anti-symmetrized molecular dynamics (AMD) calculations [9] indicate a non-negligible cluster structure in the mass density distributions for the ground state in the case of the $^{12}$C nucleus. It would therefore seem that the concept of ground state clustering is not entirely unreasonable.

The most direct experimental method to test the notion of ground state $\alpha$-clustering is by means of a knockout reaction in which the knocked out cluster is observed in coincidence with the projectile. The assumption that clusters of nucleons exist in nuclei would be strongly supported if the momentum distribution of the clusters as inferred from the coincidence spectra of emitted particles is in agreement with that expected from a preformed cluster bound in a target nucleus. This follows from good shape agreement between distorted wave impulse approximation (DWIA) [10] calculations and experimental energy sharing differential cross section data, as well as agreement between extracted spectroscopic values and theoretical predictions thereof.

However, DWIA cross sections are sensitive to inaccuracies in the often poorly known optical potentials used to generate wave functions of composite particles with nuclei, thus affecting the absolute value [11] and shape of the calculated cross sections. Fortunately for experiments using polarized beams there is an observable, the analyzing power $A_p$, that can act as a more stringent test of the reaction dynamics [12], which directly affects the interpretation of the results in terms of the existence of preformed $\alpha$ clusters in the ground state. If the reaction dynamics can be shown to be a quasi-free knockout mechanism, one expects that the analyzing power at the quasi-free peak will correspond to that of free $p+\alpha$ elastic scattering. The analyzing power is in essence a ratio of cross-sections, and is therefore in general less sensitive to the ingredients of the DWIA calculations, especially for light nuclei where there is minimal distortion of the incoming and outgoing waves.

This was indeed shown to be the case when the analyzing power distribution in the $^{12}$C($p, p\alpha$)$^{9}$Be(g.s.) reaction was studied at iThemba LABS at an incident energy of 100 MeV [13]. The experimental analyzing power of the coincidence measurement was found to be in good agreement with the DWIA prediction as well as the trend of the analyzing power of free $p+^4$He elastic scattering, as shown in Fig.1. The results are consistent with a projectile interacting with $\alpha$ clusters as if they are free entities inside the nucleus, with the rest of the target nucleus acting merely as a spectator, and can be considered as evidence for the existence of preformed $\alpha$-clusters in the ground-state of $^{12}$C. Investigations of the ($p, p\alpha$) reaction on the heavier $^{40}$Ca target with the K600 in coincidence with a single Si surface barrier detector telescope reveal a bigger influence of the distorting potentials on the analyzing power distributions, such that the results no longer agrees with free $p+^4$He elastic scattering [14]. However, proper agreement between the experimental analyzing power distribution and DWIA calculations can still be obtained provided the $\alpha+^{36}$Ar system is properly treated, which is indicative of the existence of a ground-state $\alpha$-cluster structure in $^{40}$Ca [15].

Recent interest in the use of quasi-free knockout reactions to investigate clustering in even heavier nuclei follows from theoretical calculations by Tygel [16] describing the formation of $\alpha$-clusters on the surface of Sn isotopes. While plans are afoot to use the ($p, p\alpha$) reaction on $^{112-124}$Sn at 300 MeV at RCNP to investigate these claims, Cowley [17] used existing experimental information from ($d,^6$Li) cluster pickup reactions to verify the predicted trend. The validity of the substitution of the ($d,^6$Li) reaction for the ($p, p\alpha$) knockout reaction follows from work by Carey et al. [18] who found a remarkable similarity of the relative spectroscopic factors extracted from ($p, p\alpha$) and ($d,^6$Li) reactions for target nuclei covering a large mass range across the periodic table.
Figure 1. Experimental analyzing power distribution for the $^{12}\text{C}(p,p\alpha)^8\text{Be}$ reaction (filled circles) compared with a DWIA calculation (solid line) and free $p+\alpha$ elastic scattering data (empty circles) displayed as a function of the two-body center-of-mass $p-\alpha$ scattering angle, from Ref. [13].

3. 2$^+$ excitation of the Hoyle state

Whereas quasi-free knockout reactions do not comment on the structural arrangement of clusters inside the nucleus, such information can be deduced from collective excitations of cluster states. The famous Hoyle state, the $0^+_2$ state at 7.654 MeV in $^{12}\text{C}$, is widely considered to have a 3$\alpha$ cluster structure [19, 20]. The first potential 2$^+$ state above the Hoyle state is reported to be at 11.160 MeV [21]. This state was observed in one experimental measurement only, namely in the investigation of the $^{11}\text{B}({}^3\text{He},d)$ reaction at 44 MeV with the Michigan 180$^\circ$ double-focussing magnetic spectrometer [22]. Its position is problematic, as at more then 3.5 MeV above the Hoyle state this 2$^+$ candidate does not agree with predictions for a linear chain arrangement for the Hoyle state, which would imply a collective 2$^+$ state at $\sim$0.8 MeV above the Hoyle state [23]. A Hoyle state consisting of a dilute self-bound gas of bosonic $\alpha$-particles would, from BEC calculations, locate a 2$^+$ state at $\sim$ 1.3 MeV above the Hoyle state [24]. Close, but still not quite there, FMD calculations locate the first 2$^+$ state at $\sim$ 2.3 MeV above the Hoyle state [25].

In fact, no clear peak was observed by Reynolds et al. [22], and the 2$^+$ assignment for the spin and parity of the state is only tentative. To date this observation remains unconfirmed. It is worthwhile to mention that the original $^{11}\text{B}({}^3\text{He},d)$ measurement was performed with photographic plates at the focal plane. The linear response of such detectors are typically superior to the non-uniform effects seen with the Multi Wire Drift Chambers (MWDC) used in more modern focal plane detectors. However, the event-by-event data reconstruction capabilities of modern data acquisition systems allow for a more thorough investigation of beam background and target contamination sources. In order to allow for a definitive assignment of spin and parity to this state, the measurement was revisited. The repeat of the $^{11}\text{B}({}^3\text{He},d)^{12}\text{C}$ measurement was performed at iThemba LABS with the K600 magnetic spectrometer. No evidence was found for the previously reported 2$^+$ state at 11.16 MeV [26], and it was not possible to identify contaminating candidates responsible for the strength observed around 11.16 MeV in Ref. [22],
Figure 2. Excitation energy spectra of the $^{12}$C nucleus as obtained from various experiments performed at iThemba LABS with the K600 [26, 27, 31, 32, 33]. The different datasets were normalized on the strength of the Hoyle state. The arrows on the horizontal axis indicate the position of known excited states in $^{12}$C (but excluding the 11.16 MeV 2$^+$ state [26] and the 10.13 MeV 2$^+$ state [28]). Red arrows indicate natural parity states. Contaminant peaks from other carbon isotopes as well as oxygen are especially evident in the proton inelastic scattering data.

such as different particles with the same rigidity emitted as reaction particles from possible $^{10}$B, O, C, or N contaminants in the target of Ref [22].

Without the presence of the tentatively assigned 2$^+$ state at 11.16 MeV the question is: where is the 2$^+$ excited state of the Hoyle state? The first strong evidence for the existence of a new candidate 2$^+$ excitation of the Hoyle state was provided by inelastic proton scattering measurements at iThemba LABS. The high sensitivity experiment was performed with a 66 MeV proton beam, observing the scattered protons with the K600 magnetic spectrometer at a range of angles chosen to emphasize the 2$^+$ excitation while suppressing the other $^{12}$C excited states. Evidence was found for a possible 2$^+$ state at 9.6(1) MeV with a width of 600(100) keV [27]. The state in question falls within a region dominated by other states, some of which are very broad, such as the broad 0$^+$ strength around 10 MeV. This makes the 2$^+$ excited state of the Hoyle state, itself a broad state, very difficult to observe. This can be seen in Fig.2 in the typical excitation energy spectra of $^{12}$C obtained with various probes. The definitive experiment establishing the position and width of the 2$^+$ excited state of the Hoyle state at $E_x=10.03(11)$ MeV and $\Gamma=800(130)$ keV respectively was the measurement of the $^{12}$C($\gamma$,3$\alpha$) reaction at HI$\gamma$S [28]. The major advantage of this measurement was the fact that $\gamma$-ray beams cannot populate 0$^+$ states and only populates the 3$^-$ state weakly. Therefore it does not suffer from the influence of the overwhelming background conditions as in the case of the inelastic proton scattering experiment at iThemba LABS.
4. The search for $0^+$ states

The exact nature of the structure of the Hoyle state, which is widely considered to have a 3α-cluster structure [19, 20], remains unresolved. In one interpretation it is considered to have a 3α gas-like structure similar to a Bose-Einstein condensate consisting of three α particles all occupying the lowest 0S state [29], although it has also been shown that one must be careful when referring to only three particles being in a Bose-Einstein condensation [25]. Despite the fact that the details of the structure of the Hoyle state are still debated, it is widely considered to be a prototype for a class of states near the α-particle thresholds in light self-conjugate 4n nuclei [25, 29]. In the spirit of this conjecture the neighbouring $^{16}$O and $^{20}$Ne nuclei were experimentally investigated at iThemba LABS.

A potential Hoyle-like candidate in $^{16}$O was identified by Funaki et al. [30]. They solved a four-body equation of motion based on the Orthogonality Condition Model (OCM) that succeeded in reproducing the observed $0^+$ spectrum in $^{16}$O up to the $0^+_6$ state. It was shown that a 4α condensation state could be assigned to the $0^+_6$ state located at 15.097 MeV, for which the calculation yields a large radius of 5 fm, indicating a dilute density structure. It is in principle possible to gain insight into the structure of the state by studying its the decay properties. The decay of the Hoyle state is known to take place mostly through $^8$Be+α decay, with the upper limit for direct 3-α decay known to be in the range 0.043%-0.047% [34, 35]. Although this makes it tempting to simplistically claim a $^8$Be+α structure for the Hoyle state, it was found that the observed decay is consistent with theoretical calculations that assumes an explicit 3α structure [36]. In order to investigate the particle decay of the Hoyle-like candidate in $^{16}$O the $^{16}$O($\alpha, \alpha'$) reaction was studied at $0^\circ$ with the K600 magnetic spectrometer, with coincident proton and α-decay from the natural parity states observed in a large-acceptance silicon-strip detector array called CAKE at backward angles [37], as shown in Fig. 3. Surprisingly, instead of enabling the characterization of the decay path of the $0^+_6$ state at $E_x = 15.097$ MeV, the angular correlations of charged-particle decays from $^{16}$O the $0^+_6$ state were measured with coincidence, and the decay is consistent with the decay being consistent with the decay taking place through a $^8$Be+α decay.

In the case of the $^{20}$Ne nucleus no known candidate $0^+$ state exists near the 5α breakup threshold at $E_x = 19.17$ MeV. There are 49 known states in this nucleus at excitation energies above 18.43 MeV [40], none of which have spin values below $J = 4$. The excitation energy spectrum of the $^{20}$Ne nucleus, from the ground state to $E_x = 25$ MeV, was subsequently investigated with the $^{22}$Ne($p, t$)$^{20}$Ne reaction at a beam energy of 60 MeV with the K600 magnetic spectrometer at numerous energies, including zero degrees [41]. Narrow, low-spin $J^\pi = 0^+,-1$, and $2^+$ states have been observed for the first time at high-excitation energies in $^{20}$Ne, namely at $E_x = 17.67, 18.84, 20.59, 21.16, 21.80,$ and 22.5 MeV. Shell-model and coupled reaction channel calculations were performed to determine the nature of the newly observed states. The state at 22.5 MeV, which could not be interpreted by the shell-model calculations, can be considered a tentative candidate for the 5α cluster state.

More generally, clustering phenomena can be associated with large deformation in nuclei, and associated superdeformed rotational bands have been observed in nuclei such as $^{36}$Ar and $^{40}$Ca [42]. In lighter nuclei such as $^{28}$Si the superdeformed bands are less clear, since the standard techniques to observe these bands rely on heavy ion fusion evaporation reactions in order to populate high spin states, followed by the observation of γ-rays from decays down the band. Such methods are not efficient in observing the low-spin states. Of particular importance is locating the $0^+$ bandhead of previously tentatively identified superdeformed bands. For this reason the K600 magnetic spectrometer was used for inelastic α-particle scattering on $^{28}$Si at very forward angles, to allow for the clear identification of $0^+$ states. A new $0^+$ state at 9.71 MeV
Figure 3. Two-dimensional coincidence matrix for inelastically scattered $\alpha$-particles from a $^{nat}\text{Li}_2\text{CO}_3$ target summed over all angles in the silicon-strip detector array. Three $^{16}\text{O}$ decay channels ($\alpha_0$, $\alpha_1$, $p_0$) are indicated, as well as prominent low spin states in $^{16}\text{O}$, including the supposedly $0^+_6$ state at $E_x = 15.097$ MeV. From Ref. [44].

was subsequently identified [43], which is a strong candidate for the bandhead of a previously identified superdeformed band.

5. Future work

The combination of good energy resolution through dispersion matching techniques and the zero degree capability of the K600 makes it possible to search for cluster states through low spin transfer reactions such as ($p$,$t$) and ($\alpha$,$\alpha'$). While the experimental studies so far focused on self-conjugate 4n nuclei, it is also envisaged to investigate matters relating to the $2\alpha+t$ cluster structure in $^{11}\text{B}$, where theoretical calculations [45] indicate many positive parity states around the $2\alpha+t$ threshold with features of developed clusters. Finally, it is foreseen that the polarized ion source at iThemba LABS will be put to good use in inclusive analyzing measurements to further investigations into the ground-state clustering of heavy nuclei.

Acknowledgements

The financial assistance of the South African National Research Foundation (NRF) towards research at iThemba LABS is hereby acknowledged. R.N. specifically acknowledges financial support from the NRF through Grant No. 85509. The results presented here represent the work of various collaborations within the K600 working group.

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