Conference summary: an experimental perspective

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Abstract. The experimental results reported at this conference, the themes that emerged and the implications for future work are examined. Some example highlights, chosen from a personal perspective are discussed.

1. Introduction
A wide range of experimental work has been presented in this conference, including some new approaches and some new developments of older methods. Some common themes emerged during the week, and this summary aims to bring together those themes and to examine where they might lead us in the future. The aim is not to provide a complete summary of all contributions; all of the papers are here in the proceedings. Nor is the aim to provide an up-to-date overview of clustering studies; that is addressed more by the introductory article by Freer [1]. Rather, we summarise the snapshot of themes and directions offered by this conference, and discuss some illustrative examples.

Any non-exhaustive summary will inevitably represent a personal perspective. Therefore, it is perhaps acceptable to begin with a short introduction about my own history of studying clustering, partly to declare my personal position and prejudices. This conference, the tenth in the series of Cluster conferences, was the fourth of the series that I attended, after Chester, Strasbourg and Stratford-on-Avon. The very first topic in nuclear physics that I ever studied experimentally, in 1978, was the cluster structure of $^{16}$O via inelastic scattering $^{12}$C($\alpha, \alpha_2$)$^{12}$C*, exploiting the selectivity imposed by requiring $^{12}$C in the $0^+_2$ ‘Hoyle’ state [2]. That work was based in turn upon a paper from ten years earlier, in 1967 [3]. We heard at this conference that essentially the same reaction is still being studied today, and with much the same objectives. My point is that there is something inherently difficult about these experiments — both technically and in the theoretical interpretation — or else we would surely have clear answers by now.

Clustering in nuclei is one of the most misunderstood aspects of nuclear structure. As I have remarked before [4], some of our colleagues are convinced that we cluster people are in a state of denial, because it has been evident since the earliest studies that $\alpha$-particles cannot retain an existence as real $\alpha$-particles when they are inside nuclei [5, 6]. Of course, we are not so misled, and the current theoretical models are extremely sophisticated. Nevertheless, the proper situation has not been transmitted to our non-clustering colleagues world-wide in an entirely effective fashion. One reason is experimental: what exactly is the experimental evidence that particular nuclides, or rather particular states within a nuclide, should be classified as cluster states? The values of partial widths for $\alpha$-particle emission are driven by energetics and dynamics, as well as structure, and it can be challenging to disentangle the contributions. The presence,
and mixing, of states with other structures (such as more-standard shell model structure) also complicates the interpretation of experiments. Nevertheless, better and better experiments are being performed and progress is being made both experimentally and theoretically. To return to a short review talk that I gave nearly fifteen years ago [4] I’d like to mention two points. Firstly, the comment was made with reference to $^{12}$C: ‘perhaps it is reasonable to think of this as a kind of Bose-Einstein condensate of $\alpha$-particles’. This was a musing based on little real knowledge. In recent years, however, our theoretical colleagues have applied such ideas in a rigorous way in the THSR model [7], and this has given deep new insights into the structure of cluster nuclei. The BEC description is not applicable to all states, but provides an excellent description for particular states where the individual $\alpha$-particle clusters are more distinct. The existence of such BEC states in a strong-force environment is an extraordinary feature of nuclear structure, as seen for example in the 7.65 MeV ‘Hoyle’ state in $^{12}$C. It is worth commenting that the type of condensation seen, for example, in the ground state of $^{12}$C is equally remarkable. In early models [8], and in more detailed microscopic models where the clustering arises naturally [9, 10, 11, 12], the individual $\alpha$-like mass centres are evident even in the more-compact $^{12}$C ground state. The cluster structure persists, even though the objects overlap, interact via the strong interaction and constantly exchange nucleons. As remarked by Kanada-En’yo [11], the Pauli principle inhibits the full rotational symmetry whilst still retaining strong structural symmetries. Perhaps this type of condensation is unique to nuclear physics. In that earlier review talk [4], a second remark concerned the predicted linear chain states of alpha-particles that were then popular in the literature [13] and asserted that they were ‘not compellingly in evidence experimentally beyond $^{8}$Be.’ The same conclusion was reached in the comprehensive review published just before the previous cluster conference in Stratford [14]. In the present conference, we have seen tentative new evidence for pushing this experimental boundary up to $^{12}$C [15], via a detailed analysis of inclusive and exclusive $\alpha$-particle inelastic scattering. The analysis highlights the extreme difficulty in pinning down potential chain states experimentally, in regions of excitation energy where many broad underlying states coexist. Finally, from the earlier review talk [4], Figure 1 was used to summarise the different types of clustering discussed in the literature. All of these structures were discussed, in an experimental context, at the present meeting except for the extremely speculative necklace type of state [16] and the longer chain configurations. A decline in the emphasis on simple linear chains is a change over the last fifteen years, for reasons mentioned above. A newly emerging and related topic of study is the class of covalently bound states, whereby a chain is stabilized or a cluster-core interaction is modified by one or two covalently bound neutrons.

2. Experimental Themes

This conference was wide-ranging in its scope and impressive in the number of new results presented. Some recurring themes emerged, and we choose to limit the discussion here to some examples that fall under the following headings, representing four physics themes:

- $^{12}$C: particular states, especially the 2$^+$ excitation of the Hoyle state, and 0$^+$ states
- BEC: the Bose-Einstein condensate in $^{12}$C, fascinating theory for $^{16}$O and a search in $^{24}$Mg
- Detailed studies of certain light nuclei below $^{12}$C
- Renewed interest in sd-shell cluster resonances,

and four instrumentation/methodology themes:

- Resonant scattering in inverse (or even normal) kinematics
- A resurgence in the use of magnetic spectrometers
- Renewed exploitation of gamma-ray decays to uncover cluster structure.
- Some insights and results relating to high energy knockout such as $(p,p'\alpha)$.
The fact that $^{12}\text{C}$ would, by itself, be a major theme of the conference was foreseen in the logo chosen by the organisers. The renewed interest in $^{12}\text{C}$, one of the very first nuclei to be studied from a cluster perspective, was due to the exceptionally interesting questions that have become accessible experimentally and theoretically. Many of these were described in the introduction by Freer [1].

Exciting new results for $^{12}\text{C}$ were reported by Itoh [15]. In a previous publication [17] this group showed good experimental evidence for the $2^+$ excitation of the Hoyle state, at 9.84 MeV. The analysis used the multipole decomposition (MD) technique whereby $(\alpha, \alpha')$ angular distributions are decomposed, as a function of excitation energy, into a superposition of the expected distributions for each angular momentum transfer. Their analysis also showed evidence that the broad $0^+$ strength near 10 MeV was split into two components centred at 9.04 and 10.56 MeV respectively. The analysis was admittedly complicated by the presence, right in the middle of this same region of energy, of the narrow, strongly excited $3^-$ state at 9.64 MeV. The new results from this conference [15] extend the experimental setup to measure coincident decay $\alpha$-particles. They include the angular correlation functions (ACFs) for decays feeding the $^{8}\text{Be}_{g.s.}(0^+)$ and the $^{8}\text{Be}(2^+)$ states, extracted for a series of narrow slices in the excitation energy of $^{12}\text{C}$. The ACF and decay-branching analyses are consistent with the earlier MD conclusions and significantly strengthen the association of the two regions of $0^+$ strength, respectively, with a higher nodal state of the Hoyle state (at 9.04 MeV) and the long sought-after $0^+$ linear chain state in $^{12}\text{C}$ (at 10.56 MeV).

Equally exciting were the measurements reported by Gai [18] for the reaction $^{12}\text{C}(\gamma, 3\alpha)$ studied by stepping the energy of an almost monoenergetic beam of gamma-rays through the excitation range 9.1 to 10.7 MeV in $^{12}\text{C}$. The breakup of the $^{12}\text{C}$ into three $\alpha$-particles was recorded optically in three dimensions in a time projection chamber that also served as the target. The angular correlation for the $\alpha + ^{8}\text{Be}_{g.s.}(0^+)$ channel was extracted at each incident beam energy. The excitation function was fitted, taking into account a $2^+$ contribution (E2) and a $1^-$
contribution (E1). Note that the excitation function was sensitive not only to the magnitudes and shapes of the E2 and E1 strengths, but also the phase between their contributions. An analysis including a phase difference that was consistent with theory gave precise parameters for the 2\(^+\) state, with a resonance energy of 10.03 MeV and a peak cross section (owing to the energy-dependent Breit-Wigner resonance shape) of 9.8 MeV. Gai [18] discusses the properties of this 2\(^+\) state in terms of an excitation of the Hoyle resonance. This state was also measured and discussed by Itoh [15] and Freer [1].

Kawabata [19] reported new results from searching in a heavier nucleus for a Hoyle-like state, described as an \(\alpha\)-condensed state or a dilute-gas-like structure of \(\alpha\)-particles. As in the work on \(^{12}\)C [15], inelastic scattering of \(\alpha\)-particles was studied at the Osaka cyclotron using the dispersion-matched Grand Raiden spectrometer, now with a \(^{24}\)Mg target. Again, coincident particles from the decay of the excited nucleus were detected: in this case, proton, \(\alpha\) and \(^{9}\)Be decays of \(^{24}\)Mg could be identified. The multipole strength from the MD analysis gave no candidate for a 6\(\alpha\) condensed state near the relevant energy threshold. Possible candidates were identified for \(\alpha\)-condensed states around the cores \(^{12}\)C and \(^{16}\)O near the energies that had been predicted [20]. A state at 13.9 MeV that decays mostly by \(\alpha\)-particle emission was considered to be the best candidate for a 2\(\alpha\)\(^{16}\)O condensed state. As a comment, naively the state seems remarkably narrow for a 0\(^+\) state at this energy, fitting within the 200 keV width of the bins in the MD analysis. A known isoscalar 0\(^+\) state at 11.73 MeV already has a width of 10 keV and a 0\(^+\) state at 13.04 MeV [21] has a width of 3 keV even though it is largely T = 1 in character (the 13.04 MeV T = 1 state is, as expected, very weakly if at all, in the MD analysis). There is no doubt that the states reported by Kawabata are very interesting and merit further investigation.

The technique of inverse resonant scattering was clearly evident throughout the experimental sessions. In this technique a heavy beam is incident (in inverse kinematics) on light target nuclei comprising a thick target (which may be a gas). The beam will typically pass through various resonances as it slows down. Taking advantage of the large difference in energy loss between the beam and target, the depth of the reaction can be reconstructed for each event, assuming elastic scattering. Excitation functions can be measured relatively quickly over a wide range of energies. In one talk describing this technique, Norrby discussed a study of \(^{32}\)S via the \(^{28}\)Si+\(\alpha\) reaction [22]. This revealed 30 new level assignments in a study spanning 132 resonances in total. This reaction has also been studied much more laboriously in normal kinematics using a \(^{4}\)He beam, and a direct comparison of the two methods is shown in Figure 5 of Ref. [22]. The inverse technique has poorer energy resolution and a higher background, balanced against its speed advantages. Rogachev’s talk [23] also reported work using the inverse scattering technique, including conclusive new results for the highly \(\alpha\)-clustered state at 10.16 MeV in \(^{10}\)Be, confirming the spin as 4\(^+\). Another very exciting aspect of this talk was the description of the new device ANASEN [24] used in the experiment. This device comprises a cylindrical gas target volume surrounded by silicon strip detectors that are backed by CsI scintillators. Inside the radius of the silicon array, proportional counters within the gas volume allow tracking of the detected particles, which arise from reactions of the beam as it travels through the fill gas. This is truly the Rolls Royce of devices for this type of experiment, and heralds the arrival of a new generation of results exploiting this technique.

Inverse resonant scattering wasn’t developed specifically for radioactive beam experiments, but is perfectly adapted to them. With a short-lived radioactive ion, the option of a normal kinematics experiment doesn’t exist. The ANASEN detector mentioned above is in fact designed primarily for studies with radioactive beams. Such radioactive beam experiments at the low energy CRIB facility at RIKEN, including \(^{7}\)Be+\(^{4}\)He, were described by Kubono [25]. Using a 90% pure beam of \(3 \times 10^8\) pps, the reactions \((\alpha, \alpha)\) and \((\alpha, p)\) were studied with an astrophysical motivation. The same resonant nucleus, \(^{11}\)C, has also been studied using the inverse resonant
scattering technique by Freer et al., with a weaker but pure beam of $5 \times 10^7$ pps at Louvain-la-Neuve [26], and this was extended to higher excitation energies using the much higher energy (pure $^7$Be) beam of $5 \times 10^4$ pps available at the Oak Ridge tandem [26].

The resurgence of interest in the study of nucleon transfer and compound nuclear reactions using magnetic spectrometers, with their high energy resolution, is exemplified by the reports by Milin [27] and Wheldon [28]. An example discussed by Milin was the study [29] in which many states in $^{18}$O were tentatively identified up to nearly 20 MeV excitation, and assigned to positive and negative parity rotational bands. This process is fraught with subjectivity because of the difficulty in obtaining conclusive spin assignments. This was recognised and addressed in Ref. [29] where the systematic dependence on spin of the differential cross section at a fixed angle was used to help validate the spin suggestions. The cross section should follow a $(2J + 1)$ dependence, which is statistical and independent of the reaction mechanism [29], but some scatter for specific states can, and does occur, making definitive assignments impossible. With tentative spins, the identification of rotational bands based largely on energy-spin systematics is dangerous, as discussed by Milin [27] with reference to $^{13}$C (where subsequent measurements contradicted some previous suggestions).

Two talks, in particular, described a revival in the use of gamma-ray decays to understand possible cluster structure. Jenkins [30] and Courtin [31] concentrated on studies aimed at the molecular resonances seen in $^{12}$C+$^{12}$C and $^{16}$O+$^{12}$C, respectively. This work revisits pioneering studies by Sandorfi et al. [32, 33] in the 1980’s, but with significant experimental improvements. Jenkins [34] reviewed a study of the region near 20 MeV excitation in $^{24}$Mg which showed resonances with spins of 0 or 2 that decay via isovector M1 transitions through $1^+ T = 1$ levels near 8–10 MeV. The decay of such resonances via high energy gamma-rays of order 10 MeV was predicted theoretically by Baye and Desouvemont [36] although their explanation didn’t involve the $T = 1$ states identified here. Courtin [31] reported new results showing similar behaviour in $^{16}$O+$^{12}$C. Resonances near 25 MeV excitation in $^{28}$Si decayed via enhanced isovector M1 transitions through $1^+$ and $2^+ T = 1$ states. A $^{12}$C+$^{13}$C resonance at 22 MeV in $^{24}$Mg was studied in more detail using Gammasphere [35]. The decay was largely statistical but with some enhancement in the population of a particular prolate rotational band in $^{24}$Mg. The idea that it might be possible to infer deformed cluster structure from the preferential population of prolate deformed bands was discussed earlier by Sandorfi and collaborators [33]. It also brings to mind other studies, for example that by Sanders et al. [37] where the symmetric fission of a $^{56}$Ni compound nucleus was seen to populate preferentially a prolate band in $^{28}$Si. Courtin [31] also reminded us of an ambitious experiment by Haas et al. to measure in-band gamma-ray transitions between high-lying rotational states in $^{24}$Mg [38]. This experiment was also mentioned in the introduction by Freer [1]. The $^{24}$Mg states had been seen previously to break up by fission into $^{12}$C+$^{12}$C. If these states represent a very highly deformed rotational band, then an in-band gamma-ray transition could be sufficiently enhanced to compete with particle emission at a detectable level. In the experiment, $^{24}$Mg was populated at an excitation energy of 30.5 MeV corresponding to a known $10^+$ resonance, and then the missing kinetic energy in the $^{12}$C+$^{12}$C fragments (Q-value) was compared with the observed gamma-ray energy. A measurement of $\Gamma_{\gamma}/\Gamma = (1.2 \pm 0.4) \times 10^{-5}$ was reported for the $10^+$ to $8^+$ transition ($E_{\gamma} = 6.9$ MeV) [38], which perhaps might best be interpreted as an upper limit given the extreme challenges of eliminating all background. In any case, this study has a potentially very important result and could usefully be revisited if the experimental setup can be improved.

The quasi-free knockon of preformed $\alpha$-particles from nuclei via the 100 MeV/A reaction ($p, p/\alpha$), was discussed by Cowley [39]. The results are extremely important for several high profile experiments planned around the world, such as the R3B experiment at FAIR [40], which include the possibility to study this reaction in inverse kinematics with radioactive beams. A recent result demonstrating quasi-free proton scattering from $\alpha$-particles inside the ground state...
of $^{12}$C was reviewed. With suitable kinematic cuts to satisfy the quasi-free conditions, the differential cross sections were close to identical in shape for scattering by free $\alpha$-particles and scattering from those found inside the $^{12}$C ground state. Further, the analysing power as a function of scattering angle was the same in the two cases. The important new result from this conference was the new analysis for a $^{40}$Ca target, also for 100 MeV/A. Whereas a previous analysis had failed to show consistency with quasi-free scattering, an improved distorted wave treatment for $\alpha+^{36}$Ar shows consistency with quasi-free scattering from $\alpha$-particles inside $^{40}$Ca. Another interesting knockout result was reported by Ye [41], who described a RIKEN experiment to study the knockout of a $^6$He core via $(p, p' 6^\text{He})$, performed in inverse kinematics with a $^8$He beam at around 10 MeV/A.

Tamura reported on results from experiments at J-PARC to detect gamma-rays from the hypernuclei produced when $\Lambda$ hyperons are introduced into $^8$Be and $^6$Li nuclei. Compared to $^6$Li, which is well described by a cluster structure of $\alpha+d$, the introduction of a $\Lambda$-particle (unhindered by the Pauli principle) makes $^7\Lambda$Li and binds the two clusters closer together spatially, causing a shrinkage of order 20\% [42]. The extension to results for heavier nuclei, and other future perspectives were also reviewed [43].

3. Outlook

This brief summary of highlights shows, very clearly, that we are at an exciting time in the experimental study of nuclear clustering. Some qualitatively new techniques have recently emerged, and some existing techniques have been adapted or extended to take advantage of technological advances. Of course, many other interesting results were reported, including those in the areas of: halo states, dripline structure, astrophysics, the trojan horse method, meson scattering, superheavy element studies, heavy cluster radioactivity and more.

However, even as the new results accrue, we are left with many puzzles and situations that look promising but are not resolved. More specifically, we find many experiments in which a plausible argument can be made, to link the observations with the theoretical expectations, but the measurements fall short of being conclusive. Maybe, with the newly emerging methods, we are in sight of being able to push past this limit, towards conclusive results. Certainly there is a need to achieve confident spin determinations and to measure absolute decay widths. The fact that an excited state decays by cluster emission is not sufficient, in itself, to demonstrate cluster structure - some sort of enhancement must be demonstrated. Some specific challenges spring to mind. In the case of excited molecular bands, to go beyond plausibility we need robust spin assignments, partial decay probabilities and probably B(E2) measurements. There is a lot of scope for $\alpha$-particle transfer experiments to inform these studies, possibly using radioactive beams. In $^{16}$O, what is the nature of the resonances seen by Chevallier et al. [3] in the $^{12}$C($\alpha,^8$Be) reaction? Are they related to a chain state, or a structure involving some degree of Bose-Einstein condensation, and can we decide for sure? In $^{20}$Ne and $^{24}$Mg, can the various expected Bose-Einstein condensates be located with confidence?

It is clear that leaps forward will be seen in the quality and extent of experimental results using resonant scattering in inverse kinematics. This is already happening with the emergence of devices such as ANASEN [23, 24]. It may be that through the study of hypernuclei, it will be possible to characterise some cluster configurations in light hypernuclei that cannot be studied in ordinary nuclei, taking advantage of the lowering in energy of the configuration due to the extra binding of the $\Lambda$ particle. Finally, in my personal list, the next conference may bring forth results from proton induced knockout in inverse kinematics using radioactive beams. As well as $(p, p' p)$ or $(p, p' n)$ quasi-free knockout of nucleons, $\alpha$-particle knockout $(p, p' \alpha)$ is due to be studied at facilities such as R3B at FAIR and similar setups in RIKEN, and can explore the theoretical predictions for the development of clustering towards the neutron dripline.

One last comment in this experimental summary, and one that was well demonstrated by
this conference: clustering in nuclei is one of the very best parts of nuclear physics for nurturing a close and mutually beneficial relationship between experimenters and theorists. This close cooperation will surely continue, and will underpin the breakthroughs, insights and new results that we can anticipate at Napoli, when next we meet.

Acknowledgments
Thank you to the organisers for giving me the opportunity to summarise this conference. Mine was the final talk of the conference and, as I did in my talk, I would like to finish by congratulating the organisers on producing an excellent logo, an interesting programme and an inspiring week.

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