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TWENTY FIVE YEARS OF CLUSTERS -
FROM BOCHUM TO STRASBOURG

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The organizers of CLUSTER 94 have asked me to review the developments in the area of clustering aspects of nuclear structure and reactions covered by the previous conferences in this series. These conferences¹⁻⁵⁾ span twenty-five years, having been previously held in Bochum (1969), Maryland (1975), Winnipeg (1978), Chester (1984), and Kyoto (1988). Such a review is therefore an immense task, and these remarks here can therefore only be a very superficial view of a few selected topics in the field. It is also important to note that such a "history" is likely to be somewhat confused as some of the most important points are still very much under active discussion. It may even be fraught with danger, as many of the participants in these discussions are present in the audience! So, with these words of caution, here is my contribution.

The fundamental viewpoint of this field is that of the nucleus as an assembly of clusters. The question which is then to be addressed by the comparison of theory with experiment is whether this approach is a useful one or not. Do the clusters really exist or not in the nuclear environment or is the model simply a useful formal tool for understanding nuclear structure?

There is abundant evidence in light nuclei for states which have large overlap with cluster configurations. This has been demonstrated through the experimental study of resonant scattering of the clusters themselves (d, α ...) and through reactions in which the clusters are transferred.

As far as theory goes, the basic foundations were laid already at the time of the Bochum meeting. The Resonating Group Model, originally due to Wheeler, was refined and exploited by Wildermuth and collaborators and the computationally more convenient Generator Coordinate Method and successively more phenomenological approaches such as the Orthogonality Condition Model were well known. The connection between the cluster model and the shell model was

understood and the crucial role played by the Pauli principle and antisymmetrization was also known. Many of the most important ideas such as the description of cluster states as multi-particle multi-hole shell-model excitations, the significance of molecular effects and even the discussion of exotic states such as alpha-particle chains, all appear in the proceedings of this first meeting of the series.

An example of the state of the art of calculations at that time is shown in Fig. 1 where data for elastic scattering of $d+\alpha$ at two energies are compared with the results of microscopic calculations⁶⁾ using nucleon-nucleon interactions by Thompson and Tang. The overall agreement is remarkably good.

Fig. 1. Comparison between microscopic calculations of $d+\alpha$ and experimental results at 5.98 and 8.00 MeV.

There has been a long and fruitful connection between the cluster approach to nuclear structure and nuclear astrophysics. The reason for this is clear. Reactions important in the stellar environment frequently involve the nuclei considered to form the basic clusters in nuclei and the cross-sections tend to be dominated by resonant states in light nuclei with large widths for decay into these cluster channels. Particularly important in this regard are resonances near threshold such as $^8\text{Be}(g.s)$ and $^{12}\text{C}(0_2^+)$ which make possible the burning of ^4He and eventually the production of all heavy elements. The cluster model, in which resonances and bound states are treated on the same footing, gives predictions of the existence and location of such important states and allows calculation of their radiative decay widths, some of which have proved very difficult to determine experimentally. Similarly, cluster theory allows the extrapolation of data to the very low energies important in the stellar environment and, more topically, can also give predictions for experimentally inaccessible reactions involving unstable participants.

As mentioned, one of the main themes of discussion over the period of these conferences relates to the existence of the clusters themselves. In other words, what is the overlap between the physical states or model states and the pure cluster configurations? Is this overlap large - in which case the basis of states provided by the cluster model is a good one - or not? There are some issues, both experimental and theoretical, which relate to the answering of this question. In the case of resonances, theory provides us with a set of phase shifts from which the widths of the resonant states can be derived. Difficulties arise when more than one decay channel is open and on how this is included in the calculation. In the case of many open channels, the imaginary potential used to describe the coupling to these is phenomenological at best. The question of what then constitutes a "single-particle" value of the resonance width, although well defined in the case of nucleons, becomes progressively more uncertain as the complexity of the "single-particle" increases. Uncertainties in the radius at which the matching to Coulomb wavefunctions occurs strongly influences the expected value of this "single-particle" width. For bound states, the choice of basis in which the model calculations are carried out may preclude the enhancement of the wavefunctions at large distances characteristic of clustering. The lack of simple sum rules for multiparticle overlaps also makes the definition of the "single-particle" value somewhat ambiguous.

On the experimental side, the analysis of resonance cross sections involves a number of assumptions regarding the isolated nature of the resonances and their potential interference with non-resonant background. The distinction of true resonances from statistical fluctuations has also been an issue of some importance. Experimentally, the extraction of spectroscopic information on bound states from cluster transfer reactions relies on the predictions of Distorted Wave or Coupled

Channels calculations which are subject to uncertainties introduced by choices of optical model parameters and form factors.

Notwithstanding these difficulties, a fairly consistent picture of the distribution of cluster strength in light nuclei has emerged and, at least in the case of α -particles, the quantitative evaluation of spectroscopic information is in reasonable shape. For more complex clusters the situation is, however, much worse.

Perhaps the best studied of all nuclei which display strong cluster features is ^{20}Ne . The deduced $K\pi=0^+$ bands in this nucleus are shown in Fig. 2 together with their assumed dominant shell-model configurations. These assignments into bands are based on a vast array of information on nucleon and cluster spectroscopic factors, electromagnetic transition rates and population strengths in various multi-nucleon transfer reactions. It is important to note that this information was, in many cases, a direct consequence of advances in accelerator and detector technology allowing the development of powerful new experimental techniques such as heavy-ion reactions and particle-particle correlations which have led to many of the spin and rotational band assignments of these states.

Fig. 2. Rotational band structure for $K\pi=0^+$ bands in ^{20}Ne . The proposed dominant shell model configurations are given. The large circles indicate the location of $J\pi=10^+$ states.

A detailed comparison of the structure of these bands with large basis shell-model calculations and with $^{16}\text{O}-\alpha$ cluster model calculations has been made by Tomoda and Arima.⁷⁾ They note the inability of the shell model to account for the large values of the α -particle spectroscopic factors for the ground-state band whereas the cluster model correctly reproduces this effect. This result implies a mixing of configurations involving higher shells in the ground-state rotational band.

A consequence of this mixing, if strong, is that the ground-state band now contains configurations which can couple to higher angular momenta than the maximum value of $J=8$ allowed for four nucleons in the s-d shell. The location of the lowest-lying $J=10$ states then has been the focus of a search for quite some time. In fact, for many years no 10^+ states were found in ^{20}Ne and they were finally⁸⁾ only uncovered after detailed analysis of angular correlation data in a region of excitation energy with many overlapping states of lower spin. The location of the two states found (above 20 MeV), places them definitively on the extension of the high-lying cluster bands rather than on any reasonable extension of the ground band (Fig. 2). This result then underlines the importance of shell structure in mediating the distributions of cluster strength although mixing between the different shell-model configurations is undoubtedly very important.

The extension of cluster studies to heavier nuclei was first exemplified by the discovery⁹⁾ of anomalous large angle scattering of alpha particles (ALAS) from Ca and other nearby nuclei, examples of which are shown in Fig. 3. The most striking feature of this phenomenon is the suppression of the large-angle elastic scattering cross sections as the neutron number of the target nucleus is increased from the

Fig. 3. Elastic scattering angular distributions for α +Ca and α +K showing the enhancement at large angles characteristic of "ALAS".

closed shell value. These data were interpreted as due to a family of broad overlapping resonances and the question, which was hotly debated, was whether the neutron suppression effect resulted from a real nuclear structure effect or resulted from an increase in the absorption in the scattering potential as neutrons were added. Later experiments¹⁰⁾ showed dramatic effects on fusion cross sections for the same systems, apparently outside anything that could be accounted for by the usual optical model concepts. As an aside, these fusion data also showed clear evidence

for oscillation of the fusion cross-section with bombarding energy. A much deeper understanding of these phenomena came from later experimental work¹¹⁾ of Frekers et al. and theoretical calculations by Langanke. Through careful measurement of low-energy α -particle elastic scattering excitation functions and R-matrix analysis of these data, a new band of low-spin resonances was identified which was associated with a band of so-called "Quasi-Molecular" resonances found in the microscopic calculations. In the calculations this band terminates at spin 12 and is therefore to be associated with four nucleons in the $N=3$ oscillator shell. A higher-lying band which continues to higher spins was associated with the higher energy resonances observed earlier, which were termed "Barrier" resonances. Unfortunately, the suppression of these barrier resonances by the addition of neutrons to the target nucleus was not observed in the calculation, leaving open the interpretation of this important aspect of the data. Possible explanations include increased absorption in the entrance channel which must of course have some physical origin such as an increased number of open reaction channels or a reduction of the coupling of the barrier resonances to the compound nucleus due to, for example, shell effects associated with deformed states in the compound nucleus similar to shape isomers.

A major theme in the more recent conferences in this series has been that of nuclear molecules. Surprisingly, despite having been first observed in 1960, no mention is made of the famous $^{12}\text{C}+^{12}\text{C}$ resonances in the Bochum proceedings. In part this may be due to a debate lasting many years as to the origin of the structures observed¹²⁾ in the energy dependence of the reaction cross-sections for $^{12}\text{C}+^{12}\text{C}$ etc. (Fig. 4). It was quite some time before it became clear that the observed narrow

Fig. 4. Energy dependence of $^{12}\text{C}+^{12}\text{C}$ interactions.

structures did indeed reflect the true resonances rather than fluctuations arising from interferences between overlapping compound nuclear levels. The large uncertainty in estimates of the "single-particle" widths for such complex fragments as ^{12}C also made an interpretation in terms of cluster degrees of freedom very subjective at that time. These questions have now been resolved by much more extensive experimental work and a clearer understanding of the distribution of resonance widths.

With the new generation of precision and, for the time, high-energy heavy-ion accelerators, came extensive new data¹³⁾ on the elastic scattering of $^{12}\text{C}+^{12}\text{C}$, $^{12}\text{C}+^{16}\text{O}$ and $^{16}\text{O}+^{16}\text{O}$ some of which is shown in Fig. 5. The narrow resonances observed in the Coulomb barrier region in $^{12}\text{C}+^{12}\text{C}$ break into a series of much

Fig. 5. Excitation functions for $^{12}\text{C}+^{12}\text{C}$ and $^{16}\text{O}+^{16}\text{O}$ in elastic scattering measured at $\theta_{\text{cm}}=90^\circ$.

wider structures at higher energy, somewhat reminiscent of the situation for $\alpha+^{40}\text{Ca}$ scattering. For $^{16}\text{O}+^{16}\text{O}$, only broad resonances are observed at the higher energies. The question was then whether these phenomena represented potential scattering resonances or some more complex and, perhaps, more interesting nuclear structure phenomenon. A major difficulty in the potential scattering approach was to simultaneously describe the $^{12}\text{C}+^{12}\text{C}$ data together with the simpler $^{16}\text{O}+^{16}\text{O}$ data.

The key idea in the progress towards a solution to this problem came from Nogami and Imanishi¹⁴⁾ who recognized the strong, collective nature of the first excited 2^+ state in ^{12}C at 4.43 MeV and the close similarity between this excitation

energy and the rotational energy of a dinuclear $^{12}\text{C}+^{12}\text{C}$ system. Thus, excitation of the 2^+ state and removal of two units of angular momentum from the rotational motion almost exactly compensate each other at $L=12$ and resonances in the elastic channel and inelastic channels then lie rather close to each other and can thus couple strongly. In a qualitative way then the greater complexity in the $^{12}\text{C}+^{12}\text{C}$ data results from the existence of this family of strongly coupled inelastic resonances and the simplicity of the $^{16}\text{O}+^{16}\text{O}$ data reflects the absence of a collective excited state in ^{16}O in the right energy and angular momentum range. These ideas were placed on a quantitative basis with calculations in the framework of the Band-Crossing Model¹⁵⁾ of Abe et al. and the Double Resonance Model¹⁶⁾ of Scheid, Greiner and Lemmer which include the coupling of reaction channels in the Imanishi picture. Of particular interest in this respect were calculations¹⁷⁾ of Matsuse, Abe and Kondo who predicted a rich spectrum of resonances in the Coulomb barrier region for $^{12}\text{C}+^{12}\text{C}$ which motivated very detailed new studies of this region such as those carried out by Erb et al.¹⁸⁾

The experimental demonstration of the importance of inelastic excitation of the 4.43 MeV ^{12}C 2^+ level came from excitation function measurements¹⁹⁾ of the single and double excitation of this channel in $^{12}\text{C}+^{12}\text{C}$ scattering by Cormier et al. - shown in Fig. 6. These structures were associated with the interaction of the

Fig. 6. Excitation functions for the single and mutual inelastic scattering of $^{12}\text{C}+^{12}\text{C}$ to the 4.43 MeV $J\pi=2^+$ state. Data for the total fusion cross-section are also shown.

excited molecular bands with the elastic band as shown in Fig. 7. General questions which arise in this interpretation of the data, relate to the potentials used in the

Fig. 7. Correlation between the peaks observed in the mutual inelastic scattering of $^{12}\text{C}+^{12}\text{C}$ and the crossings predicted by the Band Crossing Model.

calculation. The real scattering potential can be derived, for example, from a folding model. The imaginary potential has been related in a phenomenological way to the densities of states in the open reaction channels and must be assumed to be weak for the surface partial waves. In the spirit of the cluster model, the molecular resonances of these potential scattering models should in principle contain nuclear structure information through constraints on the nodal structure of the radial wavefunctions given, for example, by the Wildermuth condition. This is not generally done in these calculations.

The much more general nature of nuclear molecular phenomena was revealed²⁰⁾ in a series of experiments in which the large-angle scattering of ^{12}C and ^{16}O from a variety of targets was measured. An example, $^{16}\text{O}+^{28}\text{Si}$ scattering, is shown in Fig. 8. It had previously been assumed that the vastly increased number of open reaction channels for such heavy systems would lead to much stronger absorption than was the case for the lighter systems and that the angular distributions would therefore be characterized by a smooth fall off with angle such as is shown by the dashed line in the figure. Surprisingly, the data show a strong backward angle rise which, at the largest angles, is characterized by an almost pure

Fig. 8. Angular distribution for elastic scattering of $^{16}\text{O}+^{28}\text{Si}$ showing the rise at large angles. The dashed curve is an optical model calculation with a strongly absorbing potential, the solid curve includes a Regge pole.

$P_L^2(\cos\theta)$ behavior. Attempts to describe these data with potential scattering and coupled channels models met with some success, although no wholly satisfactory agreement with the entire body of data was ever achieved. As is the case for the backward angle α -scattering the question remains as to the origin of the weak surface absorption in the potentials required in these calculations and whether this has its origins in some interesting aspects of nuclear structure.

Data for much heavier systems,²¹⁾ such as $^{28}\text{Si}+^{28}\text{Si}$ shown in Fig. 9 have helped to answer these issues. Similar to the lighter systems, the elastic scattering data show a backward angle rise characteristic of a single partial wave which changes in a regular fashion with energy. These data cannot be fitted satisfactorily with simple potentials or with coupled-channels calculations. The forward angle behavior is characteristic of scattering under the influence of strong absorption and the backward rise is most economically described by the addition of narrow isolated resonances. These same resonances appear in many other reaction channels which coupled with the general characteristics of the large angle scattering cross-sections, lead to the proposal that the resonances may correspond to something like fissioning shape isomers which are predicted to occur in these compound nuclei rather than the simple molecular resonances implied in the potential scattering models. Once again

Fig. 9. Angular distribution for elastic scattering of $^{28}\text{Si}+^{28}\text{Si}$ at 120 MeV.

the damping of the resonance phenomenon with the addition of valence particles to target and/or projectile remains to be explained.

The entire body of data then poses some very important questions relating to the connection between reaction mechanism (scattering resonances and coupled channels effects in the presence of weak absorption) and purely nuclear structure effects such as shape isomeric states produced by shell effects at large deformations. The possible connection between the $^{12}\text{C}+^{12}\text{C}$ molecular resonances and such shape isomers was already suggested by Bromley in his 1975 Maryland talk where the calculation²²⁾ of Leander and Larsson for ^{24}Mg shown in Fig. 10 was shown for the first time. The experimental observation of selective decay of the $^{12}\text{C}+^{12}\text{C}$ resonances to $^{20}\text{Ne}+\alpha$, $^{16}\text{O}+^8\text{Be}$ and $^{12}\text{C}+^{12}\text{C}$ also suggested structural connections between shape isomers in these nuclei. In fact, the multi-particle multi-hole structure associated with the minima given in the original paper should have already given away the strongly clustered nature of the states in these minima. This, however, came much later with the results of the cranked cluster model calculations of Marsh and Rae²³⁾ who, as is also shown in Fig. 10, were able to establish a one-to-one correspondence between their stable cluster configurations and the potential

Fig. 10. Potential energy surface for ^{24}Mg calculated with the deformed shell model. In comparison are given density contours for the stable configurations found in the cranked cluster model.

energy surface minima from the deformed shell model. By this association, the connection between specific reaction channels and the various minima has become clear and the richness of the $^{12}\text{C}+^{12}\text{C}$ resonances has finally reached a higher level of understanding.

The connection between the multi-center shell model and the (deformed) shell model was first suggested²⁴⁾ by Harvey at the Maryland conference and these ideas have been developed to a new level in the intervening years. The relationships between superdeformed and hyperdeformed states in the single center shell model and their cluster (multi-center) parentage has been studied in some detail and is now providing a major new impetus in the field. Particularly interesting in this respect is the comparison between different calculations and the data for resonances seen in the $^{24}\text{Mg} + ^{24}\text{Mg}$ system. Calculations^{25,26)} in the single-center and multi-center shell models both show the existence of semi-stable deformed cluster configurations which also appear in the pure molecular model²⁷⁾ calculations, provided that the correct degrees of freedom are included. This concurrence reflects the symmetries which are present in all these approaches and suggests a unity despite the seeming differences of the models which is not obvious at first sight. It is likely that this avenue of research will provide the final clarification of the relationship between the potential scattering models of clustering phenomena and nuclear structure effects in

the composite system. Many of these new ideas will be discussed in detail in these proceedings.

In summary, twenty five years of clusters have seen a remarkable resilience of the basic ideas of clustering in nuclei, and, with much better and more extensive data, the widespread nature of the phenomenon has become evident. It seems that we are on the verge of understanding the nature of a delicate interplay between, on one hand, reaction mechanism aspects of the problem, and on the other, the nuclear structure features. We can therefore look forward to an exciting meeting with new experimental results and new theoretical ideas.

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