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SUMMARY TALK

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§1. Introduction

It is very fitting, that this Fifth International Conference on Clustering Aspects in Nuclear and Subnuclear Systems was held at Kyoto in view of the many important contributions to the field of clustering by the Japanese nuclear physics community. I would like to mention here in particular the Hokkaido school of Professor Tanaka, chairman of this conference, that dates back to the early sixties, the α-chain model[1], the weak coupling model[2], the threshold rule[3], the orthogonality condition model[4], and the method of vertical truncation[5], to quote a few highlights.

This conference has covered a very wide range of topics from quasi-molecular resonances and nuclear structure to neutrino astrophysics, hypernuclei and subnucleonic effects. The common denominator, of course are clusters and clustering aspects, but after having listened to the session "*what is a cluster*" and to the different talks at this meeting it has become overwhelmingly clear that everyone has his own view on clusters and clustering.

For the theorist the RGM appears to be the binding element, whether we are dealing with nuclear structure or with subnucleonic degrees of freedom, while the experimentalist is more inclined to look for the "physical cluster", whatever this may mean. Indeed we have seen in this conference the label cluster plugged on to so diverse objects as nucleons as a quark cluster, α-particles, pairing vibrations and IBM bosons, and even on closed-shell heavy nuclei undergoing fusion or fission. Certainly the two views, i.e. that of the theorist and that of the experimentalist, need not be in contradiction with each other, but as an experimentalist one would like to have a clear measure of the degree of clustering in the same way as the enhanced B(E2) strengths and rotational frequencies are a measure of the collectivity of deformed nuclei. Obviously one might think of partial widths for cluster decay or transfer as such a measure as has been suggested by Betts at this confernce .

Unfortunately, however, the discussion does not end here if one wants to make a distinction between shell model clusters and localized clusters. As is well known also the shell model can give large two- and four-nucleon transfer strengths without a localized clustering. In fact, the four-nucleon amplitude can often be factorized into a product of two-nucleon amplitudes, thus indicating that the neutron-proton correlations are unimportant. Moreover, as expressed by "Cindro's dog" the observation of clusters in the initial or final state does not necessarily imply that these lead to or originate from cluster states in the product or parent nuclei, respectively. Similarly, phase space effects cannot be ignored that often favour α-particle nuclei in the entrance or decay channels because of their tight binding. All these considerations hardly are new.

The approach suggested by Suzuki at this conference to determine as a measure of clustering the overlap between shell model wave functions and those obtained with the RGM with localized clusters therefore seems to me especially interesting in view of the foregoing discussion. I feel strongly that one must arrive at a more quantitative definition of clustering than it has been the case up to now if the cluster model wants to be more than just a convenient computational method.

§2. Quasi-molecular Resonances

Quasi-molecular resonances traditionally have taken in a prominent position in cluster conferences. Haas reported on a recent and ongoing extension to higher energies of excitation function measurements for light systems such as $^{12}C + ^{12}C$, $^{12}C + ^{14}C$, and $^{12}C + ^{15}N$ in which pronounced gross as well as intermediate width structures still are seen. Zurmuehle presented a very extensive particle-γ angular correlation measurement with the Oak Ridge spin filter for the $^{24}Mg + ^{24}Mg$ system in the vicinity of the strongly correlated resonances at 46 MeV that are seen in the elastic as well as in several inelastic scattering channels including mutual excitation. With the spin filter it was possible to obtain separately excitation functions and angular distributions for different spin projections of the γ-decaying residual nucleus and to deduce from these data spins and partial widths of the molecular resonances. The picture emerging from this study is that of two ^{24}Mg nuclei forming a molecular structure with their major axes aligned and an axis ratio of 3 : 1.

Uegaki and Abe in a contribution to this conference proposed a new model for quasi-molecular resonances based on a collinear dinuclear configuration in which the additional degrees of freedom known from fission as wriggling, tilting, bending and twisting are coupled to the entrance channel. They also enriched the language of fission with the "butterfly mode".

Rae compared for ^{24}Mg α-cluster model calculations with the Brink-Bloch model with the results from deformed shell model calculations for the same nucleus. As is well-known the deformed shell model leads for integer axis ratios to new magic numbers and shell gaps which are believed to be responsible for the occurance of fission isomers and super-deformation. Rae proposed that these same shell gaps give rise to molecular structures and resonances in light nuclei involving different geometrical arrangements of the α-particles in chains and "pancakes" etc, but also into $^{8}Be + ^{16}O$, $^{12}C + ^{12}C$ or $\alpha + ^{20}Ne$ clusters. These cluster configurations have different moments of inertia and thus different slopes of their rotational bands.

In conjunction with the discussion of quasi-molecular resonances the scheme proposed by Iachello[6] and implemented by Erb and Bromley[7] to classify the $^{12}C + ^{12}C$ resonances in the energy range between 6 and 11 MeV in terms of a rotation-vibration coupling model was mentioned several times at this conference. A word of caution, however, seems to me in order in view of recent results obtained at Münster[8] for the $^{12}C + ^{12}C$, $^{12}C + ^{16}O$, and $^{16}O + ^{16}O$ systems that cast serious doubts on the interpretation of the observed structures in terms of isolated resonances. To the best of my knowledge these studies are among the most extensive and thorough investigations of the molecular resonances to this date. The measurements were done with an intrinsic resolution of 5 keV and they for the first time exhibit fine structure from the underlying, and overlapping compound nucleus states in addition to the known intermediate width and gross structure. From the equivalent of a phase shift analysis of the angular distributions it could be shown that the resonance-like structures in the studied energy range cannot be attributed to single l-values and thus not to isolated resonances. Rather, these structures appear to result from Ericson type fluctuations of the overlapping, intermediate width doorway states.

From the view point, however, of quasi-molecular doorway states it is interesting to remark that the partial width for α-decay of the doorway states obtained at Münster[8] from a fluctuation analysis is by an order of magnitude larger than that of the underlying compound nucleus states. Thus, while treating the observed structures as isolated resonances might be too simplified a view, the (overlapping) doorway states not withstanding might still have very special structures that would clearly qualify them as quasi-molecular states.

By Shapira a very intriguing doorway state model for fusion and deep-inelastic collisions was presented. Contrary to the usual conception of deep-inelastic processes that are believed to occur in l-space above l_{crit} for fusion, both processes (fusion and DIC) in the model proposed by Shapira compete with each other with the orbiting state acting as a doorway. Since for the light systems discussed by Shapira quasi-elastic and deep-inelastic processes are not as cleanly separated as for heavier systems it would seem to me of interest to investigate in how far the observed phenomena can alternatively be described in the framework of quasi-elastic processes in the spirit e.g. of Udagawa and Tamura[9]. Vice versa, if the model proposed by Shapira is valid it should also apply to heavier systems unless the stronger absorption in the surface region for these systems prevents orbiting and all the incident flux is therefore channeled directly into fusion.

§3. Astrophysics and Breakup Reactions

The common denominator with the astrophysical studies is provided by the microscopic cluster model that for light nuclei, as was emphasized by Langanke, presents the most reliable tool to calculate the reaction rates of astrophysical interest. These computations are helped by the fact, that at the energies important for astrophysical processes onle a few channels are open.

Austin gave a fascinating review of "micro-astrophysics". Parker reported on the experimental determination of reaction rates at astrophysical energies with an emphasis on the HOT - CNO cycle. As Parker pointed out there is a growing need for radioactive beams, and in fact such beams will become available soon at several places. Short of the availability of such beams it is often possible, however, to obtain a handle on the reaction rates by exciting levels of interest via transfer or charge-exchange reactions and to measure their branching ratios. Langanke pointed out how electron screening can lead to enhanced fusion cross sections at very low bombarding energies.

Sequential decay versus direct breakup was discussed by several authors under different perspectives. Wilczynski emphasized the importance of sequential decay processes in the dynamics of heavy ion reactions at intermediate energies and Doubre showed how the relative population of sequentially decaying states may serve to measure temperatures of hot nuclei, provided that the population of these states is statistical. A question of great current interest in intermediate energy heavy ion reactions is concerning the limiting temperature the nuclei can reach and whether multifragmentation occurs whereby the hot nucleus (spontaneously) breaks up into a number of intermediate mass fragments. And what is the element distribution going to be? Shotter discussed the direct breakup of light heavy ions such as ^{7}Li and ^{9}Be.

Direct breakup and sequential decay of the projectile are the pendents to direct and resonant capture, respectively. If the breakup cross sections as a function of the relative energies of the two fragments can be measured with sufficient accuracy these measurements may hopefully serve to determine the inverse cross sections that are of astrophysical interest. As pointed out by Baur phase space favours breakup over the inverse radiative capture process. Moreover, reaction kinematics favour breakup studies with projectile beams and virtual photons over studies with real photons.

The breakup of ^{7}Li and ^{9}Be in the Coulomb field of the target nucleus predominantly occurs via E1 radiation as was shown by Shotter, and this explains why the direct breakup of self-conjugate nuclei was not observed at the energies at which these studies were performed. On the other hand direct breakup of ^{6}Li at higher bombarding energies was reported to this conference by the Karlsruhe group in a contributed paper. Because of its E2 nature the cross section for direct breakup in ^{6}Li, however, appears to be significantly smaller than that for ^{7}Li. The cross sections for Coulomb breakup rapidly increase with bombarding energy, as discussed by Baur in his talk, and become very large at relativistic energies, thus making Coulomb breakup a very promising subject to study at these energies.

In reactions with light heavy ions at intermediate energies large cross sections are found for channels[10] in which only alpha particles and nucleons are emitted. The question relevant to this conference then arises in how far these channels can be described as originating from processes in which the incident projectile dissociates on impact into alpha particles and nucleons which then independently propagate through the target to be either reemitted or captured. At low energies we know that an alpha particle will be quickly dissolved in the target nucleus, but at higher energies the Pauli principle is less important, and one might thus ask what then is the chance for the alpha particle to propagate through nuclear matter. A classical model along these lines in which the projectile is described as a "bag" of alpha particles that then interact with the target recently has been proposed by Moehring and Gross[11].

§4. Cluster Transfer and Knockout

At past conferences on clustering in nuclei cluster transfer and pickup has taken in a prominent position. In contrast little coverage was given to this topic at the present meeting, reflecting perhaps a shift in interest.

Katori reported on a systematic study of alpha decay in the N=84 - 90 lanthanum region that is believed to be a second region of stable octupole deformation next to radium and adjacent nuclei. In the radium mass region a rapid change in the alpha hindrance factors is seen as an indication of the onset of octupole deformation, respectively of alpha particle clustering in the frame work of the clustering model of Iachello and Jackson. It is of interest therefore to investigate whether or not similar abrupt changes in the alpha decay widths are seen in the lanthanum mass region. Contrary to expectation, however, no anomalous behaviour was found by Katori and coworkers.

Blok presented beautiful cluster knockout data obtained at NIKHEF with the (e,e'd) reaction on ^{4}He, ^{6}Li, and ^{12}C. The advantages of the (e,e'x) reaction as compared to hadron induced knockout reactions such as (p,p'x) are that (i) the interaction is known and weak, (ii) one is dealing with a two-body final state, amd (iii) the reaction samples the whole nucleus in contrast to hadron reactions that are confined to the surface. In the impulse approximation the cross section can be factorized into a product of the electron-deuteron scattering cross section and the nuclear structure function. By varying the momentum transfer it then is possible to test the assumption whether the incident electron has interacted with a deuteron cluster in the target or whether the detected deuteron is the product of a final state interaction. The NIKHEF results very strikingly show that while for ^{6}Li one is dealing with the quasi-free knockout of a deuteron in its groundstate, the singlet deuteron component cannot be ignored in the knockout reactions on ^{4}He and ^{12}C. Moreover, even when being in a relative state characterized by the quantum numbers of the deuteron the neutron and proton interacting with the electron may have in the nucleus a radial wave function that is different (more compact) than that of the free deuteron. The (e,e'x) results are very exciting and clearly exhibit the great promise of the quasi-elastic knockout reactions for the study of clustering in nuclei.

§5. Exotic Nuclei

Detraz reported on the production of extreme neutron rich nuclei via fragmentation reactions at GANIL. The studies of such nuclei offer severe tests of nuclear models. As pointed out by Horiuchi some of these nuclei such as ^{16}Be or ^{17}B may have pronounced cluster structures in their ground states. Particularly interesting are the observation of β-delayed 2n,3n, and even 4n decays. Are the decays going to be sequential or in the form of the emission e.g. of a tetra neutron? Furthermore, nuclei were found that are stable towards one-proton decay but unstable to two-proton decay. What will the probability be for ^{2}He emission?

Reaction cross sections σ_R for the exotic nuclei were measured by detecting the γ-rays from the interaction of these nuclei with various targets, and the results were compared with those obtained at the BEVALAC[12)] via the beam attenuation method. Strong absorption radii deduced by both independent methods agree in general well with each other except for ^{11}Li for which the breakup channel is expected to be very strong. Since elastic breakup will not give rise to γ-rays the γ-ray method will thus underpredict the reaction cross section. This result seems to me especially interesting in view of recent speculations[13)] about a two-neutron halo in Li^{11} that would give rise to an anomalously large *matter* radius. But in this case the radius deduced with the γ-ray method should also be large, and this obviously is not the case.

Armbruster reported on the synthesis of the heaviest trans-uranic elements. The production of such elements by now is well understood largely through the Darmstadt work and has long passed the state of "alchemie and black magic". In order for the excited product nuclei not to immediately fission cold fusion processes are the most promising and perhaps only way to produce these very heavy elements. The special role of the double magic ^{208}Pb nucleus in the production process was especially emphasized by Armbruster. Contrary to the collisions involving non-closed shell nuclei the "extrapush" energy that is required on the way in to fusion is significantly lower if lead is one of the collision partners. There thus appears to be a close connection to the cluster aspects in nuclear fission proposed by Faissner and Wildermuth[14)] many years ago and that show up most pronounced in asymmetric fission when the intrinsic excitation energies of the fission fragments are low. Evidently the closed shell nature of Pb has the consequence that the lead "cluster" longer retains its identity on the way to fusion and that for this reason less kinetic energy is dissipated into deformation energy.

As was also pointed out by Armbruster the heaviest transuranic elements 107 - 109 appear to be strongly shell stabilized against fission, -by as much as 15 orders of magnitude- and thus clearly qualify as superheavy nuclei. The shell stabilization against fission of the heaviest elements is most impressively demonstrated by the decay chain of element 109, that involves the successive emission of two alpha particles followed by fission.

§6. Hypernuclei and Subnucleonic Effects

Another species of exotic nuclei are the Λ-hypernuclei reported by Bandō, Pile and Tamura. An impressive number of Λ-hypernuclei by now has been produced ranging from the lightest nuclei to $^{209}_{\Lambda}$Bi. Pile showed how the binding energies of the Λ in different major shells as a function of mass can be reproduced with a simple potential model. Bandō made the intriguing suggestion that the relative energy shift between shell model and cluster states in hypernuclei might be used to identify cluster states in light nuclei. Tamura reported on unexpectedly large production cross sections of $^{4}_{\Lambda}$H with stopped kaons for a range of target nuclei, and he presented a statistical model to explain these results. One may wonder, however, whether the last word on this intriguing process has been already said.

Sick reviewed the present state of our knowledge on quark effects as they are expected to manifest themselves in electronuclear interactions. Aside of putting our understanding of nuclei onto a more fundamental level nuclei may serve as a laboratory to study quark confinement in nuclear matter. In the celebrated EMC effect nuclear binding and meson exchange currents rather than new QCD effects appear to be the main explanation. Treating nucleons as quark clusters and taking quark antisymmetrization effects into account elastic formfactors were recently computed for several few-nucleon systems. The interesting feature is the prediction of effects due to quark antisymmetrization that are of the same order of magnitude as effects due to meson exchange currents and that thus are clearly detectable. The challenge will be to unambigiously unravel the different contributions that may affect the formfactors. Calculations so far have been done with the non-relativistic quark cluster model, and as was pointed out by Arima at this conference the major challenge to theory in the near furture will be to develop a relativistic RGM.

§7. Concluding Remarks

Quite naturally it was not possible in this summary talk to adequately deal with all topics discussed at this conference. I must therefore apologise to all speakers who might feel that not proper justice was done to their work. I would also like to take this opportunity to thank my colleagues who have helped me in the preparation of this talk by making their manuscripts and other material ahead of time available to me.

This conference has covered a very wide range of topics, in the view of some perhaps even too wide a range. As a consequence this meeting has brought together physicists of very different background and interests, an aspect I particularly enjoyed. It has been a lively conference with some excellent talks, and the pleasant and informal atmosphere in spite of the large number of attendants has helped to stimulate discussions.

Finally, as the last speaker of this conference it rests on me to thank the organizers of this meeting for their great effort to make this conference a success and for their kind hospitality that made all of us feel very much at home.

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