Chapter 1

Introduction

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(Received January 20, 1999)

1. Since the discovery of the nucleus by E. Rutherford,[1] the α-particle has been one of the key particles in understanding the structure and reactions of nuclei. The α-particle model is one of the oldest nuclear models. It first appeared in the 1930's and was initially based on classical theory. In a second stage, the model was revived in the 1950's within a quantum framework at a time when the shell model and the collective model of the nucleus were developing rapidly. In the 1960's and 1970's very many α-particle model (α-cluster model) studies of nuclei were carried out, both in experimental and theoretical contexts. These studies revealed that the concept of α-clustering is essential for understanding the structure of *light* nuclei. The relation between the α-cluster model and the shell model was also theoretically clarified. A comprehensive discussion of the α-cluster model studies can be found in conference proceedings and review articles.[2)-7)]

Although the α-cluster model enjoyed much success, its applicability was mostly limited to light nuclei where the LS coupling scheme works. It was of great interest and importance to investigate whether the model can be extended to the $A \geq 40$ region, where the jj-coupling scheme becomes important. Many efforts were devoted theoretically and experimentally to find evidence for α-cluster structure in the fp-shell nuclei. However, the results remained rather controversial until the beginning of the 1980's.

Research projects were initiated at the end of the 1980's by the Yukawa Institute for Theoretical Physics to investigate the persistency of α-clustering and molecular structure in medium-weight and heavy nuclei. In this supplement, we review the developments of the last decade in this field within the light of phenomenological, semi-microscopic and microscopic cluster models, and of many-body theories and experiment.

2. However successful the α-cluster model is in *light* nuclei, its status cannot be raised to that of a universal nuclear model — like the shell model and the collective model — unless it is shown to work throughout the Periodic Table. Therefore, it was of vital importance to explore nuclei heavier than $A = 40$. The ^{44}Ti nucleus, which marks the boundary between the region of the *medium-weight* and *heavy* nuclei, turned out to be a Rosétta stône in the understanding of the α-cluster properties of heavier nuclei. Indeed many experimental and theoretical studies focused on this nucleus from the viewpoint of the α-cluster [8)-15)] and quartet models. [16)-20)] In addition to states of the ground state band, states suggestive of α-cluster structure were observed in this nucleus in α-transfer reactions and elastic α-particle scattering from ^{40}Ca.

The observed structure was interpreted within the frame of the shell-, collective and α-cluster models, but none of these was capable of explaining the basic band structure of ^{44}Ti in a consistent way. For example, the microscopic α-cluster models like the Resonating Group Method (RGM), [21)] the Generator Coordinate Method (GCM) [22)] and the Orthogonality Condition Method (OCM), [23)] which proved so successful for light nuclei, could not describe the ^{44}Ti structure observed experimentally up to $\sim$ 12 MeV excitation energy; in particular, the α-cluster model was unable to explain why the band structure observed experimentally in ^{44}Ti was essentially different from that of ^{20}Ne. This negative result led some to speculate that the α-cluster model cannot be applied in the ^{44}Ti region.

In fact, another line of attack was needed to understand the ^{44}Ti structure. Michel, Reidemeister and Ohkubo [24)] pointed out the importance of the phenomenon of Anomalous Large Angle Scattering (ALAS) observed in α + ^{40}Ca elastic scattering — which up to then had not seemed to have any connection with the structure problem in ^{44}Ti at low excitation energy — for solving this puzzle. A historical review of the properties of α-nucleus scattering and the α-nucleus interaction is presented in Chapter 2. The authors show how a unique phenomenological potential can describe in a unified way the bound and scattering states of the α + ^{40}Ca system up to $\sim$ 160 MeV, and how the problem of the description of the structure of the ^{44}Ti nucleus within the α-cluster model is solved provided one admits the existence of a (still at that time unobserved) parity-doublet $K^\pi = 0^-$ band starting just above the α-particle threshold. This viewpoint was emphasized and confirmed in subsequent works. [25)-28)] This negative-parity band must of course be confirmed experimentally if this interpretation is to be accepted.

In Chapter 2, this unified description of the α + core system is discussed in detail, by comparing the α + ^{40}Ca system and the better understood α + ^{16}O lighter system. The same unified description is applied to α + ^{36}Ar, which leads to the prediction of the existence in the ^{40}Ca nucleus of a parity-doublet $K^\pi = 0^-$ band with an α-cluster structure similar to that found in the ^{16}O nucleus. The spectroscopic properties of the α-cluster states in ^{44}Ti and ^{40}Ca are studied within the α + core potential model. The validity of such a unified description of bound and scattering states within a phenomenological potential approach is investigated within a semi-microscopic α-cluster model, and the mechanisms of ALAS and of the oscillations seen in the α + ^{40}Ca fusion cross section, and their relation to α-cluster structure at high excitation energies, is discussed within the frame of quantum and semi-classical approaches. The α-clustering properties of nuclei in the vicinity of the *sd*-shell closure is also studied from the same viewpoint; medium-weight and heavy nuclei are finally studied within the double folding model, and α-clustering aspects in ^{94}Mo and ^{212}Po are discussed.

3. Many experimental studies had been carried out in order to investigate the α-cluster properties of nuclei in the *fp*-shell region. The new theoretical developments described in Chapter 2 concerning α-cluster structure in the ^{44}Ti region called for additional experimental investigations in this mass region. New (^{6}Li,d) transfer experiments were thus carried out by Yamaya et al.[29)-32)] first at the Research Center for Nuclear Physics and later at the Institute for Nuclear Study. These experiments, which are presented in Chapter 3, provided clear evidence for the existence in ^{44}Ti and ^{40}Ca of the hypothetical $K^{\pi} = 0^{-}$ parity doublet band suggested by the theoretical studies, as well as of many other states with properties suggestive of an underlying α-cluster structure. In particular, the existence of well-developed higher nodal states in these two nuclei is supported by the DWBA analysis of the (^{6}Li,d) data. One surprising result is the fragmentation of the α-strength observed not only in the parity doublet bands, but also in the higher nodal bands. It was experimentally shown by Yamaya et al. that the band structure in ^{44}Ti and ^{40}Ca is surprisingly similar to that in ^{20}Ne and ^{16}O with parity doublet bands,[33)] respectively. The (^{6}Li,d) α-transfer reaction thus proves to be a very powerful tool in the study of α-cluster structure in nuclei of the *fp*-shell region.

4. The existence of the α-cluster parity-doublet band in both ^{44}Ti and ^{40}Ca prompts us to understand more fully the α-clustering aspects at the beginning of the *fp*-shell, as compared with those in the ^{16}O–^{20}Ne region. For this purpose, a systematic semi-microscopic OCM study was undertaken in the ^{40}Ca–^{44}Ti region,[34)] and is reported in Chapter 4. Since the OCM spans the model space for the α-cluster and shell-model spaces simultaneously, it makes it possible to investigate why α-cluster structure can survive in spite of the high density of the shell-model states in this mass region. This also made possible the study of the interplay between α-cluster and shell-model structure in the ^{40}Ca, ^{41}Ca, ^{42}Ca, ^{42}Sc and ^{43}Sc nuclei through the examination of the energy levels, electromagnetic transitions and α-particle widths in these nuclei. This study also clarified the reasons for the fragmentation of the α-strengths in the $K^{\pi} = 0^{-}$ band in ^{40}Ca. In ^{42}Ca it is shown that the structure is understood only in the α-cluster model in a unified way. Although experimental data are rather insufficient in odd nuclei, it is shown that the α-cluster structure and weak coupling picture persist in spite of the strong spin-orbit force. The OCM is shown to be a powerful model in the fp-shell region.

5. When the excitation energy of the nucleus increases, clusters heavier than α-particles come into play. Indeed in light systems like ^{12}C + ^{12}C, ^{12}C + ^{16}O and ^{16}O+ ^{16}O, molecular resonances have been observed and interpreted within the frame of macroscopic and microscopic models. In medium-weight systems such as ^{24}Mg + ^{24}Mg and ^{28}Si + ^{28}Si,[35),36)] narrow resonances suggestive of di-nuclear molecular structure have been observed at excitation energies as high as 60 to 70 MeV. In Chapter 5, these di-nuclear resonances are investigated within a new type of geometrical molecular model,[37)] where the rotation of the whole system is described using a rotating molecular frame and other degrees of freedom are treated as internal collective variables. Their dynamical motions are studied by the method of normal modes; various excitations around the equilibrium molecular configuration were thus revealed, such as radial vibration and butterfly and anti-butterfly motion. In the ^{24}Mg+ ^{24}Mg (^{28}Si + ^{28}Si) system, the resonance is found to have a stable pole-pole (elongated equator-equator) touching configuration around equilibrium. Partial decay widths from the resonances are analyzed, and butterfly and anti-butterfly modes are investigated in terms of spin alignment or anti-alignment. These molecular structures with a large deformation are interesting to view in terms of superdeformation or hyperdeformation nuclear collective degrees of freedom.[38)]

6. A longstanding problem is the understanding of the origin of α-clustering in nuclei in terms of many-body theory. Marumori and Suzuki[39)] originally investigated the existence of α-like four-nucleon correlations within the New Tamm Dancoff approach from a shell model point of view. Although localized α-cluster correlations were found to be essential in light nuclei, in medium-weight nuclei α correlations have also been investigated from a many-body theory viewpoint.[40)-42)] In Chapter 6, the persistence of α-clustering in the ground states of medium-weight nuclei is studied by calculating the energy gain of the ground state due to α-like four-nucleon correlations. A good reproduction of the ground state energy of the *fp*-shell nuclei is achieved within a multiple α-like cluster model based on many-body theory, which supports the persistence of α-clustering in this mass region.

7. Much progress has also been made recently in the understanding of α-clustering in heavy nuclei. It has been shown that the α-decay properties of heavy nuclei can be systematically explained within a phenomenological model taking into account α-clustering in these nuclei.[43)] The structure of ^{212}Po, and especially its large α width in the ground state, has been studied extensively within various models ranging from the shell model to the cluster model.[44)-49)] It is now generally accepted that α-clustering is an essential ingredient for explaining this large α width.[47)-49)] This point is discussed in Chapter 2 where the structure of ^{212}Po and the scattering properties of the α + ^{208}Pb system are described within a folding model.

The amount of α-clustering has been shown within a realistic model to be significant even in the nuclear interior.[46)] Little is however known about the mechanism of α-clustering in the interior of heavy nuclei; it has been pointed out that the latter is enhanced in the low density surface region. The many-body aspects of α-clustering in the interior of heavy nuclei are described in Chapter 7, using the Green's function formalism of the BCS theory;[51)] the model takes into account the correlation between the neutron and proton Cooper pairs. The correlation is determined self-consistently with pairing interaction and it is shown that the resulting state with α correlation is more stable than the BCS state, which gives possible α-clustering not only at the surface but also inside the nucleus.

8. Ordinary nuclear matter has played an essential role in laying the foundations of the independent particle model of nuclei. Similarly α-cluster matter plays a central role in the understanding of the roots of the α-cluster model. Elaborate microscopic α-cluster matter calculations, taking into account the dissociation of the clusters, were performed within the frame of the GCM.[52)] The model describing the aggregation of the nucleons within the α-cluster matter, which takes fully into account the inter-nucleon interaction and the Pauli principle, is presented in Chapter 8, together with the results of the calculations. α-cluster matter predominates by far over ordinary nuclear matter in the nuclear surface, suggesting a picture where hard α-clusters are "floating" on the surface of the nucleus:[52] In the nuclear interior, α-clusters tend to dissolve into ordinary nuclear matter; however, even in dense regions, α-cluster matter tends to be more stable than nuclear matter.

Acknowledgements

The authors express their sincere thanks to the Yukawa Institute for Theoretical Physics, Kyoto University, for supporting their research projects for nearly ten years, and the Research Center for Nuclear Physics, Osaka University, for continuous support of the experiments. They are also grateful to Professors H. Tanaka, R. Tamagaki, S. Nagata, K. Ikeda, M. Kamimura, H. Horiuchi, Y. Abe, D. M. Brink, R. Lovas, B. Buck and H. Ejiri for their interest in the projects and encouragements, and to the members of the projects for useful discussions and collaborations. They are thankful to Dr. F. Michel and Dr. A. C. Merchant for careful reading of the manuscript.

They would like to dedicate this supplement to the late Professor T. Yamaya.

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