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Molecular structure of nuclei

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Abstract. Cluster structures of nuclei are discussed, with emphasis on nuclear clustering in unstable nuclei. The subjects we discuss are alpha condensed states, clustering in Be and B isotopes, and clustering in ^{32}Mg and ^{30}Ne. The subject of alpha cluster condensation comes from the clustering nature of dilute nuclear matter. We discuss that recent heavy-ion central collision experiments give us nice evidence of the clustering in dilute nuclear matter. We then present a new prediction of the existence of the "alpha cluster condensed states" in the self-conjugate $4n$ nuclei around the breakup threshold energy into n alpha-particles. As for the clustering in neutron-rich Be, we discuss the comparison between the antisymmetrized molecular-dynamics results and the recent experimental data, which shows that the clustering feature manifests itself very clearly in neutron-rich Be isotopes both in the ground and excited states. Clustering in Be isotopes near neutron dripline is intimately related to the breaking of the neutron magic number $N = 8$. We report our recent study about the possible relationship between the clustering and the breaking of the neutron magic number $N = 20$ in ^{32}Mg and ^{30}Ne.

PACS. 21.60.-n Nuclear-structure models and methods

1 Alpha "condensed states"

In central Au + Au collisions above about 100 MeV/nucleon on the basis of the results of FOPI Collaboration, it is reported that, even at 1 GeV/nucleon, about 50% of protons are contained in clusters. It is considered that clusters are formed in radially expanding dilute nuclear matter [1]. These experiments can be said to present us with the first observation of clustering in dilute nuclear matter. Antisymmetrized molecular dynamics (AMD) was applied to the study of fragmentation in radial expansion in the ^{197}Au + ^{197}Au system at incident energies of 150 and 250 MeV/nucleon [2]. Good reproduction of the fragment mass distribution was obtained, together with a good reproduction of the observed linearity of the fragment kinetic energy as a function of the fragment mass.

One of the fundamental questions of the nuclear clustering in finite nuclei is what kind of cluster states can be expected to exist around the threshold energy of $n\alpha$ breakup in self-conjugate $4n$ nuclei. In this excitation energy region the clustering state is expected to have dilute density and to reflect the clustering feature in dilute nuclear matter. One possible answer to this question is the cluster state with $n\alpha$ linear-chain structure. The idea of the α linear-chain state, which was first proposed by Morinaga [3], is so fascinating that recently the existence of 6α linear-chain states in ^{24}Mg was studied extensively by experiments and by theoretical analyses of them [4]. The possibility of the 3α linear-chain state in ^{12}C, which is the simplest α linear-chain state, was studied in detail by many authors by solving the 3α problem microscopically [5]. These three-body studies all showed that the 3α cluster states around the 3α threshold energy do not have linear-chain structure. The calculated second 0^+ state, which corresponds to the observed second 0^+ state located 0.39 MeV above the 3α threshold energy, was found to have a structure where α clusters interact with each other dominantly in a relative S-wave. Thus, the theory concluded that the cluster state near the 3α threshold energy has not the 3α linear-chain structure but an α-gas–like structure which can be approximately expressed by the wave function

$$\mathcal{A}\{e^{-\gamma(\mathbf{X}_1^2+\mathbf{X}_2^2+\mathbf{X}_3^2)}\phi(\alpha_1)\phi(\alpha_2)\phi(\alpha_3)\}, \tag{1}$$

where $\mathbf{X}_i$ stands for the center-of-mass coordinate of the i-th α cluster α_i and $\phi(\alpha_i)$ the internal wave function of the α cluster α_i. It is to be noted that this wave function of eq. (1) expresses the state where three α clusters occupy the same $0s$ harmonic-oscillator orbit $\exp[-\gamma\mathbf{X}^2]$, *i.e.* it expresses a 3α cluster condensed state. Recently, Tohsaki, Schuck, Röpke and myself investigated the possibility of a 4α cluster condensed state by adopting a wave function similar to eq. (1) [6]. It was shown that we can expect the existence of the 4α cluster condensed state near the 4α threshold energy.

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2 Clustering in Be and B isotopes

The AMD studies of Be isotopes [7–9] provide a very good example of the importance of clustering in neutron-rich nuclei. AMD calculations show that in all Be isotopes from ^{8}Be up to the neutron dripline nucleus ^{14}Be there exists the α-α core. The motion of neutrons is well understood by the concept of molecular orbits [10] around the α-α core. Many years ago, Seya, Kohno and Nagata made a structure study of Be and B isotopes with the model of molecular orbits around the α-α core up to the neutron dripline [11]. The *ab initio* AMD model now confirmed theoretically the formation of the α-α core in Be isotopes up to the neutron dripline. An important valence orbit for neutrons in Be isotopes is the so-called σ orbit coming down from the *sd*-shell due to the clustering deformation.

Especially in ^{10}Be AMD reproduces well the energy spectra of the observed states which are classified into four rotational bands: $K^\pi = 0_2^+$ and $K^\pi = 0_1^-$ bands have the neutron configurations with two neutrons and one neutron in the σ orbit, respectively, whereas $K^\pi = 0_1^+$ and $K^\pi = 2_1^+$ bands have neutron configurations with no neutrons in the σ orbit. The Gamow-Teller transition strengths from the ^{10}B ground state to $K^\pi = 0_1^+$ and $K^\pi = 2_1^+$ band states are well reproduced by AMD, as are the electric transitions in ^{10}Be [8].

The recent AMD study of ^{12}Be [9] shows further exciting features of clustering in Be isotopes. The ground rotational band with $K^\pi = 0^+$ has a 2p-2h neutron configuration, which means the vanishing of the $N = 8$ neutron magic number. The second $K^\pi = 0^+$ band has a closed shell structure of neutrons. What is interesting is the third $K^\pi = 0^+$ band, which again has a 2p-2h neutron configuration. Its band head 0^+ state is located around 10 MeV excitation energy and is close to the ^{6}He + ^{6}He threshold at 10.17 MeV. The third $K^\pi = 0^+$ band has a moment of inertia larger than the ground band and its decay width into the ^{6}He + ^{6}He channel is larger than that into the ^{8}He + ^{4}He channel. The excited rotational band with $K^\pi = 0^+$ —first observed experimentally at RIKEN [12] and recently at GANIL [13] in more detail— has a good correspondence with this theoretical third $K^\pi = 0^+$ band. This band has the characteristic of a molecular band of ^{6}He + ^{6}He structure.

According to the AMD study of B isotopes [14], B isotopes near the neutron dripline nucleus ^{19}B have prominent di-cluster density distribution. Here five protons are divided spatially into two groups —one of two protons and one of three protons— which are surrounded by neutrons. The reliability of such AMD results is assured by the good reproduction of data for ^{13}B $\sim$ ^{19}B, which include binding energies, radii, electric quadrupole moments, and magnetic moments.

3 Clustering feature in ^{32}Mg and ^{30}Ne

The neutron-rich nuclei ^{32}Mg and ^{30}Ne have been studied by using the Gogny force with a new version of AMD in which the single nucleon wave packet is described by a deformed Gaussian [15]. After the angular-momentum projection, both ^{32}Mg and ^{30}Ne are shown to be considerably deformed and the experimental data of ^{32}Mg are well reproduced [16]. The ground states of these nuclei have neutron 2p-2h structure, which means that the neutron magic number $N = 20$ is broken. The *pf* orbits intrude into the *sd*-shell for large deformation. While the ground state of ^{32}Mg has a mean-field–like structure, cluster-like excited states with the neutron 4p-4h configuration show up in the vicinity of the ground state. What is very interesting is that in ^{30}Ne the mean-field–like structure and cluster-like structure are mixed in the ground state. In this respect, the ^{30}Ne ground state is similar to the ^{20}Ne ground state where the mean-field–like structure and ^{16}O+α cluster structure are mixed [5]. However, the clustering characteristic of ^{30}Ne is quite different from that of ^{20}Ne when we compare the negative-parity excited states. As is well known, in ^{20}Ne we have the excited rotational band with $K^\pi = 0^-$, which is a parity doublet partner of the ground rotational band with $K^\pi = 0^+$ and has a clear ^{16}O + α cluster structure. In the case of ^{30}Ne, the low-lying negative-parity rotational band with $K^\pi = 0^-$ does not have a clear clustering characteristic and cannot be regarded as a parity doublet partner of the ground rotational band. The low excitation energy of the negative-parity rotational band is not due to the clustering but to the intrusion of the *pf* orbits into *sd* orbits.

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