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ALPHA CLUSTERING IN NUCLEUS*

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The nuclear structure, as we know now, is a roughly homogeneous distribution of neutrons and protons. However, the clustering phenomena is important to determine the structure of light nuclei. Here, we present the semi-classical microscopic approach to the Liquid Drop Model and the emergence of alpha clusters as a result of spin–isospin pairing of nucleons in the variational energy minimization procedure.

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1. Introduction

Binding energy curve is the experimental evidence about the nuclear structure. The shape of this curve is the reflection of structure of nucleus. Hence every theory which evolved from 1930s till this time was trying to reproduce the binding energy curve. It started from the Liquid Drop Model (LDM), Alpha Clustering Model and now it reaches at the shell model, which is the most successful model in describing the structure of nucleus so far.

LDM could fit smoothly with the binding energy curve and explain the fission mechanism successfully, but could not explain why there is a large binding energy for even nuclei such as ^{4}He, ^{12}C, *etc.* The success of the shell model is that it could explain the reason behind the large binding energy for even nuclei. According to the simplest shell model, every nuclei is spherical in structure. But many experimental results revealed that 90% of the nuclei are not spherical. Therefore, the extension of the shell model for the deformed nuclei shape is given first by S.G. Nilsson in 1955, so this version is often referred to as the Nilsson model. Recently, some experimental studies at CERN [1] show that the structure of Rn is not spherical but pear shaped and they expect to see more such nuclei near Th. These results show that

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there is a need for a new theory to well explain the structure of nuclei. If we are taking into account the interaction between nucleons (as it is in reality) in the model approach, we can expect the formation of clusters. Clustering is a natural energy minimization mechanism. If we look at a large scale, we can see Galaxy clusters, star clusters, planets, *etc.*, if we go to the small scales, we can also see clustering, quarks clustered to build nucleons, nucleons clustered to form alpha particles, atoms clustered to form molecules. So it would be surprising if we did not find any clustering in nuclei.

2. History of alpha clustering

The idea of alpha clustering has a history back to 1930s. By observing alpha decay from nucleus, people speculated that nuclei are made up of alpha particles. Bethe in his paper [2] published in 1936 predicted that nuclei are made of alpha particles and gave also a geometrical arrangement of alpha particles inside nuclei. According to him, ^{8}Be has one bond between two alpha particles and they have dumbbell-like shape, ^{12}C has three alpha bonds and triangular shape, and ^{16}O has six alpha bonds and tetrahedral shape. He predicted that after O, for each new addition of alpha particles, the number of bonds increased is three. In 1938, Hafstad and Teller [2] extended this work and they plotted the binding energy *versus* the number of bonds till the nucleus ^{32}S. This study did not grow much further beyond ^{56}Ni, because the systematic increase in binding energy breaks at ^{60}Zn. Everybody knows something is happening to the structure of nucleus around ^{60}Zn but there is no good explanation for this. At that time, this was too a big challenge for the alpha clustering models and eventually these models disappeared from the nuclear structure theories.

3. Experimental evidences for alpha clustering

There are many experimental evidences for the alpha clustering in nuclei. Alpha particle decay from nuclei is known from the discovery of nucleus. For example, ^{8}Be undergo two alpha decay. The Hoyle state [2] is an excited state of ^{12}C, were it has been experimentally shown that nuclei exist as a three alpha state. This state is important for nuclear synthesis in stars. After these studies, Ikeda [2] came up with the famous IKEDA diagram in which he stated that all even nuclei, near to the decay threshold, exist as alpha condensed state, but at ground state nucleon interaction dominates alpha interaction. Some of the recent experimental studies [3] strongly support the alpha cluster structure in ^{56}Ni. In the reaction $\alpha+^{56}$Ni, they got alpha multiplication of 7 which cannot be explained by the Hauser–Feshbach statistical decay model. Also some preliminary studies [4] show alpha-cluster structure in the ground state of ^{40}Ca displayed in a $(p,p\alpha)$ knockout reaction.

4. Semi-classical microscopic approach to the liquid drop model — brief discussion

As we all know, in LDM total nucleon interaction is represented by the volume interaction, surface interaction, Coulomb interaction and so on ... as $\langle E\rangle = B_{\rm v} + B_{\rm surf} + B_{\rm Coul} + \ldots$ Our microscopic model also considered the same form of interaction. In this model, nuclei are represented as the superposition of nucleons $\Phi = \prod_{k=1}^{M} \phi_k$ and every nucleon is considered as the wave packet of the form $\phi_k = \frac{1}{\left(2\pi\sigma_k^2\right)^{3/4}} \exp\left(\frac{-(\boldsymbol{r}-\langle \boldsymbol{r}_k\rangle)^2}{4\sigma_k^2} + \frac{i}{\hbar}\boldsymbol{r}\,\langle \boldsymbol{p}_k\rangle\right)$. So the average interaction is given by the potential of the form $V\left(\{\langle \boldsymbol{r_k}\rangle\}, \{\sigma_k\}\right) = V_N\left(\{\langle \boldsymbol{r_k}\rangle\}, \{\sigma_k\}\right) + V_S\left(\{\langle \boldsymbol{r_k}\rangle\}, \{\sigma_k\}\right) + V_{\rm Coul}\left(\{\langle \boldsymbol{r_k}\rangle\}, \{\sigma_k\}\right)$. Average value of kinetic energy of the system is represented by $\langle \Phi\,|T|\,\Phi\rangle = \sum_{k=1}^{k=M} \left[\frac{\langle \boldsymbol{p}_k\rangle^2}{2m} + \frac{3\sigma_{p_k}^2}{2m}\right]$, were first term represents the excited energy and the second term represents the internal fermionic motion of nucleons. Now, the average value of the Hamiltonian of the system is represented by $\langle \Phi\,|H|\,\Phi\rangle = \sum_{k=1}^{k=M} \left[\frac{\langle \boldsymbol{p}_k\rangle^2}{2m} + \frac{3\sigma_{p_k}^2}{2m}\right] + \langle \Phi\,|V_N|\,\Phi\rangle + \langle \Phi\,|V_S|\,\Phi\rangle + \langle \Phi\,|V_{\rm Coul}|\,\Phi\rangle$. In the ground state of nuclei, excited energy term will be zero. The second and third term in the right-hand side of the equation is replaced by the Equation-of-State of nuclear matter (EOS) as $B_V = \sum_{k=1}^{k=M} \frac{3\sigma_{p_k}^2}{2m} + \langle \Phi\,|V_N|\,\Phi\rangle = \int e(\rho, \delta, \sigma_n, \sigma_p)\rho(\boldsymbol{r})\, d^3\boldsymbol{r}$ and can be treated as a volume term of binding energy. The ground state energy of nuclear matter is described by the EOS [5, 6], which considers the energy density as the sum of kinetic energy, associated with the internal fermionic motion, and energy given by the potential interactions. Therefore, in our approach, we do not have to deal with finding the appropriate distribution of the nucleon momenta, provided that a correct description is given by the selection of appropriate EOS parameters. Such an EOS parameterization replaces the potential parameterization normally used in such approaches.

As a result of spin–isospin pairing, we could observe the alpha cluster structures in the ground state of nuclei in the variational energy minimization process. These alpha clusters and the number of bonds between alphas are similar to that predicted by Bethe and other studies as shown in Fig. 1 (a). We plotted the total binding energy of nucleus as a function of number of alpha–alpha bonds predicted by Bethe as shown in Fig. 1 (b).

From this plot, we can see that there is a linear relationship from ^{12}C to ^{56}Ni and from ^{60}Zn, this relation changes. From our calculation results with the discussed model, we obtained the number of bonds between alphas the same as that predicted by Bethe up to ^{56}Ni. From ^{60}Zn we observed a sudden growth in the number of bonds. We strongly believe that this structural change from ^{60}Zn may be the reason behind the change in slope as shown in Fig. 1 (b).

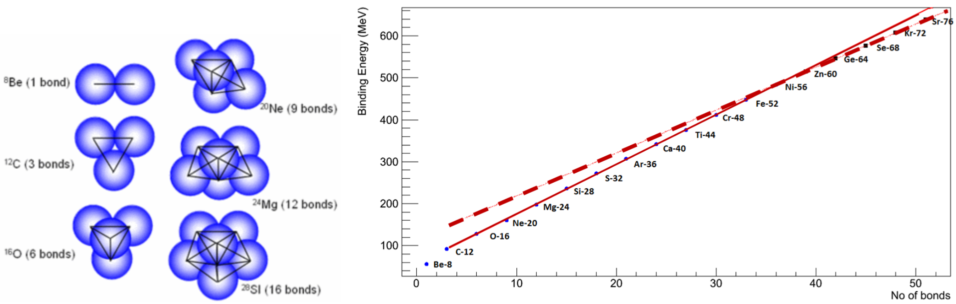

Fig. 1. The alpha clustering in nuclei. (a) Geometrical arrangement of alphas and the bonding between them (from [2]). (b) The total binding energy as a function of number of bonds predicted by Bethe.

5. Conclusions and perspectives

Here, we presented a semi-classical microscopic approach to the Liquid Drop Model which results in alpha clustering nuclei. This model is very promising since it considers the EOS and can calculate the alpha cluster structures not only in light nuclei but also in heavier nuclei. This model is still in an embryonic stage. We need to consider all the experimental and theoretical evidences and also need to get good parameters of EOS for finding the global minimum of Hamiltonian used.

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