Pair phase transition and its evolution on even $^{64\sim68}$Ge isotopes

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Abstract By using a microscopic sdIBM-2+2q.p. approach which is the phenomenological core plus two-quasi-particle model and the experimental single-particle energies, the levels of the ground-band, β-band, γ-band, and partial two-quasi-particle states on $^{64\sim68}$Ge isotopes are successfully reproduced. Based on the phenomenological model and microscopic approach, it has been deduced that no s-boson in the nucleus is breaking up and aligning; and that when one d-boson does, the minimum aligned energy can be calculated. This paper explicitly indicates that, with the increase of neutron number, an evolution process of PPT objectes, i.e. from the two-quasi-proton states (on ^{64}Ge nucleus) to the two-quasi-neutron states (on ^{68}Ge nucleus) may take place in even Ge isotopes.

Keywords Pair phase transition, Low-energy spectra, High-spin state, Even $^{64\sim68}$Ge isotopes

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1 Introduction

The nuclear pair correlation is significant in the theory of nuclear structure. The typical spectral property depends on the formation or destruction of nucleonic pair. In studying this problem an important aspect in the theory of nuclear structure — the pair phase transition (PPT) — has taken shape.[1-5] The phenomenological interacting boson model (IBM), as one of the pair model theories, has been proved very successful in the description of the low-lying spectrum on middle heavy nuclei and heavy nuclei; its extension, the interacting boson-fermion model (IBFM), has been obtained a larger success in the description of nuclear high-spin state; [1,3] recently attention has been drawn to the study of nuclear shape transition and coexisting phase in transitional region by IBM.[6,7] Following the maturation and wide application of the phenomenological IBM theory, one of its microscopic accomplishments, the microscopic sdIBM-2 approach, develops very quickly.[8-12] Because of the effect of single-particle energies (SPE), particularly the effect of exact energies at intruder orbits, for the light mass number nucleus, in which neutrons and protons are located at same major shell, it is obviously not deeper that the understanding of the PPT mechanism, exact identification of the PPT objects (neutrons or protons) and the evolution process of the PPT objects are investigated. So it will be of significance if the process and some detail of this phenomenon can be revealed from microscopic viewpoint.

In this paper, from the microscopic viewpoint, the property of PPT for the light mass number $^{64\sim68}$Ge isotopes is deeply investigated, the PPT objects have been identified exactly, and the evolution process of the PPT objects has been revealed. The valence nucleons of $^{64\sim68}$Ge isotopes are located at shell N=28~50. Although there is the spin-orbit coupling in this shell, the level-crossing does not happen, the experimental SPE values can be read from the low-lying states of doubly magic nucleus ^{56}Ni and its nearest neighboring nuclei.[13~17] The theoretical results calculated from these experimental values are directly examined by experiments more easily.

2 Outline of the theoretical approach

The phenomenological IBM assumes that nucleons exist as pair-form in a nucleus while a nucleus is in a low-excited and ordinary rotational state, i.e. a superfluid phase. Once the nucleus is in a high-energy

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excited or high-speed rotational state, at least one boson may be decoupled from the strong-coupled collective state as a non-collective and non-coupled fermion-pair, and then breaks into two nucleons which would occupy one of the intruder orbits $g_{9/2}$, $h_{11/2}$, $i_{13/2}$, and pass into an aligning. The breaking up and aligning in the nucleus are completed; and the PPT from the collective superfluid phase to single-particle phase has taken place. All other valence nucleons can form a collective core described approximately by the phenomenological IBM-2, then the nucleus is in a coexisting phase, i.e. the concurrence of collective phase and single-particle phase, which can be described by so-called phenomenological IBM-2+2q.p. model.[3] The microscopic theory for the high-spin states is simply obtained by applying the microscopic sdIBFM-2 formalism to the sdIBM-2+2q.p. model. The detailed description of the microscopic theory for the high-spin states theory can be found in Refs. [8], [9] and [12].

If the breaking up results from the fact that nucleus is in a high-energy excited or high-speed rotational state, PPT of nucleonic pair has taken place in nucleus, so PPT at zero temperature and the coexisting phenomenon of collective-single phase can be described by this approach.[12, 18~21] On the other hand, if the breaking up is attributed to heat influence by the nucleus, the nuclear phase transition of thermo-excited mode has taken place, then the nuclear finite-temperature behavior can be described by this approach.[22~24]

Based on phenomenological model and this microscopic approach, when one boson is produced due to the decoupling, breaking up, occupying the intruder orbit, and passing into the aligning, the requisite energy should be:

$$E_{\text{align}}^{(\sigma)} = -\left(E_{\text{d}}'^{(\sigma)} + E_{\text{d}}''^{(\sigma)}\right) + 2E_{\text{int}}^{(\sigma)} = 2E_{\text{int}}^{(\sigma)} - E_{\text{d}}^{(\sigma)}. \quad (1)$$

where $E_{\text{align}}^{(\sigma)}$, $E_{\text{d}}'^{(\sigma)}$, $E_{\text{d}}''^{(\sigma)}$ and $E_{\text{d}}^{(\sigma)}$ are the boson's aligned energy, non-perturbation energy, correlation energy and total energy respectively; while $E_{\text{int}}^{(\sigma)}$ is the energy of the intruder orbit. These values can be obtained in the running of the sdIBM-2+2q.p. approach. Obviously, the boson that requires less energy may first of all break up, and pass into the aligning. The criterion (1) may not only identify which kind of bosons presenting PPT first of all, but also classify angular momentum multiple-states.[20] When appling Eq.(1) to isotopes, one should employ $[E_{\text{d}}^{(\sigma)} - E_{\text{s}}^{(\sigma)}]$ instead of $E_{\text{d}}^{(\sigma)}$, because each isotope is at different ground state.

It is well known that the intrinsic structure of *U (5)*-, *O (6)*-, and *SU (3)*-symmetries at zero temperature for the phenomenological IBM results from the variation in levels caused by a stronger spin-orbit coupling. In this approach, by means of adjusting parameters of nucleon-nucleon effective interaction, the spectra of Hamiltonian of coupled bosons will reproduce the experimental results, the macroscopic process of phase transition will reappear microscopically, and the microscopic information on the boson structure and the variation in single-particle levels is obtained. In short, it will avail to demonstrate the evolution process of PPT objects, and to understand the formatting, breaking up, occupying the intruder orbit, and passing into the aligning.

3 Calculated results and discussion

For $^{64\sim68}$Ge isotopes, the valence nucleon configurations are

$$(2p_{3/2}, 1f_{5/2}, 2p_{1/2}, 1g_{9/2})^{8}(2p_{3/2}, 1f_{5/2}, 2p_{1/2}, 1g_{9/2})^{N_n}$$

with N_n= 4, 6, 8. As usual, parameters $g_0^{(\sigma)}$, $G_2^{(\sigma)}$, $K^{(\sigma)}$ (σ=n, p) and $K^{(np)}$ denote the strength of the pairing force, quadrupole pairing force, quadrupole- quadrupole force for the identical nucleons, and the neutron-proton force of quadrupole-quadrupole type respectively. SPE, particularly the exact $E_{1g9/2}$ energy value, is the key parameter to calculate the sequence of PPT on neutron and proton. For former three levels, experimental energies on neutron are taken from Refs. [13]~[17], while those on proton from Refs. [14] and [15]. Since $E_{1g9/2}$ energy values cannot be measured by experiments, they are taken from results calculated by models: for neutron 7.70 MeV [13]; for proton 7.70 MeV [13], 7.51 MeV [16], or 7.15 MeV [15], and in this paper we take the middle value of 7.51 MeV. All the SPE data are listed in Table 1. The strengths of nucleon-nucleon effective interactions are listed in Table 2. Other energy values requisite for calculation in this paper are given in Table 3.

A comparison between the calculated and experimental spectra for isotopes $^{64\sim68}$Ge is illustrated in Fig.1.

Table 1 Single-particle energies of valence nucleon (MeV)

nlj	$2p_{3/2}$	$1f_{5/2}$	$2p_{1/2}$	$1g_{9/2}$
Neutron	4.00	4.77	5.11	7.70
Proton	4.00	5.06	5.11	7.51

Table 2 Parameters of nucleon-nucleon effective interaction (MeV)

Isotopes	$g_0^{(n)}$	$G_2^{(n)}$	$K^{(n)}$	$g_0^{(p)}$	$G_2^{(p)}$	$K^{(p)}$	$K^{(np)}$
^{64}Ge	0.0717	0.0712	0.0490	0.0740	0.0900	0.0900	0.0640
^{66}Ge	0.0755	0.0430	0.0550	0.0745	0.0900	0.0920	0.0630
^{68}Ge	0.0850	0.0440	0.0300	0.0750	0.0900	0.0920	0.0580

Table 3 Total energy *E*, non-perturbation energy *E'*, and aligned energy E_{align} of boson (MeV)

Isotopes	$E_s^{(n)}$	$E_d^{(n)}$	$E_s^{(p)}$	$E_d^{(p)}$	$E_s'^{(n)}$	$E_d'^{(n)}$	$E_s'^{(p)}$	$E_d'^{(p)}$	$E_{align}^{(n)}$	$E_{align}^{(p)}$
^{64}Ge	6.377	7.644	6.113	7.382	8.584	8.020	8.501	8.052	7.756	7.638
^{66}Ge	6.225	7.738	6.084	7.373	8.623	7.877	8.504	8.050	7.662	7.647
^{68}Ge	6.118	7.816	6.041	7.373	8.833	7.948	8.528	8.050	7.584	7.647

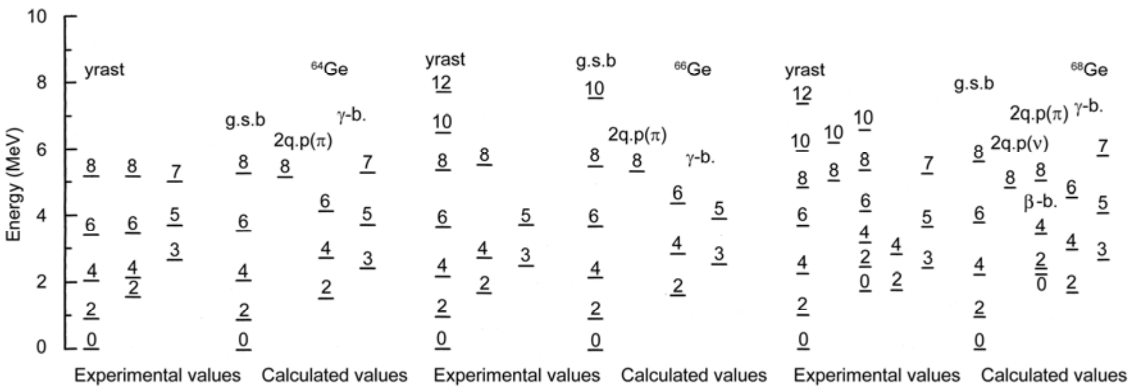

Fig.1 Comparison of the calculated and experimental spectra [26,27] for $^{64\sim68}$Ge.

Based on the data or the results in Tables 1~3 and Fig.1, we may conclude that the ground-band, β-band, γ-band and the spectra of partial two-quasi-particle, calculated by the microscopic sdIBM-2+2q.p. approach, are consistent satisfactorily with the experimental values. It is noted that four valence neutrons and four valence protons in ^{64}Ge nucleus are located at the same major shell. Generally speaking, the excited probability and total boson energies for the two nucleonic pair should be equal. According to this, the parameters of nucleon-nucleon effective interaction for neutrons and protons are determined. In the following calculations of ^{66,68}Ge nuclei, the parameters for protons are nearly constant, their spectra have been fitted out by means of adjusting parameters for neutrons.

The calculated results show that the breaking up takes place not in s-boson, but always in d-boson; and when one boson suddenly breaks up and then two neutrons pass into the aligning, the structure coefficients and some energies do not alter obviously after the change of states, so we can neglect the change of these states.[12,18, 24]

The data in Table 3 show that for ^{64}Ge nucleus, the $E_{1g9/2}$ at intruded orbit of proton is the minimum, and according to the above criterion (1), PPT of proton pair will take place first of all. With the increase of neutron number, PPT of neutron pair becomes easier. For ^{66}Ge nucleus, the $E_{1g9/2}$ for proton is slightly larger than that for neutron, and PPT of proton pair will still take place first of all. But this approach cannot rule out the probability that PPT of neutron pair will take place first of all by fluctuation, or that PPT of both nucleonic pairs will take place at the same time.[28] For ^{68}Ge nucleus and more heaver isotopes, the situation is opposite, PPT of neutron pair will always take place first of all, thus demonstrating the possibility of transfer of the PPT objects on Ge isotopes.

It is noted that if the energy difference at intruded orbits, $\Delta E_{1g9/2}=E_{1g9/2}^{(n)} - E_{1g9/2}^{(p)}$, is over-large, the transfer of PPT objects will not take place, so the exact energy values at intruded orbits are vital. In terms of Ge isotopes, if $\Delta E_{1g9/2}$ is larger than 0.25 MeV, i.e. $E_{1g9/2}$ for neutron and proton are 7.70 MeV and 7.15 MeV respectively, the transfer of objects will be not so quickly. So far, while the prediction on ^{64}Ge nucleus in this paper remains to be experimentally verified, the assertion on ^{66}Ge nucleus is in good agreement with the conclusion in Ref. [26], and the prediction on ^{68}Ge nucleus has been supported by the experiment.[29]

4 Conclusion

In summary, the microscopic sdIBM-2+2q.p. approach may satisfactorily reproduce the ground-band, β-band, γ-band and partial two-quasi-particle band. Based on the phenomenological model and microscopic approach, it has been deduced that the nucleus requires the minimum aligned energy threshold (Eq.(1)) when one boson in nucleus presents PPT. It is indicated that, with the increase of neutron number in the Ge isotopes, the evolution may take place from the two-quasi-proton state (for ^{64}Ge nucleus) to the two-quasi-neutron state (for ^{68}Ge nucleus). This paper has revealed the evolution process of the PPT objects for Ge isotopes.

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