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SHELL MODEL APPROACH TO PROTON–NEUTRON ALIGNMENT IN $N \sim Z$ Ge–As NUCLEI*

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Large-scale shell model calculations were carried out for $N \sim Z$ Ga–As nuclei with isospin invariant pairing plus QQ interaction. A particle alignment mechanism was investigated by focusing on the role of the $g_{9/2}$ orbital. The proton–neutron pairing with isospin zero and angular momentum 9 was found to play an important role in these $N \sim Z$ nuclei.

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1. Introduction

Due to the development of experimental techniques, spectroscopy experiments were recently performed for $N \sim Z$ medium-heavy nuclei, *e.g.* ^{62}Ga [1], ^{66}Ge [2], ^{68}Ge [3], ^{72}Kr [4], and ^{69}As [5]. These experiments revealed new levels and bands, including high spin non-yrast states, and have shown that many interesting phenomena such as shape coexistence,

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shape change, particle alignment, band termination, super deformation and so on, are present in this region of nuclei. There are several methods, such as cranked Nilsson–Strutinsky calculations, Vampir calculations, projection shell model and shell model calculations, which allow to study these nuclei theoretically.

In this paper, we report a shell model calculation study of particle alignment mechanism for these nuclei.

2. Shell model calculations

For shell model calculations, the $p_{3/2}, f_{5/2}, p_{1/2}$ and $g_{9/2}$ orbitals are considered and will be later called pfg shell. As this shell model space is bigger than full fp shell, we need large-scale shell model calculations. For this purpose, we use the MSHELL [6] code, which has been recently developed, and can easily solve shell model problems with up to 150 Million dimensions, running on a present day personal computer. Beyond this dimensions, we use energy variance extrapolation method, the details are given in Refs. [7,8]. In this model space, the $g_{9/2}$ orbit plays an important role as a high-j intruder orbit.

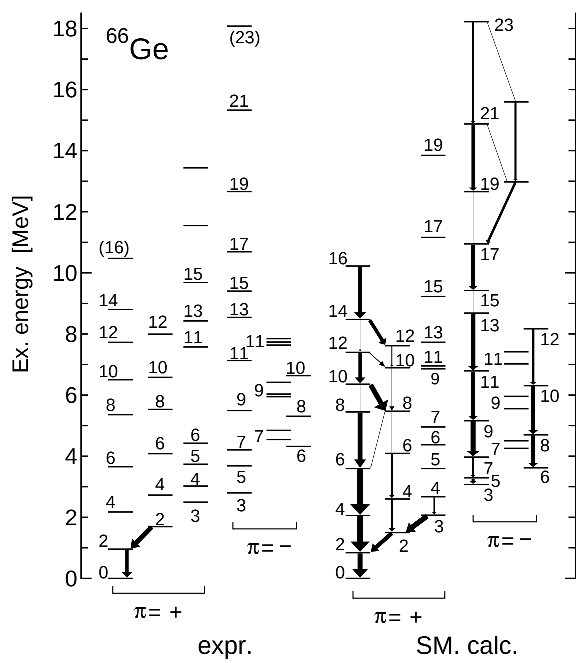

Fig. 1. Experimental (left) and theoretical energy levels (right) for ^{66}Ge. The parity of each state is specified by $\pi = +$ and $\pi = -$.

Residual interaction is a central issue in shell model calculations. In fp shell, residual interaction has been well determined by GXPF1 [9, 10] and KB3G [11], which are based on microscopic G-matrix but are somewhat modified, especially in its monopole part. On the other hand, in pfg shell, there is no standard shell model interaction yet. Here we use rather schematic interaction proposed by Hasegawa and Kaneko recently, who consider extended isospin invariant $P+QQ$ (EPQQ) interaction.

The EPQQ Hamiltonian is composed of the single-particle energies, monopole corrections, $J=0$ and $J=2$ isovector pairing forces, quadrupole–quadrupole (QQ) force and octupole–octupole (OO) force, the details are presented in Refs. [12, 13]. This Hamiltonian has several parameters which were chosen to reproduce energy levels of Zn, Ge and As isotopes [12–16]. Although this Hamiltonian is rather simple and schematic, it can nicely describe experimental levels, including high spin states. As an example, comparisons between experimental data and shell model calculations for positive and negative parity states of ^{66}Ge are shown in Fig. 1. The agreement seems to be quite good. Other comparisons for ^{65,66,67,68}Ge and ^{67,69}As nuclei have been presented in Refs. [12–15].

In the present paper, we further tested this shell model interaction for ^{62,63}Ga nuclei to extend the validity of this schematic interaction. The shell model results for ^{62,63}Ga are shown in Figs. 2 and 3, respectively, compared with recent experimental data [1]. The overall agreement also seems to be good.

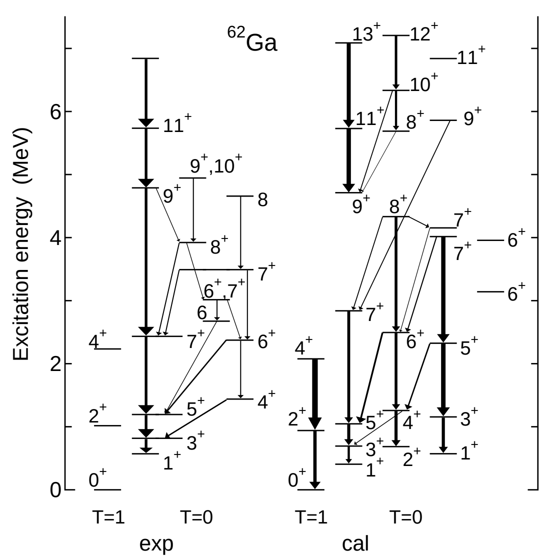

Fig. 2. Experimental (left) and theoretical energy levels (right) for ^{62}Ga.

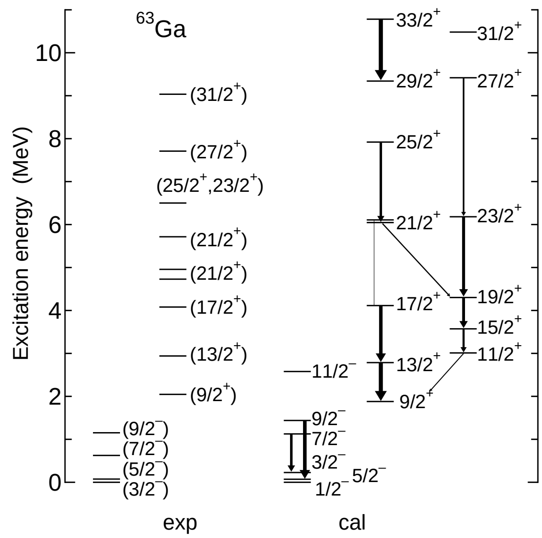

Fig. 3. Experimental (left) and theoretical energy levels (right) for ^{63}Ga.

3. Particle alignment

For $N \sim Z$ Ga–As nuclei, the $g_{9/2}$ orbit plays an important role as an intruder orbital. We will see, in the following, that nucleon pair in the $g_{9/2}$ orbit is rather weakly coupled with the fp shell nucleons, and that the nucleon pair has an aligned angular momentum. Such particle alignment schemes are clarified as two-neutron ($2n$) alignment coupled to $T = 1$, $J = 8$; one-proton–one-neutron ($1p1n$) alignment coupled to $T = 0$, $J = 9$; two-proton–two-neutron ($2p2n$) alignment coupled to $T = 0$, $J = 16$. By taking ^{66}Ge as an example, such particle alignments was investigated in our shell model wave functions.

To analyze this alignment picture, we calculate expectation values of the spin and isospin for the $g_{9/2}$ orbit, which are denoted as $J_{g_{9/2}}$ and $T_{g_{9/2}}$ respectively, $J_{g_{9/2}} = [\langle(\hat{j}_{g_{9/2}})^2\rangle + 1/4]^{1/2} - 1/2$ and $T_{g_{9/2}} = [\langle(\hat{t}_{g_{9/2}})^2\rangle + 1/4]^{1/2} - 1/2$, where $\hat{j}_{g_{9/2}}$ and $\hat{t}_{g_{9/2}}$ denote the spin and isospin operators for the $g_{9/2}$ orbit. Calculated $J_{g_{9/2}}$ and $T_{g_{9/2}}$ of the yrast states are shown in the middle and lower panel of Fig. 4.

At $J \sim 8$, the $J_{g_{9/2}}$ of the yrast states becomes about 8 and the $T_{g_{9/2}}$ of the yrast states becomes about 1. The neutron occupation number in the $g_{9/2}$ orbit becomes about two [12, 13]. These expectation values show that two neutrons in the $g_{9/2}$ orbit are coupled with $J = 8$ and $T = 1$. This shows that the $2n$ aligned band crosses the gs band at $J \sim 8$.

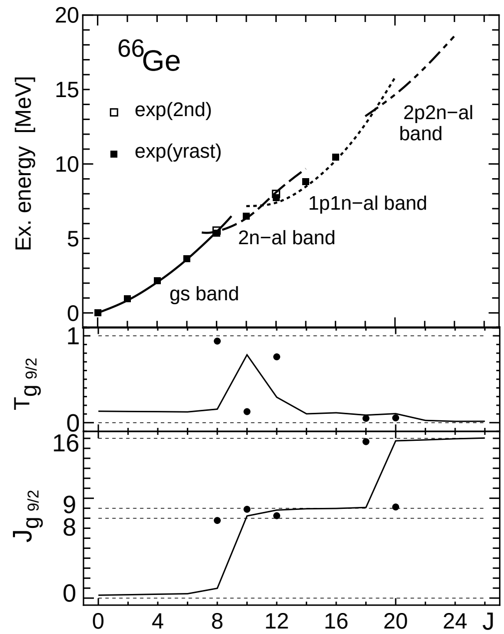

Fig. 4. Upper panel: Yrast states are classified by alignment scheme. Middle and lower panels: J_g and T_g for the $g_{9/2}$ orbit for yrast states.

Next we consider $J = 10 \sim 14$ states, where approximately $J_{g_{9/2}} = 9$ and $T_{g_{9/2}} = 0$. The respective proton and neutron occupation numbers become about one. These expectation values show that one proton and one neutron in the $g_{9/2}$ orbit are coupled with $J = 9$ and $T = 0$. The $1p1n$ aligned band competes with the $2n$ aligned band near $J = 10$ and $J = 12$. The $1p1n$ alignment overwhelms the $2n$ alignment at 14^+_1, and the $1p1n$ aligned band becomes yrast from 14^+_1 to 18^+_1.

Moreover, at $J > 20$, where $J_{g_{9/2}} = 16$ and $T_{g_{9/2}} = 0$ approximately hold, the proton and neutron occupation numbers become about two, respectively. This means that two protons and two neutrons in the $g_{9/2}$ orbit are coupled with $J = 16$ and $T = 0$. The $2p2n$ aligned band takes over as the yrast state at 20^+_1, continuing up to the 26^+_1 state which terminates the band.

We have also investigated the alignment structure of ^{69}As (see Ref. [14]). Experimentally observed positive and negative parity states [5] can be well reproduced by our shell model calculations and the same aligned structure concerning the high-j intruder $g_{9/2}$ orbit is found to play an important role for high spin states [14].

In the present shell model calculations of ^{63}Ga, $1p1n$ alignment modes appear also for negative parity states, $\frac{21}{2}^-$, $\frac{23}{2}^-$ and $\frac{25}{2}^-$, though there is no corresponding experimental data.

4. Summary

We have investigated the $N \sim Z$ medium-heavy nuclei in $60 \sim 70$ mass region by means of large-scale shell model calculations with isospin invariant pairing plus QQ interaction [12–15]. Our shell model calculations nicely reproduce recently observed excited states and bands, including high spin non-yrast states. In this paper, we further test our shell model interaction for ^{62,63}Ga and extended the validity of our shell model framework. We also report that various type of particle alignments, like two-neutron alignment, one-proton–one-neutron alignment, two-proton–two-neutron alignment and so on, become significant, especially for ^{66}Ge as demonstrated by shell model calculations [12,13]. This alignment scheme remains valid for ^{63}Ga, ^{68}Ge [12, 13] and ^{69}As [14]. Through these studies, we have shown that proton–neutron particle alignments plays a significant role in these $N \sim Z$ nuclei.

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