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Research on High Spin States of ^{68}Ge, ^{65}Ga and ^{67}Ga

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The high spin states of ^{68}Ge, ^{65}Ga and ^{67}Ga are studied in the in-beam gamma-ray spectroscopy experiment. The reaction ^{46}Ti (^{25}Mg, *xpxn*) with the beam energy of 68 MeV is used. In ^{68}Ge, the multiplicity of band structures, crossing transitions among bands and a new band with possible big deformation are observed. The experimental results agree with the calculated result in the new microscopic model (EXCITED FED VAMPIR). In ^{65}Ga and ^{67}Ga, some band structures with strong collectivity are observed and the new level schemes are given.

1. INTRODUCTION

In recent years, great attention has been paid to the research on the nuclear structures in the A = 70-80 region. Many important discoveries have been made, such as the deformed shell gapes for N, Z = 38, spherical subshells for N, Z = 40, "shape coexistence", which describes the co-existences of the near-spherical ground band and big deformation band ($\beta \sim 0.4$) whose shapes are different in the same nucleus (e.g. ^{72,74}Se, etc.), and a new "isotopic island" with the greatly deformed ground state (e.g., ^{74,76}Kr, ^{76,78}Se, etc.) [1]. Thus, the multiplicity of nuclear structures in this region and their rapid changes with respect to N and Z become important test points of nuclear models.

Nuclei ^{68}Ge, ^{65}Ga and ^{67}Ga are located in the transitional region between the spherical shell with N, Z = 28 and well deformed subshell with N = Z = 38. The structures for these nuclei at high spin states exhibit complex behaviors. According to an earlier report [2] about the high spin states of ^{68}Ge,

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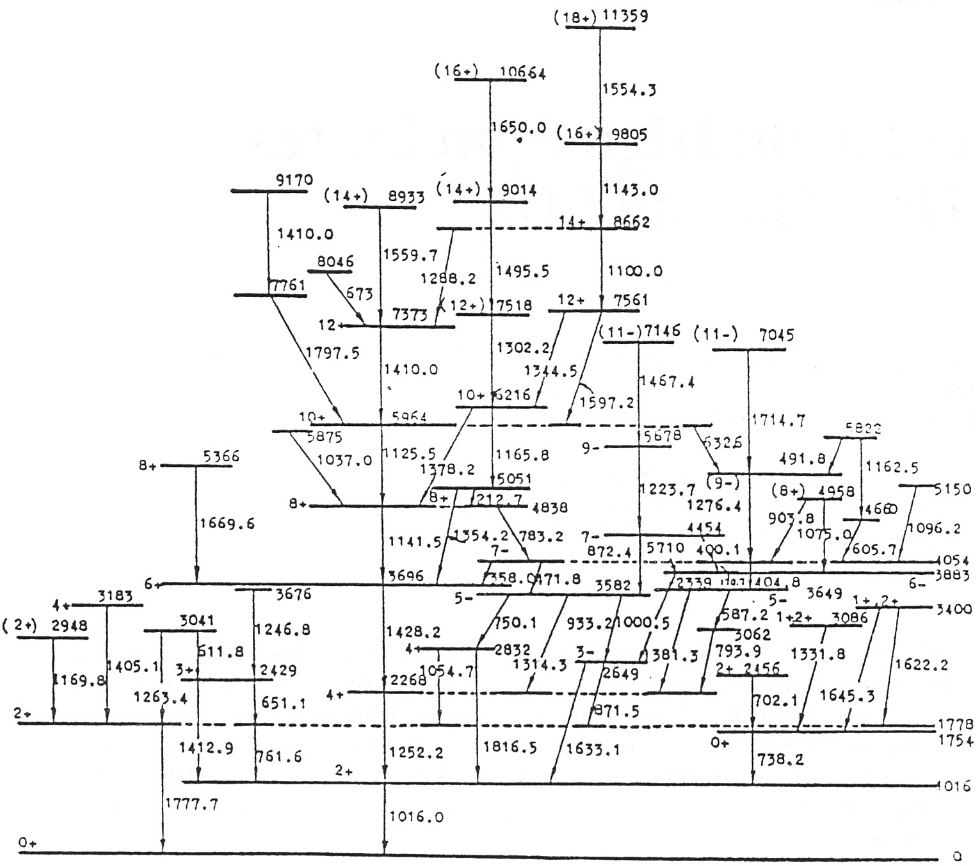

Fig. 1
The level scheme of ^{68}Ge (the high spin states with the positive parity only).

the near-spherical ground band exists above 6^+ and triply forks into three 8^+ levels and the collective band structure exists with the highest spin state up to the 14^+ level. That structure calls for a theoretical explanation. However, due to technical limitations, the spin states observed were not high enough above the 8^+ level, and some members of the bands should be confirmed further and no crossing transition among bands was observed. As to the odd-A nucleus ^{65}Ga, one author reported evidence of weakly collective bands and triaxial structure and observed a band based on the $9/2^-$ level, which has crossing phenomenon at the $21/2^-$ level [3]. But so far, no one reported the high spin states in the odd-A nucleus ^{67}Ga.

By using the in-beam gamma ray spectroscopy technique, we studied experimentally ^{68}Ge, ^{65}Ga and ^{67}Ga to search for high spin states, especially band structures. In this report, the experimental methods and main results are briefly mentioned in Section 2 and the discussion is given in Section 3.

2. EXPERIMENT AND RESULTS

The experiment was conducted at Holifield Heavy Ion Research Facility (HHIRF) in Oak Ridge National Laboratory (ORNL, U.S.A). A spin spectrometer with 19 compton suppressed Ge detectors was employed to detect gamma rays. The reactions used were

$$^{25}Mg + {}^{46}Ti \longrightarrow \begin{cases} {}^{68}Ge + 2p + n, \\ {}^{65}Ga + 3p + 3n, \\ {}^{67}Ga + 3p + n, \\ \cdots. \end{cases}$$

A beam of ^{25}Mg with the energy of 68 MeV was drawn from the HHIRF Tandem accelerator. ^{46}Ti target with the total thickness of 0.777 mg/cm^2 was enriched to about 85%. About 2×10^8 double or multiple coincidence events were obtained.

Based on the previous level schemes [2-4], the high spin states of these nuclei were searched by using the "gate" coincidence method. In ^{68}Ge, 19 new levels and many crossing transitions between different bands were observed. The partial level scheme of ^{68}Ge is shown in Fig. 1, which only includes the high spin states with positive parity. Above the 8^- level, the members of each band were re-confirmed and rearranged. As a more important result, a new band with the large moment of inertia, that is, the cascade gamma transitions 1533.4 → 1143.0 → 1100.0 keV, was found. Through the crossing transitions among bands, the deexcited gamma decays were finally fed into the 6^+ level of the yrast band. The new level schemes of ^{65}Ga and ^{67}Ga are shown in Figs. 2 and 3, respectively. Twelve new gamma ray transitions were found in ^{65}Ga and ^{67}Ga, respectively, in addition to the former reports [3,4]. Three new band structures with band heads 3733 keV ($15/2^-$), 4433 keV ($21/2^+$) and 5022 keV ($21/2^+$), respectively in ^{65}Ga and two bands with heads 3578 keV ($15/2^+$) and 5492 keV ($21/2^+$), respectively in ^{67}Ga were observed. The spins and parities in brackets were conjectured in terms of the intensity relation of the gamma transition as well as the systematics comparison. They should be confirmed further by experiment.

3. DISCUSSION

3.1. ^{68}Ge

Here we mainly discuss the high-spin-state bands with the positive parity. We plot the moment of inertia $2\ell/\hbar^2$ versus the rotational frequency $(\hbar\omega)^2$ along the yrast line and the main band structure above the 6^+ level in Fig. 4. There are three different forks in the region of $2\ell/\hbar^2$ 15-35 (MeV)$^{-1}$. The first one is the yrast line, which, after backbending, becomes a new band with the band head 8_1^+ and the moment of inertia about 35 (MeV)$^{-1}$. The second one with the band head 8_2^+ has smaller backbending than the first one. Above the 10^+ level, it forks into two bands. One of the forks is similar to the yrast band (8_1^+) but has larger moment of inertia, while the other has the second big backbending where the moment of inertia greatly increases between the 12^+ and 14^+ levels. The third one with the band head 8_3^+ has no backbending. It is the continuation of the ground band.

There were several theoretical interpretation for those triple forked 8^- states. In the two-quasi-particle-plus-axial-rotor model, the calculation [2] showed that all the bands with positive parity originate from the quasiparticle aligned in the $g_{9/2}$ orbit. The 8_1^- level is a band head with two quasineutrons aligned and the 8_2^+ level, two quasiprotons and the 8_3^- level is the continuation of the ground band. However, in the shell model, the calculations [5] suggested that only neutron alignment caused the band forking. But their result that the 8^+ state is considered the continuation of the ground band and the 8_3^+ state, a neutron-aligned band head, disagrees with the phenomenon of the back-bending of the moment of inertia. The calculation in the asymmetric rotor model where two quasiparticles were mixed up [6] showed that the 8_2^+ and 8_3^+ states are all the neutron-aligned band heads and the band with the 8_1^+ state is the continuation of the ground band. This is also in disagreement with the experimental result. The g factor measurements in ^{68}Ge [7] support the interpretation that both 8_1^+ and 8_3^+ states are aligned neutron configurations and the band with the 8_3^+ state is the continuation of the ground state band.

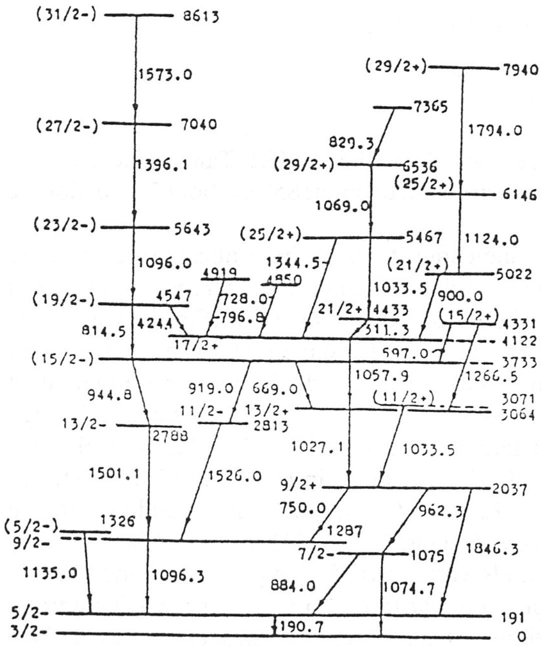

Fig. 2
The level scheme of ^{65}Ga.

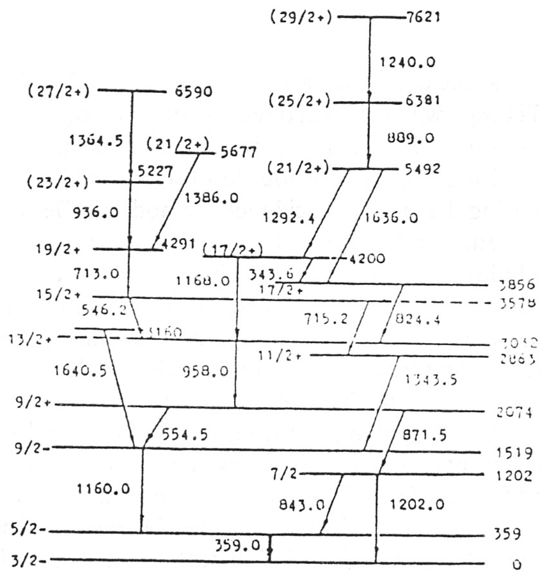

Fig. 3
The level scheme of ^{67}Ga.

Recently, new microscopic calculations for ^{68}Ge and ^{72}Se were made by Petrovici *et al.* [8]. The result is in better agreement with our result of ^{68}Ge. It is called EXCITED FED VAMPIR approach [9] (excited few determinate variation after mean-field projection in realistic model space) based on the EXCITED VAMPIR [10]. For comparison, the calculated result is plotted on the left in Fig. 5 and the experimental data are plotted on the right, where only the bands with the positive parity are shown. The levels with the same spin from the low to high are specified by subscripts.

For the ground band, up to the 6_1^+ level, the calculated yrast levels are almost pure oblate states. The theoretical g factor for the 6_1^+ level is 0.37 while the experimental value is 0.4. This oblate band extends to the 8_2^+ level (with 85% oblate component). It may be associated with the experimental 8_3^+ state. The 10_3^+ state has a pure oblate nature, thus they form an oblate band labeled by "O" at the upper left in Fig. 5. This ban extends to the rather high angular momentum states as indicated by another calculation [11]. These oblate states have considerably higher excitation energy in comparison with the states in the other bands but are weakly populated. This is the possible reason why none of the band members above the 8_3^+ level was observed experimentally.

Besides the oblate structure, we obtained four other bands with prolate deformations in calculations. Their differences were in the magnitudes of their quadruple and hexadecapole moments as well as in their pairing properties and particle alignments. The band labeled by "ν-al" corresponds to the experimental band with the band head 8_2^+. It has the following characteristics. There is an almost empty $Og_{9/2}$ proton level while the neutrons give the main contribution to the total angular momentum. For band members 8_3^+, 10_2^+, 12_3^+, 14_3^+, 16_5^+ and 18_7^+ levels, the calculated g factor values are −0.03, 0.12, 0.07, 0.01, 0.07 and 0.08, respectively. The experimental g factor for the 8_2^+ level [7] is −0.028 ± 0.14. These g factor values indicate the strong neutron alignment. The other two bands labeled by "D" and "S" almost have the same quadruple deformation for the neutron part. But for the proton part, the "S" band has more deformation. We can see this from the intrinsic quadruple moments as well as from the $B(E2)$ values. The calculated β_2 values are 0.42 and 0.34 for the "S" and

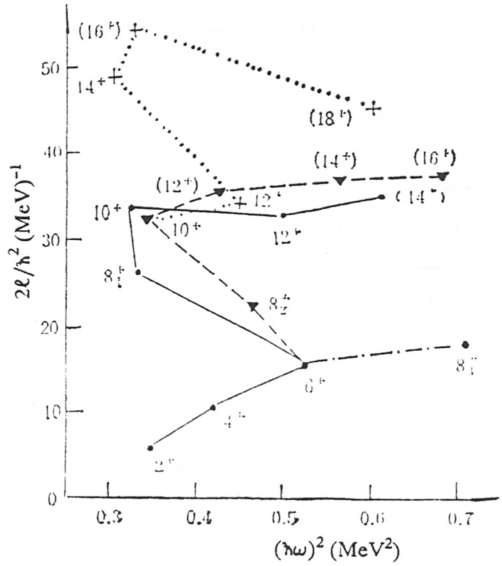

Fig. 4
Moment of inertia $2\ell/\hbar^2$ as a function of $(\hbar\omega)^2$ in ^{68}Ge.
The forked structures above the 6^+ level are shown.

"*D*" bands, respectively. Above the 12^+ level, the $B(E2)$ values for the "*S*" band are about twice as large as those for the "*D*" band. The calculated "*S*" band has a large moment of inertia. This agrees well with the observed band shown on the right of Fig. 5. It indicates that this new experimental band is a possible band with big deformation ($\beta_2 \sim 0.4$). The "*D*" band may be associated with the experimental band starting from 7761 keV. The $18_2 \rightarrow 16_2 \rightarrow 14_2$ sequence, labeled by "*Y*", may be associated with the experimental yrast spectrum. It should be further studied. Another calculated $18_1 \rightarrow 16_1 \rightarrow 14_1$ transition chain has small transition energies, thus it was difficult to observe in the experiment.

All these prolate bands discussed above have the common feature: their members whose spin values are below 12 or 14 become strongly mixed. Consequently, there are many competing transition branches for various 14^+, 12^+, 10^+ and even 8^+ states. Thus, the transitions are not only the stretched $E2$ transitions within various bands but also some strong $M1$ transitions with $\Delta I = 0$ (indicated by "*m*" in Fig. 5), which mainly feeds into the yrast band, and strong $E2$ transitions with $\Delta I = 2$. We can see these crossing transitions from the experimental data, too.

In summary, the new experimental structures observed in high spin ^{68}Ge are explained in terms of the new microscopic calculations. The bands with the band head 8_1^- or 8_2^- and a new band with the big moment of inertia are originated from the different proton and neutron alignments. The deformation parameters for these bands are also different. The 8_3^+ state in the oblate shape is still the continuation of the ground band.

3.2. ^{65}Ga and ^{67}Ga

In high spin states of ^{65}Ga and ^{67}Ga, several collective band structures (see Fig. 2 and Fig. 3) were found in the experiments, that is, the bands with the band head $(15/2^-)$, and level sequence 8613-7040-5643-4547-3733 keV, with the band head $21/2^+$ and sequence 6536-5467-4433 keV and with the band head $(21/2^+)$ and sequence 7940-6146-5022 keV in ^{65}Ga; with the band head $15/2^+$ and

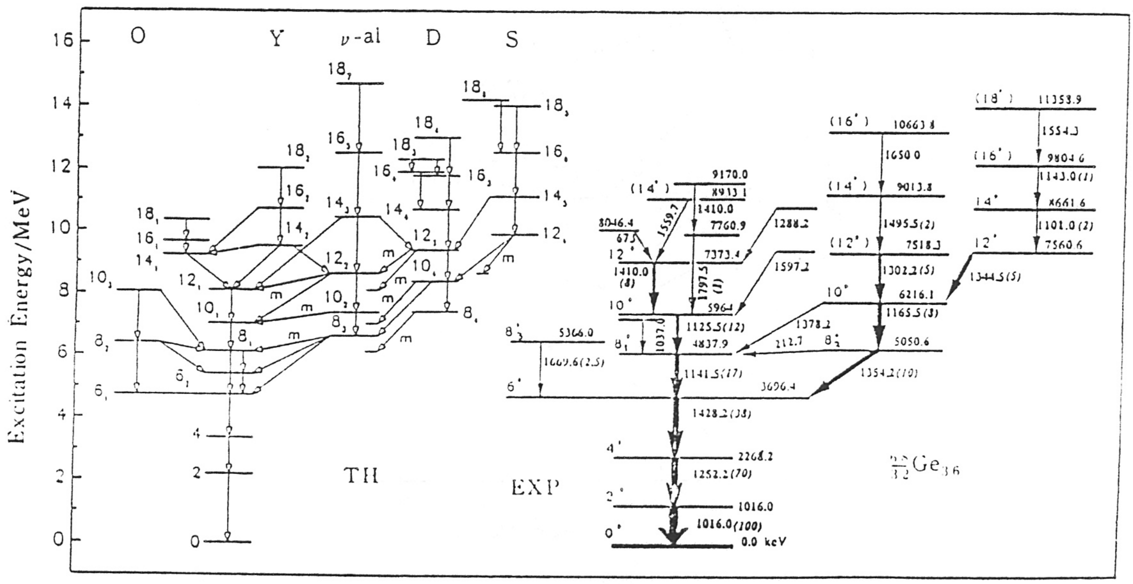

Fig. 5
A comparison between the calculations of ^{68}Ge with the EXCITED FED VAMPIR approach (left) and the results of our experiment (right).

sequence 6590-5227-4291-3578 keV and with the band head 21/2⁻ and sequence 7621-6381-5492 keV in ^{67}Ga, respectively.

For ^{65}Ga, some theoretical explanations [12,13] were successfully offered up to the 9/2 level, above which, however, no successful theoretical calculation was made. In a previous report [3], the triaxial deformation (with $\gamma < 20°$) was suggested and the $21/2^+$ level with $(1g_{9/2})^3$ configuration was observed. In this study, two band members based on this configuration were observed, which once again demonstrates that the single particle $1g_{9/2}$ orbit plays an important role in this region.

Besides the band based on the $(1g_{9/2})^3$ configuration in ^{65}Ga, there are two similar band structures in ^{65}Ga and ^{67}Ga. One of them has the band head $21/2^+$, which might still belong to the type of triaxial deformation. The other has the band head $15/2^-$ in ^{65}Ga and band head $15/2^+$ in ^{67}Ga, respectively. It shows stronger collectivity, greater $E2$ transition intensity and more regular energy spacings. The excitation energy E_x as a function of $I(I + 1)$ is plotted in Fig. 6. In the region of $I \geq 15/2$, the curves of both bands become straight lines. Obviously, both bands based on the 15/2 levels in ^{65}Ga and ^{67}Ga belong to the rotational bands in which the collectivities are completely established. This indicates that the shapes of ^{65}Ga and ^{67}Ga at high angular momenta are rearranged from the triaxial form to the well-deformed form. Clearly, we need more experimental and theoretical studies to better explain these complex structures.

4. CONCLUSION

In the A = 70 region, the high spin states of ^{68}Ge, ^{65}Ga and ^{67}Ga with transitional characteristics were studied. The level schemes of high spin states were drawn and several collective band structures were found. The remarkable triple forked structure was reconfirmed. A band with big moment of inertia as well as most probable big deformation was found. This band is also shown at the second backbending in Fig. 4. The crossing transition among different bands were also identified. The

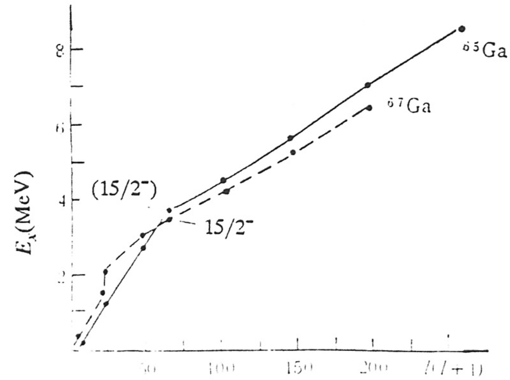

Fig. 6
Excitation energy E_x as a function of $I(I + 1)$ for the high spin states of the strong collective bands in ^{65}Ga and ^{67}Ga (main deexcitation path below the 15/2 level only).

agreement between our experimental result and the new microscopic calculation for ^{68}Ge was obtained. This encourages the theoretical research in this region. For the odd-A nuclei ^{65}Ga and ^{67}Ga, the level structures of high spin states are also very complex. The band based on the $(g_{9/2})^3$ configuration in ^{65}Ge and the bands with strong collectivities in both ^{65}Ga and ^{67}Ga were found. It was shown that the collectivity enhances as the angular momentum increases. In order to understand well the nuclear structures at this region, more research is needed.

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