

## LOW-LYING STATES OF $^{67}\text{Ge}$ AND $^{67}\text{As}$ NUCLEI IN PARTICLE – QUADRUPOLE - PHONON MODEL (PTQM)

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*Abstract.* The energy levels and electromagnetic properties in  $^{67}\text{Ge}$  and  $^{67}\text{As}$  nuclei on the basis of the SU(6) particle – quadrupole – phonon model (PTQM) were described. A rather good description of the low-lying negative and positive parity states was obtained using the parametrization in vibrational SU(5) limit of the  $^{66}\text{Ge}$  core.

Key words: energy levels, electromagnetic properties negative and positive states.

### 1. INTRODUCTION

In the recent years, the region of nuclei with  $N \sim Z$  and  $A \sim 70$  has been extensive theoretical and experimental study. Since these nuclei are in the interesting transitional region, these nuclei exhibit a range of features, including oblate and prolate deformations as well as rapid variations in shape as a function of both spin and particle number.

In the last time we have studied the double-odd  $^{68}\text{As}$  nucleus [1] via the  $^{54}\text{Fe}(^{16}\text{O}, \text{pn})^{68}\text{As}$  reaction. Nuclear excited states have been assigned from investigations of  $\gamma$ -rays using in-beam-spectroscopic techniques. For a theoretical interpretation of this nucleus it is essential to know the experimental and theoretical nuclear structure of the neighboring odd  $^{67}\text{Ge}$  and  $^{67}\text{As}$  nuclei. The even-odd  $^{67}\text{Ge}$  and odd-even  $^{67}\text{As}$  were investigated in-beam  $\gamma$ -ray spectroscopy [2, 3].

In the present work we tried to describe the energy levels and electromagnetic properties in  $^{67}\text{Ge}$  and  $^{67}\text{As}$  on the basis of the SU(6) particle-quadrupole-phonon model (PTQM) [4] by coupling of the odd neutron and odd proton respectively in the  $2p_{1/2}$ ,  $2p_{3/2}$ ,  $1f_{5/2}$  and  $1g_{9/2}$  orbitals with the anharmonic quadrupole vibrational core,  $^{66}\text{Ge}_{34}$ . The calculations were performed with the computer code PTQM [5].

### 2. LEVELS SCHEME OF $^{66}\text{Ge}$ IN THE TQM

The experimental levels scheme of  $^{66}\text{Ge}$  nucleus is well known. Fig.1. [6]

First we calculated the excited states for the even-even core  $^{66}\text{Ge}$  nucleus, in the truncated quadrupole phonon model (TQM) [4], equivalent at the phenomenological level, with the interacting boson model (IBM) [7] which describes the collective states in terms of  $J=0^+$  (s) and  $2^+$  (d) bosons. The

anharmonicity parameters of the core,  $(h_i)$  have been fitted to the experimental energy spectrum in the rotational SU(3), vibrational SU(5) and O(6) limits, respectively. (Table 1).

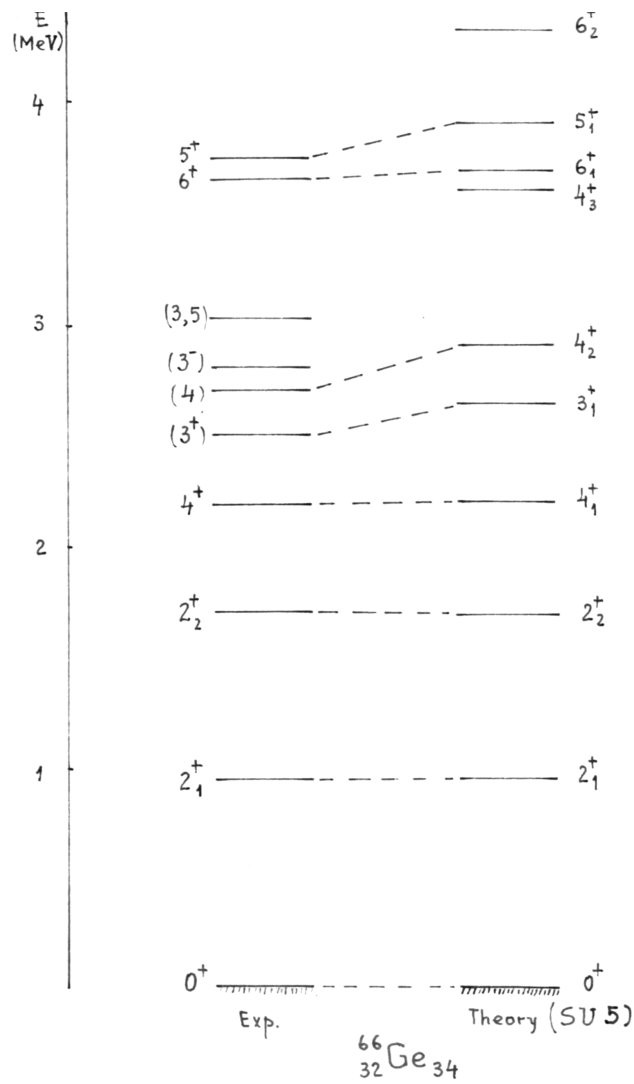


Fig.1- Levels scheme of  $^{66}\text{Ge}$  nucleus

In the interpretation of  $^{66}\text{Ge}$  the total boson number  $N=5$  has been included. This is equal to half the number of valance-shell proton particles and neutron particles in the 28 proton and neutron shell.

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Table 1- TQM parameters for the  $^{66}\text{Ge}$  core nucleus.

The calculated parameters				The fitted parameters to the experimental spectrum		
	SU(3)	O(6)	SU(5)	SU(3)	O(6)	SU(5)
$h_1$	0.957	-0.181	0.957	0.957	-0.181	0.957
$h_2$	-0.141	-0.224	0	-0.141	-0.224	0
$h_3$	-0.379	0	0	-0.379	0	0
$h_{40}$	0.410	-0.020	-0.134	-0.010	-0.015	-0.098
$h_{42}$	-0.142	0.221	-0.273	-0.142	0.120	-0.240
$h_{44}$	1.167	1.123	0.344	0.167	1.020	0.334

The TQM theoretical level spectrum is shown in fig.1 in the comparison with experimental results [6]. We remark that the level scheme of the  $^{66}\text{Ge}$  nucleus is to be best explained in the vibrational SU(5) limit, with the fitted anharmonicity parameters to the experimental spectrum. (Table 1)

### 3. PTQM CALCULATIONS

Calculations for the levels scheme of the even-odd  $^{67}\text{Ge}$  and odd-even  $^{67}\text{As}$  nuclei were performed in the SU(6) particle-quadrupole-phonon model (PTQM) [4] which is equivalent with the interaction boson-fermion model (IBFM)[7]. The IBFM introduces an odd particle in addition to boson.

The Hamiltonian of the PTQM employed here is in the form:

$$H_{\text{PTQM}} = H_{\text{P}} + H_{\text{TQM}} + H_{\text{PVI}}$$

where  $H_{\text{P}}$  is the spherical single-particle (or quasi-particle) hamiltonian;  $H_{\text{TQM}}$  denotes the TQM hamiltonian for the quadrupole vibrational even-even core nucleus [7] and  $H_{\text{PVI}}$  denotes the interaction between the odd quasiparticle and the quadrupole vibrations [7]. This interaction consists of three terms:

$$H_{\text{PVI}} = H_{\text{MON}} + H_{\text{DYN}} + H_{\text{EXC}}$$

where  $H_{\text{MON}}$  is the hamiltonian of the monopole interaction with the  $\Gamma_0$  strength and  $H_{\text{EXC}}$  denotes the hamiltonian of the exchange interaction with the  $\Lambda_0$  strength. Another parameter of the PTQM is  $\chi = -1.323$  [7].

The PTQM hamiltonian was diagonalized in the particle-phonon basis  $|j, n, I, J\rangle$  where the quasiparticle  $|j\rangle$  and the  $n$ -phonon state  $|n, I\rangle$  are coupled to the total angular momentum  $J$ . Here is an additional quantum number to distinguish, if needed, between different states of the same  $n$  and  $I$ .

Second the calculation of negative and positive parity states of the even-odd  $^{67}\text{Ge}$  nucleus was performed in the PTQM representation of IBFM by coupling of the odd neutron in the  $p_{1/2}$ ,  $p_{3/2}$ ,  $f_{5/2}$  and  $g_{9/2}$  orbital with the vibrational even-even core  $^{66}\text{Ge}$ . For the calculation of negative-parity states following parameterization was used:

- the core  $^{66}\text{Ge}$  excitations have been approximated with anharmonic vibration in the SU(5) limit (Table 1); The energy of the first  $2_1^+$  states in  $^{66}\text{Ge}$  was used as an effective phonon energy ( $\hbar\omega_2$ );

- the quasineutron energies ( $E$ , in MeV) and the occupation probabilities ( $v^2$ ) were taken from BCS calculations:  $E(\nu p_{3/2}) - E(\nu p_{1/2}) = 0.11$ ;  $E(\nu f_{5/2}) - E(\nu p_{1/2}) = 0.20$ ;  $v^2(\nu p_{1/2}) = 0.12$ ;  $v^2(\nu p_{3/2}) = 0.82$ ;  $v^2(\nu f_{5/2}) = 0.71$ .

- the boson-neutron interaction parameters  $A_0^\nu = 0.1$ ,  $\Gamma_0^\nu = 0.4$ ,  $\Lambda_0^\nu = 5.7$  (all in MeV and  $N=5$ ) have been adjusted to the experimental negative – parity states of  $^{67}\text{Ge}$ .

For the positive-parity states in  $^{67}\text{Ge}$  the occupation probability  $v$  ( $\nu g_{9/2}$ ) = 0.10 as obtained from BCS model, the other parameters are the same as in the calculation of negative parity states.

In the third step we have undertaken the IBFM/PTQM investigations for odd-even  $^{67}\text{As}$ , by coupling of the odd proton in the  $p_{1/2}$ ,  $p_{3/2}$ ,  $f_{5/2}$  and  $g_{9/2}$  orbital with vibrational even-even  $^{66}\text{Ge}$  nucleus in the SU(5) limit. (Table 1). For the interpretation of negative-parity states in  $^{67}\text{As}$  the following parameterization is used:

- the same boson core,  $^{66}\text{Ge}$ , as in the calculation for  $^{67}\text{Ge}$ ;

- the BCS quasiproton energies ( $E$ , in MeV) and the occupation probabilities ( $v^2$ ):  $E(\pi p_{3/2}) - E(\pi p_{1/2}) = 0.037$ ;  $E(\pi f_{5/2}) - E(\pi p_{1/2}) = 0.081$ ;  $v^2(\pi p_{1/2}) = 0.100$ ;  $v^2(\pi p_{3/2}) = 0.690$ ;  $v^2(\pi f_{5/2}) = 0.250$ .

- the bosons-proton interactions parameters are the same as in the calculations for  $^{69}\text{As}$  [8] with a slight modification in order to obtain better agreement with experimental data:  $A_0^\pi = 0.07$ ,  $\Gamma_0^\pi = 0.4$ ,  $\Lambda_0^\pi = 6.9$  and  $\chi = -1.323$ .

The positive-parity state in  $^{67}\text{As}$  was fitted to the experimental levels using the occupation probability  $v^2$  ( $g_{9/2}$ ) = 0.09 as obtained from BCS model and the other parameters are the same as in the calculations of the negative-parity states.

#### 4. RESULTS AND DISCUSSION

The calculated negative and positive parity spectra and the experimental energy spectrum of  $^{67}\text{Ge}$  and  $^{67}\text{As}$  are shown in Figs.2 and 3. We can see that it is a relatively good agreement between the theoretical level scheme of  $^{67}\text{Ge}$  and  $^{67}\text{As}$  nuclei with the available experimental data. In Table 2 the IBFM/PTQM the wave functions amplitudes ( $\xi$ ,  $nI$ ) of the lowest-lying calculated states are presented for both  $^{67}\text{Ge}$ ,  $^{67}\text{As}$  nuclei, where the wave functions are expressed in the boson-fermion coupled basis  $|J\rangle = \xi_{jnI} |j, nI; J\rangle$  (only squares amplitudes higher than 2% are listed).

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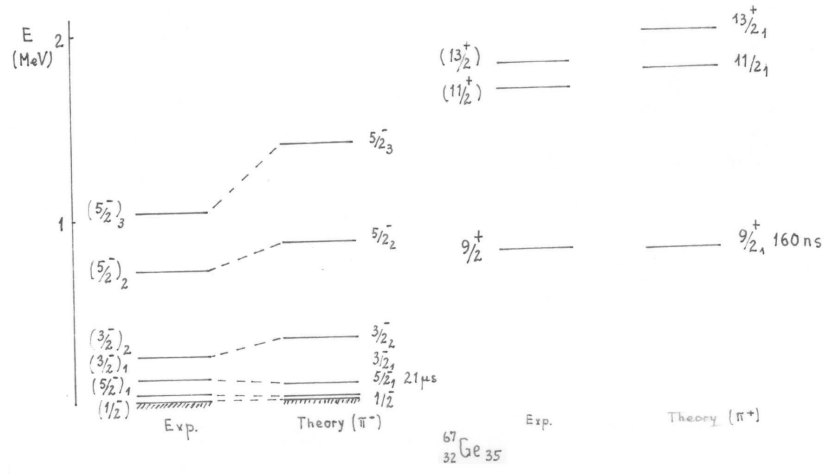


Fig.2- Levels scheme of  $^{67}\text{Ge}$  nucleus

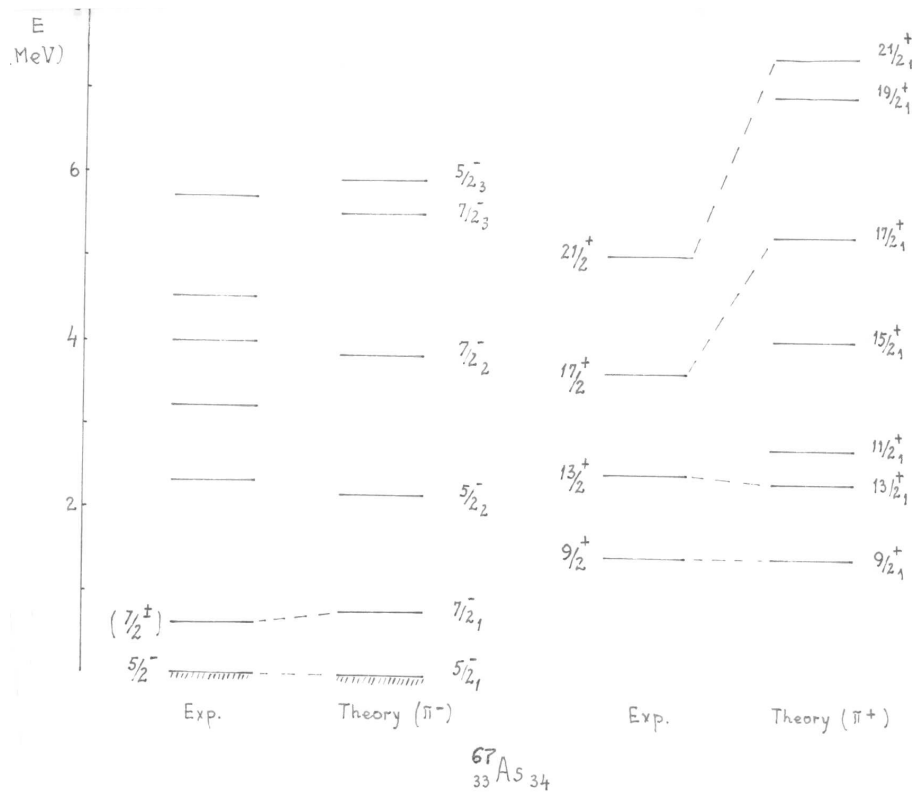


Fig.3- Levels scheme of  $^{67}\text{As}$  nucleus

Table 2- PTQM wave functions of the states in  $^{67}\text{Ge}$  in the quadrupole-phonon model

<b>J</b>	<b>j</b>	<b>n</b>	<b>I</b>	$(\frac{\xi_{ny}}{\xi_{2^+}})^2$	<b>J</b>	<b>j</b>	<b>n</b>	<b>I</b>	$(\frac{\xi_{ny}}{\xi_{2^+}})^2$
$1/2^-_1$	1/2	0	0	0.360	$5/2^-_2$	3/2	4	2	0.048
	1/2	2	0	0.340		3/2	4	4	0.321
	1/2	4	0	0.090		5/2	4	0	0.088
	3/2	2	4	0.030		5/2	4	2	0.018
	5/2	2	0	0.020		5/2	4	4	0.143
$3/2^-_1$	3/2	2	0	0.063	$9/2^+$	9/2	0	0	0.498
	3/2	2	2	0.210		9/2	1	2	0.109
	5/2	2	2	0.079		9/2	2	2	0.240
	5/2	2	4	0.640	$11/2^+$	9/2	1	2	0.322
$5/2^-_1$	3/2	2	2	0.058		9/2	2	2	0.303
	3/2	2	4	0.382					

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	5/2	2	0	0.061		9/2	3	2	0.118
	5/2	2	2	0.232		9/2	4	2	0.094
	1/2	2	2	0.029					
5/2 <sub>2</sub>	3/2	4	2	0.048	13/2 <sub>1</sub> <sup>+</sup>	9/2	1	2	0.041
	3/2	4	4	0.321		9/2	2	2	0.803
	5/2	4	0	0.088		9/2	2	4	0.087
	5/2	4	2	0.018		9/2	3	2	0.058
5/2 <sub>1</sub>	1/2	2	2	0.03	5/2 <sub>2</sub>	3/2	4	2	0.051
	3/2	2	4	0.591		3/2	4	4	0.294
	5/2	2	0	0.089		5/2	2	2	0.440
	5/2	2	2	0.347		5/2	4	0	0.069
	5/2	2	4	0.029		5/2	4	2	0.022
					5/2	4	4	0.161	
7/2 <sub>1</sub>	3/2	2	4	0.048	11/2 <sub>1</sub> <sup>+</sup>	9/2	2	2	0.843
	3/2	3	4	0.492		9/2	2	4	0.122
	5/2	2	4	0.018		9/2	3	3	0.029
	5/2	3	3	0.057					
	5/2	3	4	0.181					
	1/2	3	3	0.029					
5/2 <sub>2</sub>	3/2	4	2	0.051	13/2 <sub>1</sub> <sup>+</sup>	9/2	2	2	0.881
	3/2	4	4	0.294		9/2	2	4	0.087
	5/2	2	2	0.440		9/2	3	2	0.022
	5/2	4	0	0.069					

Employing these wave functions we have calculated the electromagnetic properties of the low-lying states. For the <sup>67</sup>Ge nucleus the following effective charges and gyromagnetic ratios were used:  $e^v = 0.5$ ;  $e^{vib} = 0.9$ ;  $g_R = 0.477$ ;  $g_e = g_e^{free} = 0$ ;  $g_s = 0.7g_s^{free} = -2.68$  and for <sup>67</sup>As nucleus:  $e^\pi = 1$ ;  $e^{vib} = 1$ ;  $g_e = 1g_R = Z/2A = 0.240$ ;  $g_s = 0.5g_s^{free} = 2.78$ .

The PTQM electromagnetic properties, which results from this parameterization, are presented in Tables 3a,b. In this Table we list the calculated B(E2) and B(M1) value, and branching ratios for the transitions between the low-lying negative parity states and positive parity state in comparison with the experimental data.

Table 3.a.- The B(E2), B(M1) values and  $\gamma$ -branching ratio for some transitions in <sup>67</sup>Ge (between negative parity states).

Transition	B(E2)	B(M1)	branching ratio
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Initial state (keV)	$(e^2b^2)$		$(\mu_N^2)$	branching ratio	
	Final state	$(e^2b^2)$	$(\mu_N^2)$	calc.	exp.
182.4	$5/2^-_1 - 1/2^-_1$	0.003	-	100	100
229	$3/2^-_1 - 1/2^-_1$	0.29	0.48	100	100
	$3/2^-_1 - 5/2^-_1$	0.04	0.24	6.9	23.7
243.9	$3/2^-_2 - 1/2^-_1$	2.7	0.42	138	81
	$3/2^-_2 - 5/2^-_1$	0.05	0.24	5.2	15.5
	$3/2^-_2 - 3/2^-_1$	0.34	0.37	100	100
711.6	$5/2^-_2 - 5/2^-_1$	1.9	0.001	100	100
	$5/2^-_2 - 3/2^-_1$	0.2	12.1	89	41

Table 3.b.- The B(E2), B(M1) values and  $\gamma$ -branching ratio for some transitions in  $^{67}\text{As}$  (between negative parity states and positive parity states).

Initial state (keV)				branching ratio	
				calc.	exp.
697	$7/2^+_1 - 5/2^+_1$	0.02	1.4	100	100
	$13/2^+_1 - 9/2^+_1$	5.84	0.002	100	100
	$17/2^+_1 - 13/2^+_1$	0.48	0.01	7.3	60
243.9	$21/2^+_1 - 17/2^+_1$	2.1	0.27	5	35

As can be seen from the Table 3a,b the experimental electromagnetic intensity for the low-lying states are relatively well reproduced by the calculated results.

Concluding, the present PTQM calculations give a rather good description of the low-lying negative and positive parity states of  $^{67}\text{Ge}$  and  $^{67}\text{As}$  for parameterization in vibrational SU(5) limit of the  $^{66}\text{Ge}$  core.

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