STRUCTURE OF NEUTRON-RICH NUCLEI BEYOND $N = 50$*

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The measurement of the β-decay scheme of ^{85}Ga triggered questions on the properties of the low-lying states in ^{85}Ge. In order to inspect the sensitivity of the results to the neutron $d_{5/2}$ and $s_{1/2}$ single-particle states, we performed an analysis of the level structure in the $N = 51$ ^{83}Ge and $N = 53$ ^{85}Ge isotopes.

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1. Introduction

Decay studies of radioactive nuclei far away from the valley of beta-stability offer important test data and guidance for the further development of nuclear models of exotic nuclei. Particularly interesting is the evolution of single-particle levels with increasing neutron number in the ^{78}Ni region, which was analyzed, *e.g.*, by Otsuka *et al.* [1–3]. Recently, experiments confirmed the postulated evolution of single-particle levels, for example the increasing energy of proton $p_{3/2}$–$p_{1/2}$ and $f_{7/2}$–$f_{5/2}$ spin–orbit partners splitting, when the $g_{9/2}$ neutron shell is filling up [4–6]. The crossing of the low lying $1f_{5/2}$ and $2p_{3/2}$ orbitals [5–7] in neutron-rich Cu nuclei is one of the consequences of this process. For neutron-rich nuclei beyond $N = 50$ in the ^{78}Ni region, shell-model calculations are using different values for the single-particle energy of the $3s_{1/2}$ neutron orbital with respect to the $2d_{5/2}$ near the Fermi surface [8, 9]. Furthermore, it is predicted that by adding a few protons and neutrons to the doubly magic ^{78}Ni core, deformation can

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set up quickly [10]. In this work, we performed shell-model calculations for ^{83,85}Ge in order to analyze the energies, spin and structure of $N = 51$ ^{83}Ge and $N = 53$ ^{85}Ge. We mainly investigate the change of relative energies of neutron $s_{1/2}$ and $d_{5/2}$ orbitals.

2. Comparison of experimental results with shell-model calculations

In our recent work [11], we proposed a partial level scheme for the nuclei populated in the β and β–n decay of ^{85}Ga. The spins and parities were deduced from systematics and experimental information.

To inspect further the properties of low-lying excited states and ground state in ^{85}Ge, we performed shell-model calculations with a closed ^{78}Ni core and the N3LO nucleon–nucleon interaction [12, 13]. The valence space used in the calculations contains all orbitals active outside ^{78}Ni core, the $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$ for protons and $2d_{5/2}$, $3s_{1/2}$, $1g_{7/2}$, $2d_{3/2}$, $1h_{11/2}$ for neutrons. The values of single-particles energies used in these analysis are reported in Table I.

TABLE I

Proton and neutron single-particle energies, ϵ, used in the shell-model calculations. These values were adopted from [14, 15] and [9]. See the text for details.

π orbital	ϵ [MeV]	ν orbital	ϵ [MeV]
$1f_{5/2}$	0.0	$2d_{5/2}$	0.0
$2p_{3/2}$	1.1	$3s_{1/2}$	1.3
$2p_{1/2}$	2.5	$1g_{7/2}$	1.8
$1g_{9/2}$	4.5	$2d_{3/2}$	2.4
		$1h_{11/2}$	3.0

We also performed calculations for ^{83}Ge ($N = 51$) in order to understand better the evolution of level structure in odd-mass Ge isotopes. From the beta decay of $I^{\pi} = 5/2^{-}$ ^{83}Ga ground state [16], we expect to populate mainly 3/2, 5/2 and 7/2 states in ^{83}Ge. The results of the calculations are presented in Figs. 1 and 2 in comparison with the respective experimental level schemes [11, 14].

From the results of the shell-model calculations, we expect $5/2^{+}$, $1/2^{+}$ and $3/2^{+}$ as the g.s. and first excited states in ^{83}Ge, respectively. The $p_{3/2}$ and $f_{5/2}$ protons are the most abundant in all wave functions. Additionally, the $5/2^{+}$ ground state is dominated by one neutron on $\nu d_{5/2}$ (90%), while the other two states have admixture with the $\nu s_{1/2}$ or the $\nu d_{3/2}$ orbitals, respectively. The wave function of the $1/2^{+}$ level corresponds to one neutron

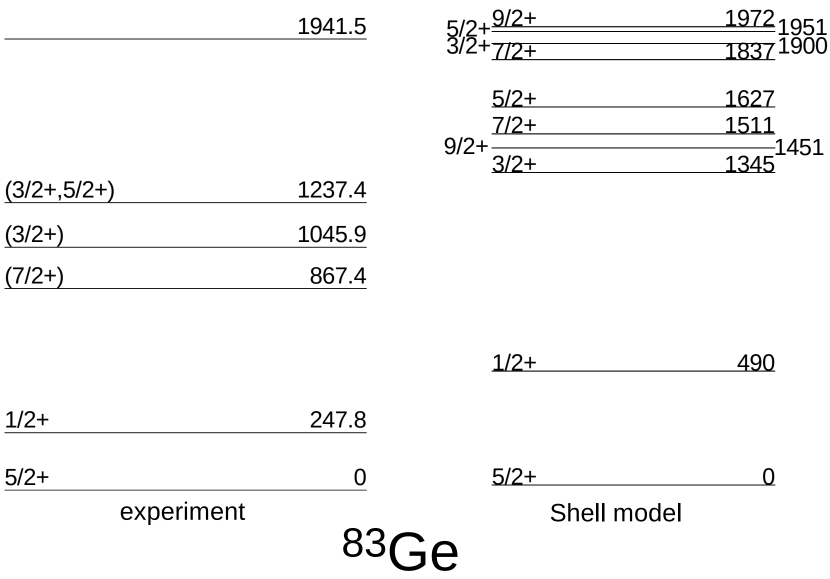

Fig. 1. Experimental [14] and shell model excited states in ^{83}Ge. All energies are given in keV. See the text for details.

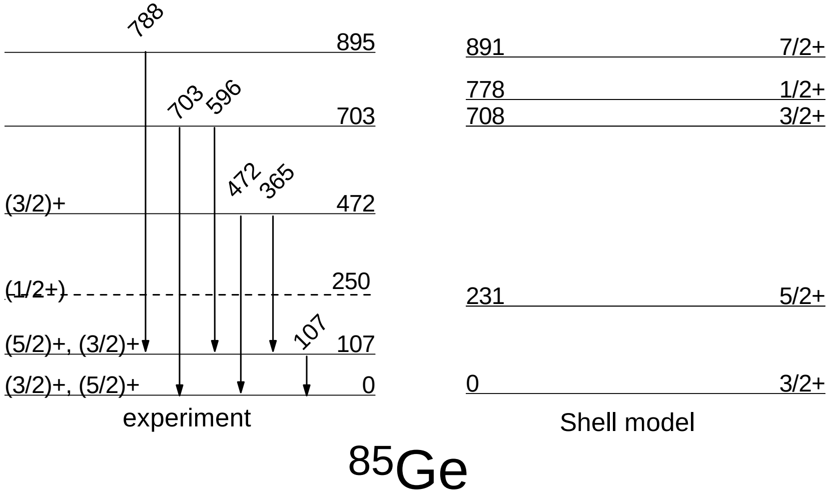

Fig. 2. Experimental [11] and shell model excited states in ^{85}Ge. All energies are given in keV. See the text for details.

TABLE II

Wave function of the excited states in ^{85}Ge nucleus predicted in the shell-model calculations; the values correspond in % the occupation of 4π and 3ν. See the text for details.

I^π state	Orbital	Configuration				
$3/2^+$	π	$1g_{9/2}$ 3.8%	$1f_{5/2}$ 44.3%	$2p_{3/2}$ 41.9%	$2p_{1/2}$ 10.00%	
	ν	$1h_{11/2}$ 1.6%	$1g_{7/2}$ 2.4%	$2d_{5/2}$ **72.4%**	$2d_{3/2}$ 8.0%	$3s_{1/2}$ **15.6%**
$5/2^+$	π	$1g_{9/2}$ 4.0%	$1f_{5/2}$ 44.0%	$2p_{3/2}$ 42.2%	$2p_{1/2}$ 9.8%	
	ν	$1h_{11/2}$ 1.8%	$1g_{7/2}$ 3.2%	$2d_{5/2}$ **73.4%**	$2d_{3/2}$ 8.6%	$3s_{1/2}$ **13.0%**
$3/2^+$	π	$1g_{9/2}$ 3.3%	$1f_{5/2}$ 47.0%	$2p_{3/2}$ 40.0%	$2p_{1/2}$ 9.7%	
	ν	$1h_{11/2}$ 1.7%	$1g_{7/2}$ 12.7%	$2d_{5/2}$ **53.8%**	$2d_{3/2}$ 16.5%	$3s_{1/2}$ **15.3%**
$1/2^+$	π	$1g_{9/2}$ 3.1%	$1f_{5/2}$ 44.4%	$2p_{3/2}$ 42.2%	$2p_{1/2}$ 10.3%	
	ν	$1h_{11/2}$ 1.6%	$1g_{7/2}$ 4.3%	$2d_{5/2}$ **63.5%**	$2d_{3/2}$ 12.6%	$3s_{1/2}$ **18.0%**

on the $\nu d_{5/2}$(52%) and $\nu s_{1/2}$ (43%), while the $3/2^+$ state to $\nu d_{5/2}$(56%) and $\nu d_{3/2}$(26%). The calculated energy for all states is higher than the experimental results (see Fig. 1). In order to reproduce the experimental value of the $I^\pi = 1/2^+$, $E^* = 248$ keV level in ^{83}Ge, we modified the neutron $s_{1/2}$ single-particle energy to the value $E_{\nu s_{1/2}} = 0.7$ MeV. Note that decreasing the energy difference between $\nu d_{5/2}$–$\nu s_{1/2}$ to 0 creates a $1/2^+$ state as the ground state and $5/2^+$ at ~ 100 keV in ^{83}Ge, which does not agree with the experiment results.

The addition of two neutrons to ^{83}Ge reduces the predicted energy between the first $3/2^+$ and $5/2^+$ states in ^{85}Ge to 231 keV, and changes the order of the states. Furthermore, the first $1/2^+$ state in ^{85}Ge is expected as the fourth excited state at $E^* = 778$ keV (Fig. 2). This can indicate that the $\nu s_{1/2}$ single-particle energy used in the calculation (see Table I) is too high. Using the reduced value of $E_{\nu s_{1/2}} = 0.7$ MeV did not influence significantly the values of the predicted energy of excited states in ^{85}Ge; only the sequence of the states is slightly different: now the second $3/2^+$ is expected 100 keV above the first $1/2^+$.

The inspection of the $3/2^+$, $5/2^+$ and $1/2^+$ wave function for ^{85}Ge (Table II) shows that these states belong to the $\nu d^3_{5/2}$ multiplet with about 15% admixture of the $\nu s_{1/2}$ state. Changing the neutron single-particle $d_{5/2}$–$s_{1/2}$ energy gap from 1.3 MeV to zero pushes down the predicted energy for the first $1/2^+$ level from 800 keV to 690 keV. Experimental results point towards the lower value of 250 keV for the same state [11, 17].

3. Summary

We have investigated the low-lying structure of the very neutron-rich ^{83,85}Ge by means of shell-model calculations. We propose $(3/2^+)$ as the ground state for ^{85}Ge on the basis of the experimental tentative assignment $(3/2^+,5/2^+)$, of the two sets of shell-model calculations from this work and from [11], and of systematics of $N = 53$ isotones [18]. The shell-model calculations shown in Fig. 2 reproduce the experimental trend in low lying excited states in ^{85}Ge. The addition of two neutrons to the $N = 51$ ^{83}Ge in the $\nu d_{5/2}$ orbital, changes the ordering of the low-lying levels: the first excited state in ^{85}Ge is no longer $1/2^+$ as in ^{83}Ge, but $(5/2^+)$. The predicted position of the first $1/2^+$ level in ^{85}Ge is not very sensitive to the energy difference of the $\nu d_{5/2}$–$\nu s_{1/2}$ orbitals because of the admixed configuration of the states involved. We also need to keep in mind that in this region of the chart of nuclei, low-excited states start to show a degree of collectivity [18].

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REFERENCES

[1] T. Otsuka *et al.*, *Phys. Rev. Lett.* **87**, 082502 (2001).
[2] T. Otsuka *et al.*, *Phys. Rev. Lett.* **95**, 232502 (2005).
[3] T. Otsuka *et al.*, *Phys. Rev. Lett.* **104**, 012501 (2010).
[4] K.T. Flanagan *et al.*, *Phys. Rev. Lett.* **103**, 142501 (2009).

[5] S.V. Ilyushkin *et al.*, *Phys. Rev.* **C80**, 054304 (2009).
[6] S.V. Ilyushkin *et al.*, *Phys. Rev.* **C83**, 014322 (2011).
[7] K. Sieja, F. Nowacki, *Phys. Rev.* **C81**, 061303(R) (2010).
[8] K. Sieja, F. Nowacki, K. Langanke, G. Martinez-Pinedo, *Phys. Rev.* **C79**, 064310 (2013).
[9] S. Padgett *et al.*, *Phys. Rev.* **C82**, 064314 (2010).
[10] K. Sieja, T.R. Rodriguez, K. Kolos, D. Verney, *Phys. Rev.* **C88**, 034327 (2013).
[11] A. Korgul *et al.*, *Phys. Rev.* **C88**, 044330 (2013).
[12] M. Hjorth-Jensen, T.T.S. Kuo, E. Osnes, *Phys. Rep.* **261**, 125 (1995).
[13] R. Machleidt, `arXiv:0704.0807 [nucl-th]`.
[14] J.S. Thomas *et al.*, *Phys. Rev.* **C76**, 044302 (2007).
[15] J. Duflo, A.P. Zuker, *Phys. Rev.* **C59**, R2347 (1999).
[16] J.A. Winger *et al.*, *Phys. Rev.* **C81**, 044303 (2010).
[17] K. Miernik *et al.*, *Phys. Rev. Lett.* **111**, 132502 (2013).
[18] T. Rzaca-Urban *et al.*, *Phys. Rev.* **C88**, 034302 (2013).