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

A. KORGUL$^a$, R. GRZYWACZ$^{b,c}$, K.P. RYKACZEWSKI$^c$

$^a$Faculty of Physics, University of Warsaw, 00-681 Warszawa, Poland
$^b$Department of Physics and Astronomy, University of Tennessee
Knoxville, Tennessee 37996, USA
$^c$Physics Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831, USA

(Received December 20, 2013)

The measurement of the $\beta$-decay scheme of $^{85}\text{Ga}$ triggered questions on the properties of the low-lying states in $^{85}\text{Ge}$. 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 $N = 51$ $^{83}\text{Ge}$ and $N = 53$ $^{85}\text{Ge}$ isotopes.

DOI:10.5506/APhysPolB.45.223
PACS numbers: 23.20.Lv, 23.35.+g, 27.50.+e, 29.38.–c

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 $^{78}\text{Ni}$ 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 $^{78}\text{Ni}$ 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 $^{78}\text{Ni}$ core, deformation can

$^*$ Presented at the XXXIII Mazurian Lakes Conference on Physics, Piaski, Poland, September 1–7, 2013.
set up quickly [10]. In this work, we performed shell-model calculations for \(^{83,85}\text{Ge}\) in order to analyze the energies, spin and structure of \(N = 51\) \(^{83}\text{Ge}\) and \(N = 53\) \(^{85}\text{Ge}\). 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 \(\beta\) and \(\beta-n\) decay of \(^{85}\text{Ga}\). 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 \(^{85}\text{Ge}\), we performed shell-model calculations with a closed \(^{78}\text{Ni}\) core and the N3LO nucleon–nucleon interaction [12, 13]. The valence space used in the calculations contains all orbitals active outside \(^{78}\text{Ni}\) 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>
<thead>
<tr>
<th>(\pi) orbital</th>
<th>(\epsilon) [MeV]</th>
<th>(\nu) orbital</th>
<th>(\epsilon) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1f_{5/2})</td>
<td>0.0</td>
<td>(2d_{5/2})</td>
<td>0.0</td>
</tr>
<tr>
<td>(2p_{3/2})</td>
<td>1.1</td>
<td>(3s_{1/2})</td>
<td>1.3</td>
</tr>
<tr>
<td>(2p_{1/2})</td>
<td>2.5</td>
<td>(1g_{7/2})</td>
<td>1.8</td>
</tr>
<tr>
<td>(1g_{9/2})</td>
<td>4.5</td>
<td>(2d_{3/2})</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1h_{11/2})</td>
<td>3.0</td>
</tr>
</tbody>
</table>

We also performed calculations for \(^{83}\text{Ge}\) \((N = 51)\) in order to understand better the evolution of level structure in odd-mass Ge isotopes. From the beta decay of \(I^\pi = 5/2^-\) \(^{83}\text{Ga}\) ground state [16], we expect to populate mainly \(3/2\), \(5/2\) and \(7/2\) states in \(^{83}\text{Ge}\). 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 \(^{83}\text{Ge}\), 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.
Wave function of the excited states in $^{85}\text{Ge}$ nucleus predicted in the shell-model calculations; the values correspond in % the occupation of $4\pi$ and $3\nu$. See the text for details.

<table>
<thead>
<tr>
<th>$I^\pi$ state</th>
<th>Orbital</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3/2^+$</td>
<td>$\pi$</td>
<td>$1g_9/2$ 1f$_5/2$ 2p$_3/2$ 2p$_1/2$</td>
</tr>
<tr>
<td></td>
<td>$\nu$</td>
<td>$1h_{11/2}$ 1g$_7/2$ 2d$_5/2$ 2d$_3/2$ 3s$_1/2$</td>
</tr>
<tr>
<td>$5/2^+$</td>
<td>$\pi$</td>
<td>$1g_9/2$ 1f$_5/2$ 2p$_3/2$ 2p$_1/2$</td>
</tr>
<tr>
<td></td>
<td>$\nu$</td>
<td>$1h_{11/2}$ 1g$_7/2$ 2d$_5/2$ 2d$_3/2$ 3s$_1/2$</td>
</tr>
<tr>
<td>$3/2^+$</td>
<td>$\pi$</td>
<td>$1g_9/2$ 1f$_5/2$ 2p$_3/2$ 2p$_1/2$</td>
</tr>
<tr>
<td></td>
<td>$\nu$</td>
<td>$1h_{11/2}$ 1g$_7/2$ 2d$_5/2$ 2d$_3/2$ 3s$_1/2$</td>
</tr>
<tr>
<td>$1/2^+$</td>
<td>$\pi$</td>
<td>$1g_9/2$ 1f$_5/2$ 2p$_3/2$ 2p$_1/2$</td>
</tr>
<tr>
<td></td>
<td>$\nu$</td>
<td>$1h_{11/2}$ 1g$_7/2$ 2d$_5/2$ 2d$_3/2$ 3s$_1/2$</td>
</tr>
</tbody>
</table>

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 $^{83}\text{Ge}$, 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 $\sim 100$ keV in $^{83}\text{Ge}$, which does not agree with the experiment results.

The addition of two neutrons to $^{83}\text{Ge}$ reduces the predicted energy between the first $3/2^+$ and $5/2^+$ states in $^{85}\text{Ge}$ to 231 keV, and changes the order of the states. Furthermore, the first $1/2^+$ state in $^{85}\text{Ge}$ 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 signifi-
cantly 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 $\nu d_{5/2}^3$ 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].

We wish to acknowledge the Holifield Radioactive Ion Beam Facility (HRIBF) staff for their assistance with the experiments and for providing excellent quality neutron-rich radioactive beams. This research is sponsored by the Office of Nuclear Physics, U.S. Department of Energy and supported under U.S. DOE grants DE-AC05-00OR22725 and DE-FG02-96ER40983 National Nuclear Security Administration Grant No. DE-FG52-08NA28552, DE-FC03-03NA00143, and the National Science Centre of the Polish Ministry of Science and Higher Education, Grant No. 2011/01/B/ST2/02476.

REFERENCES