Probing nuclear structures in the vicinity of ^{78}Ni with β- and βn-decay spectroscopy of ^{84}Ga

K. Kolos,[1,2,*] D. Verney,[1] F. Ibrahim,[1] F. Le Blanc,[1,3] S. Franchoo,[1] K. Sieja,[3] F. Nowacki,[3] C. Bonnin,[1] M. Cheikh Mhamed,[1] P. V. Cuong,[4] F. Didierjean,[3] G. Duchêne,[3] S. Essabaa,[1] G. Germogli,[1] L. H. Khiem,[4] C. Lau,[1] I. Matea,[1,5] M. Niikura,[1,5] B. Roussière,[1] I. Stefan,[1] D. Testov,[1,6] and J.-C. Thomas[7]

[1]*Institut de Physique Nucléaire, CNRS/IN2P3 and Université Paris Sud, Orsay, France*
[2]*University of Tennessee, Knoxville, Tennessee 37996, USA*
[3]*Institut Pluridisciplinaire Hubert Curien, CNRS/IN2P3 and Université de Strasbourg, Strasbourg, France*
[4]*Center of Nuclear Physics, Institute of Physics, Vietnam Academy of Science and Technology, Hanoi, Vietnam*
[5]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan*
[6]*Flerov Laboratory of Nuclear Reactions, Joint Institute of Nuclear Research, Dubna, Russia*
[7]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3, Caen, France*

(Received 4 August 2013; revised manuscript received 2 September 2013; published 14 October 2013)

The decay of ^{84}Ga has been reinvestigated at the PARRNe online mass separator of the electron-driven installation ALTO at IPN Orsay. The nominal primary electron beam of 10 μA (50 MeV) on a ^{238}UC$_x$ target in combination with resonant laser ionization were used for the first time at ALTO. Improved level schemes of the neutron-rich ^{83,84}Ge ($Z = 32$) isotopes were obtained. The experimental results are compared with the state-of-the-art shell model calculations and discussed in terms of collectivity development in the natural valence space outside the ^{78}Ni core.

DOI: 10.1103/PhysRevC.88.047301 PACS number(s): 23.20.Lv, 23.40.−s, 29.30.Kv, 21.60.Cs

The present study is a continuation of the previous (and to some extent pioneering) studies of ^{83,84}Ga decays undertaken at PARRNe (see Refs. [1–4] and references therein). Understanding the structure of the Ge ($Z = 32$) neutron-rich isotopes close to $N = 50$ is of particular interest because a local energy minimum of the correlated gap $\Delta(N = 50) = S_{2n}(N = 52) - S_{2n}(N = 50)$, as can be extracted, e.g., from the 2012 AMDC mass evaluation [5], is found exactly at $Z = 32$. This minimum seems to be associated with collective γ-soft structure in ^{80}Ge [6]. Further evidence for the survival of γ-softness close to and beyond $N = 50$ could in some way confirm the intuition of Lebois *et al.* [1] based on five-dimensional collective Hamiltonian (5DCH) calculations. Statistics were insufficient in the previous study performed at IPN Orsay [1] to unambiguously assign the second excited state in ^{84}Ge, so the assignment was made on the basis of activity balance. Direct observation of a 765.1(8) keV transition in coincidence with the $2_1^+ \rightarrow 0_{gs}^+$ transition at 623.9(6) keV was achieved for the first time at the ORNL Holifield Radioactive Ion Beam Facility (HRIBF) by Winger *et al.* [7] ruling out our first proposal. The authors assigned then (4_1^+) to the state at 1389.0(10) keV in ^{84}Ge.

In order to improve the ^{84}Ga ion production yield, in the present experiment the maximum electron driver beam intensity of 10 μA was used and Ga atoms were selectively photoionized using the newly commissioned ALTO laser ion source. This dramatic increase in available beam rates allowed us to obtain new experimental results from the β and βn decay of ^{84}Ga which we present in this report. A brief discussion of the results in the framework of the shell model (SM) is then proposed.

The fission fragments were produced in the interaction of the 50 MeV, 10 μA electron beam delivered on to a thick uranium carbide target in a standard UC$_x$ form at ALTO [8]. To allow fast fission products effusion and diffusion, the target was heated up to 2000 °C. The gallium atoms were ionized with in a two-step process with the laser ion source. The performance of this laser configuration was tested with a stable ^{69}Ga sample prior to the experiment. The measured ionization efficiency of the stable gallium with the laser on was a factor of 15 higher than with the laser off (surface ionization) which approaches the result reported in [9] (0.7% and 20% for surface ionization and laser ionization, respectively). The Ga^{1+} ions were extracted at 30 keV, mass separated, and implanted on an Al-coated mylar tape surrounded with the detection setup. For the detection of γ rays we used two large-volume coaxial high-purity germanium (HPGe) detectors with resolutions of 2.3 and 2.6 keV at 1.3 MeV. These two detectors were placed in a 180° geometry close to the collection point. The total photo-peak efficiency was 2% at 1.3 MeV. The collection point on the tape was surrounded with a plastic scintillator for β tagging. The isotopes were collected on the tape in cycles of four seconds for collection and one second decay time. This arrangement maximized the accumulation of γ statistics while leaving enough decay time for very short period identification[1] and keeping the accumulation of longer lived daughter isotopes at an acceptable level.

The experimental β-gated γ-spectrum corresponding to the whole statistics of the experiment is presented in Fig. 1. All main lines present in this spectrum have half-lives determined from the experimental time spectra compatible with the known half-lives of ^{84}Ga and its β and βn daughters. The only exceptions are a few small lines (see Fig. 1), having no time structure, and which are due to random coincidence with the β detector of strong γ emissions from the decay of neutron-rich

*kkolos@utk.edu

[1]The half-life of ^{84}Ga is 0.085(10) s [10].

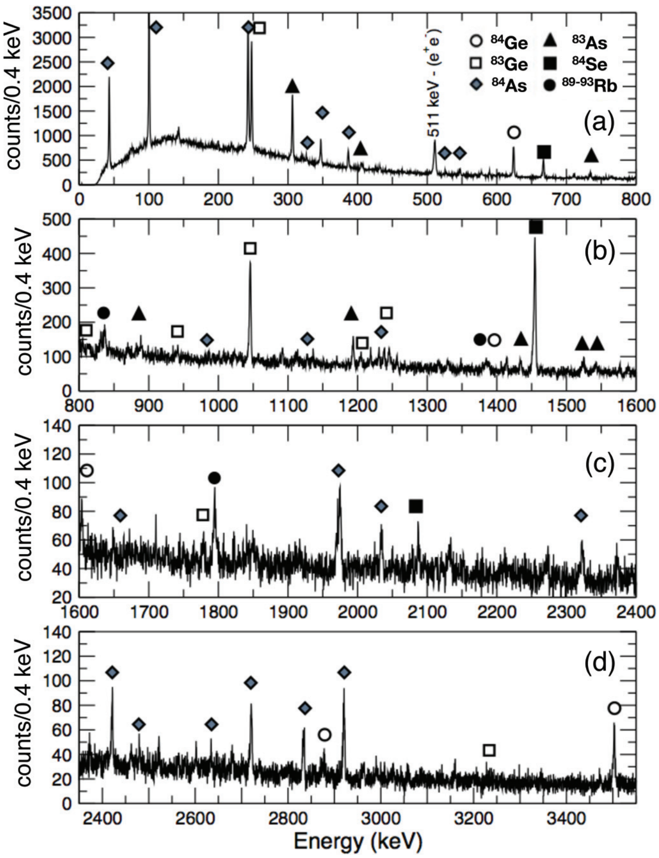

FIG. 1. (Color online) Experimental β-gated γ-ray spectrum. (a), (b), (c) and (d) represent subsequent energy ranges 0–800, 800–1600, 1600–2400, and 2400–3700 keV, respectively.

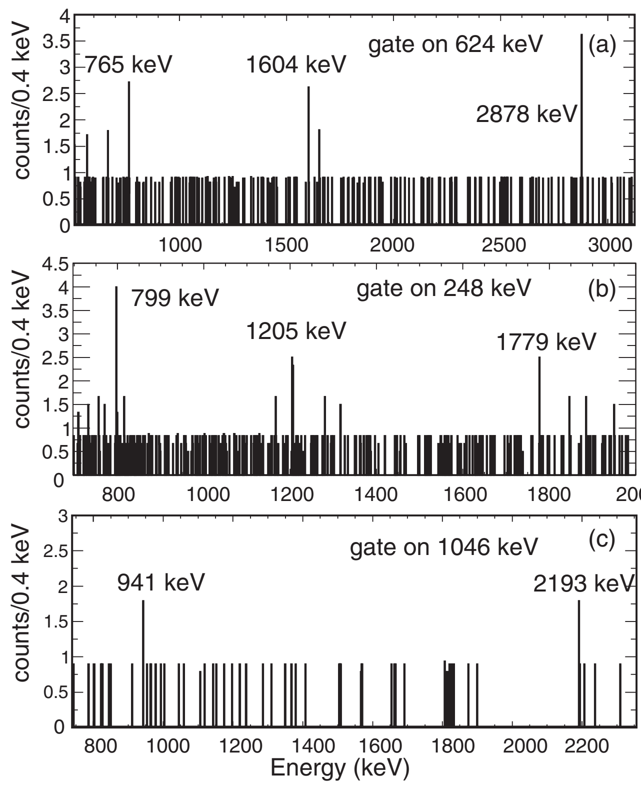

FIG. 2. Experimental β-gated γ-ray spectra represent coincidences (a) with 624 keV, (b) with 248 keV, and (c) with 1046 keV γ ray.

Rb isotopes accumulated upstream in the PARRNe focal plane. The γ transitions which were attributed to ^{83}Ge and ^{84}Ge based on measurements of their half-lives (obtained from the decay curve during the decay cycle) and γ-γ coincidence measurements (Fig. 2) are listed in Table I. Some of the transitions were already assigned to one of the two nuclei in Refs. [1,2,7].

For ^{84}Ge, we confirm the coincidence of the 624.2 keV γ ray with the 765.1 keV γ ray previously reported in [7]. We found two new coincidences with the 624.2 keV γ ray: 1603.9 and 2878 keV, and two transitions to the ground state of ^{84}Ge with energies 1389.3 and 3502.3 keV. With this result we propose to assign two new excited levels to the ^{84}Ge level scheme; see Fig. 3.

For ^{83}Ge, three coincidences with the γ ray of energy 247.7 keV ($1/2_1^+ \rightarrow 5/2_{gs}^+$) were found: at 798.9, 1204.9, and 1778.7 keV, and two very weak coincidences with the line at 1045.9 keV, one at 941 keV and the second at 2193 keV. Having seen the coincidence between the 247.7 and 798.9 keV transitions we confirm the existence of the excited state at 1045.9 keV (previously reported in [7]). We confirm the γ ray at 1238 keV (previously reported in [2]); no coincidence with this γ ray was found. The corresponding ^{83}Ge level scheme deduced from the ^{84}Ge βn decay is reported in Fig. 3.

The absolute branching ratios (B) to the different excited and ground state levels are evaluated from the absolute number of ^{84}Ga β decays and relative γ-ray intensities reported in Table I. The former was estimated, considering $B = 15.3(11)\%$ [7] to the 306.5 keV transition in ^{83}As, and considering $P_n = 74(14)\%$ from the same reference, to be $2.40(19) \times 10^6$. It amounts to an averaged ^{84}Ga production yield of $\sim$120 pps. Obtained B values are reported in Table II. The log ft values were then calculated using mass values from the 2012 AMDC evaluation [5], and are reported in Table II. Those values must be considered only as the lowest possible limits as level schemes are only partial and there can be a significant amount of unobserved γ transitions. The ^{84}Ga ground state was proposed to have $J^\pi = (0^-)$ in Ref. [1] essentially because $\pi = -$ is the natural parity for an odd-odd nucleus ground state in this sector of the ^{78}Ni valence space, and because the strongest γ transition fed in the ^{84}Ga decay is from the unambiguously determined $J^\pi = 1/2_1^+$ state in ^{83}Ge [12]. However, the massive branching to both 0_{gs}^+ and $1/2_1^+$ states in ^{84}Ge and ^{83}Ge suggested in Ref. [1] is not so obvious from this higher statistics measurement. If the ^{84}Ga has certainly a very low spin, a value such as $J = 1$ cannot be excluded. Because the log ft evaluations are only lower limits here, as the parity change is inherent to the valence space (negative parity fp protons and positive parity sdg neutrons), and assuming $J = 0, 1$ for the ^{84}Ga ground state, we propose to assign $J^\pi = 0^+, 1^+, 2^+$ and $J^\pi = 1/2^+, 3/2^+, 5/2^+$ to the levels of ^{84}Ge and ^{83}Ge populated in this experiment. Taking into account further constraints from electromagnetic transition selection rules, we

TABLE I. The list of γ rays observed in the $\beta/\beta n$ decay of ^{84}Ga assigned to the deexcitation of ^{83}Ge (top) and ^{84}Ge (bottom), with intensities relative to the most intense line in ^{83}Ge, and the γ-γ coincidences. The γ rays marked with asterisks are of low statistics and their assignment is tentative.

E_γ (keV)	I_{rel}(%)	γ-γ	$T_{1/2}$ (s)
247.7(3)	100(3)	798.9, 1204.9, 1778.7	0.078(9)
798.9(3)	5(1)	247.7	0.164(95)
*941.5(4)	5(1)	1045.9	
1045.9(4)	55(3)	941.5, 2193	0.085(19)
1204.9(6)	7(2)	247.7	0.112(73)
1238.4(8)	9(3)		0.110(66)
1778.7(4)	6(2)	247.7	
2026(1)	3(1)		
*2193(1)		1045.9	
3238(1)	6(2)		
624.2(2)	61(3)	765.1, 1603.9, 2878.1	0.097(17)
765.1(3)	9(3)	624.2	0.107(93)
1389.3(4)	5(4)		
1603.9(2)	10(2)	624.2	0.159(100)
2878.1(6)	13(4)	624.2	
3502(1)	36(5)		0.086(29)

propose the spin-parity assignments listed in Table II and also reported in Fig. 3.

Experimental results were compared with the theoretical calculations. We present the results of the SM calculations performed with the m-scheme code ANTOINE [13] and j-coupled scheme NATHAN [13,14] using an effective interaction with a ^{78}Ni core and a valence space composed

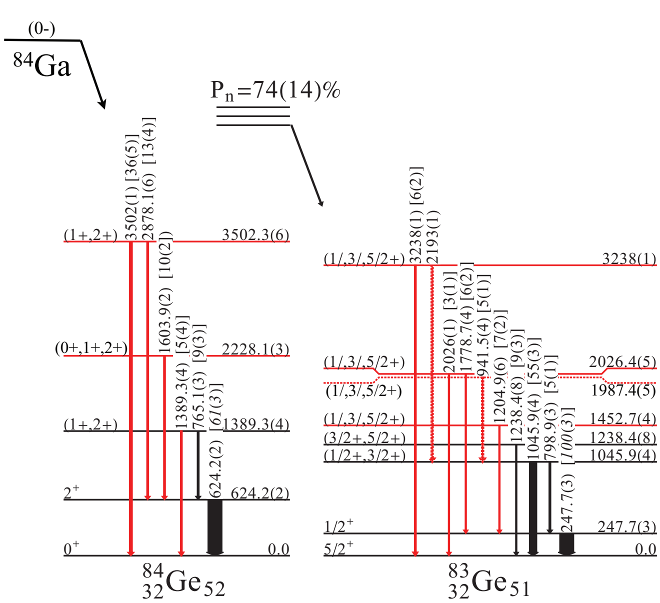

FIG. 3. (Color online) Level scheme of ^{83}Ge and ^{84}Ge populated in the $\beta/\beta n$ decay of ^{84}Ga. Relative intensities of each γ transition are normalized to the 247.7 keV transition in ^{83}Ge. The probability of neutron emission was reported in [7]. Drawn in black are previously reported transitions in ^{84}Ge [1,7] and in ^{83}Ge [2,7,11,12]. In red are the transitions assigned from this experiment.

TABLE II. The table presents possible spin and parity assignments for the excited levels in ^{83}Ge (top) and ^{84}Ge (bottom), proposed based on their relative branching ratios and calculated $\log ft$ values.

Energy (keV)	Spin and parity J^π	B (%)	$\log ft$
0.0	$5/2^+$	<61	
247.7(3)	$1/2^+$	8.4(1.8)	
1045.9(4)	$(1/2^+, 3/2^+)$	5.2(1.1)	
1238.4(8)	$(3/2^+, 5/2^+)$	1.1(3)	
1452.7(4)	$(1/2^+, 3/2^+, 5/2^+)$	0.8(3)	
2026.4(5)	$(1/2^+, 3/2^+, 5/2^+)$	1.1(4)	
3238(1)	$(1/2^+, 3/2^+, 5/2^+)$	0.8(3)	
0.0	0^+	<29	>5.6(2)
624.2(2)	2^+	4.4(8)	6.3(1)
1389.3(4)	$(1^+, 2^+)$	1.6(5)	6.5(2)
2228.1(3)	$(0^+, 1^+, 2^+)$	1.1(3)	6.6(1)
3502.3(6)	$(1^+, 2^+)$	5.1(1.2)	5.7(1)

of $2p_{3/2}, 1f_{5/2}, 2p_{1/2}, 1g_{9/2}$ orbits for protons and $1g_{7/2}$, $2d_{5/2}, 2d_{3/2}, 3s_{1/2}, 1h_{11/2}$ for neutrons. In this interaction the effective neutron-neutron and neutron-proton parts were taken from [15] while the proton-proton two-body matrix elements (TBMEs) were obtained from the JJ4B interaction [16]. The monopole part of the proton-neutron effective Hamiltonian was adjusted to ensure a correct propagation of the single-particle states between ^{79}Ni and ^{91}Zr. Taking the proton-proton part from the JJ4B interaction allows for a consistent discussion of the $Z = 32$ proton effects with results already obtained below $N = 50$ in [6]. Electromagnetic quantities were calculated using the effective charges $e_\pi = 1.6$, $e_\nu = 0.6$ [as with those effective charges we obtained the best result for $B(E2)$ for the $N = 50$ isotonic chain] and the gyromagnetic factors $g_\pi = 4.1895$, $g_\nu = -2.8695$ [14,17,18].

As the calculated level density is relatively important beyond the two phonon energy in the even-even case and close to the core-coupled multiplet centroid in the odd case, we cannot assume a one-to-one correspondence of the calculated and experimental levels in energy order. A way around this limitation is found by associating theoretical and experimental levels based on their similitude in the relative intensities of the γ transitions through which they are depopulated (we restricted the calculation here to $M1$ and $E2$ transitions). This method is limited to states which are seen to decay by two or more γ transitions and could be applied in the present case only to the 1046 and 2026 keV levels in ^{83}Ge and to the 1389 keV level in ^{84}Ge. The only theoretical counterparts having similar decay properties and calculated at less than 300 keV energy distance from the experimental value are found to be the $3/2^+_1$ and $1/2^+_4$ states for the excited level at 1046 and 2026 keV, respectively, in ^{83}Ge and for the 2^+_2 state at 1389 keV in ^{84}Ge. Results from the calculations and comparisons are provided in Table III.

The other interesting level in ^{83}Ge is the one located at 1238 keV, which was proposed by Perru *et al.* [2] as the $3/2^+$ or $5/2^+$ member of the core-particle coupling multiplet since its energy is very close to that of the 2^+_1 state of ^{82}Ge (1348 keV). The population of this state in the β decay of

TABLE III. The calculated reduced transition probabilities and the partial γ-ray transition probabilities for the assignment of the spin and parity of the experimental levels in ^{84}Ge and ^{83}Ge. In the last two columns theoretical and experimental ratios are compared ("t" = theory, "e" = experiment).

E_{lev_e} (keV)	Transitions E_{lev_t} (keV)	$B(M1)$ μ_N^2	$B(E2)$ e^2fm^4	$P_{i\to f}$ $(\frac{1}{s})$	Ratio$_t$ (%)	Ratio$_e$ (%)
^{84}Ge	$(2_2^+ \to 0_1^+)$		16	10.14×10^{10}	34	37
1389	$(2_2^+ \to 2_1^+)$	0.015	227	19.13×10^{10}	66	63
	1528					
^{83}Ge	$(\frac{3}{2}{}_1^+ \to \frac{5}{2}{}_1^+)$	0.43	105	8.66×10^{12}	89	90
1046	$(\frac{3}{2}{}_1^+ \to \frac{1}{2}{}_1^+)$	0.117	66	1.06×10^{12}	11	10
	1181					
^{83}Ge	$(\frac{1}{2}{}_4^+ \to \frac{5}{2}{}_1^+)$		0.16	1.07×10^{10}	4	33
2026	$(\frac{1}{2}{}_4^+ \to \frac{1}{2}{}_1^+)$	0.012		2.33×10^{12}	96	66
	2225					

^{83}Ga [7] was estimated to be twice as high as that of the $1/2_1^+$ state or the state at 1046 keV, which (as we stated previously) could be the $(3/2_1^+)$ state. This could give an indication that the 1238 keV excited state has $J^\pi = 5/2^+$ and is favored over the $1/2_1^+, 3/2_1^+$ states in the β decay from the ground state of ^{83}Ga (proposed $J^\pi = 5/2^-$). It is, in contrast, relatively unfavored in the βn decay of the ^{84}Ga ground state (proposed $J^\pi = 0^-, 1^-$) as seen from our results. Qualitatively, the fact that this state is seen experimentally to depopulate only towards the $5/2^+$ ground state is not in contradiction with its supposedly core-coupled (collective) nature. In a pure core-particle coupling scheme such a transition would amount to $5/2_2^+[2^+ \otimes \nu d_{5/2}] \to 5/2_1^+[0^+ \otimes \nu d_{5/2}]$, that is, mainly a collective core transition without single-particle contribution.

The further (theory dependent) spin-parity determination resulting from this discussion is reported in Fig. 4 along with the theoretical level schemes. The most important feature of the newly determined ^{84}Ge level scheme is the transition at 1389 keV bypassing the 2_1^+ level, which allows the definite assignment of $J^\pi = 2^+$ to the second excited state. Due to the low spin ($J = 0, 1$) of the mother state, the 4^+ state may have been fed only weakly and could not be observed. It is a longstanding prediction from the beyond-mean-field (5DCH-D1S Gogny) calculations [19–21] (values available in [22]) that the second excited state of ^{84}Ge should indeed be the 2^+ state, calculated at 1542 keV. The ^{84}Ge ground state is described as very soft against triaxiality with $\gamma_{\text{rms}} = 28^\circ$, $\delta(\gamma) = 13^\circ$ ($\beta_{\text{rms}} = 0.219$). SM calculations as described above also give the 2^+ state as the second excited state of

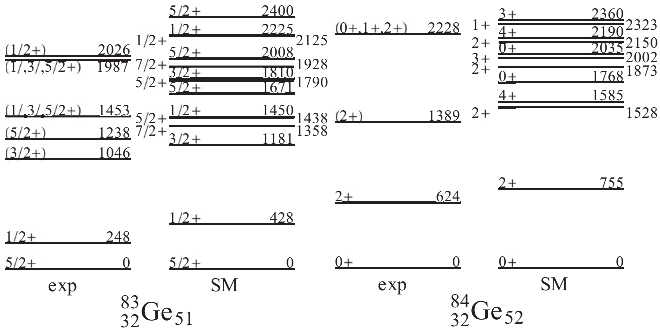

FIG. 4. Experimental low-lying spectra of (left) ^{83}Ge and (right) ^{84}Ge compared with the shell model (SM) calculations with the ^{78}Ni core and the effective interaction obtained in this work.

^{84}Ge at very similar energy: 1528 keV. By evaluating the n-body quadrupole moments in a similar way as in [6], the intrinsic parameters of the SM 0_{gs}^+ and 2_2^+ states are $\beta_{\text{rms}} = 0.213$, $\gamma_{\text{rms}} = 23^\circ$ (strikingly similar to the 5DCH results) and $\beta_{\text{rms}} = 0.181$, $\gamma_{\text{rms}} = 28^\circ$ respectively. Inspection of the main $E2$ transitions shows that the 2_2^+ state is the band head of a quasi-γ band. Such a striking resemblance between beyond-mean-field and SM calculations is also noted in heavier Ge and Se isotopes and will be discussed in a forthcoming paper [23]. Inspection of the SM wave functions reveals a similar proton structure to the triaxial states in ^{80}Ge [6].

Concerning ^{83}Ge, the analysis of SM calculation supports the interpretation of the low lying structure in terms of core-particle coupling as proposed in [2]. The calculated ^{83}Ge ground state has a main component $0^+(f_{5/2}^4 + f_{5/2}^2 p_{3/2}^2)_{v=0} \otimes \nu d_{5/2}$ (v is a seniority number). The $3/2_1^+$ state associated previously to the excited level found experimentally at 1046 keV is found with its main component along with a $2^+(f_{5/2}^4 + f_{5/2}^2 p_{3/2}^2)_{v=2} \otimes \nu d_{5/2}$ configuration. In fact the majority of the calculated low-lying states are clearly associated with core-coupled ^{82}Ge $\otimes\, \nu d_{5/2}$ configurations, with the exception of the $1/2_1^+$ state consistently described as $0_1^+ \otimes \nu s_{1/2}$.

We wish to acknowledge the technical staff of the Tandem/ALTO facility for their assistance with the experiments and for providing excellent quality radioactive beams. We thank the members of the Radiation Protection Service of the Institute of Nuclear Physics in Orsay for their help. Use of one Ge detector from the French-UK IN2P3-STFC Gamma Loan Pool is acknowledged. Two of us (P.V.C. and L.H.K.) acknowledge support from the bilateral agreement VAST-CNRS and the FV-PPL Collaboration.

[1] M. Lebois *et al.*, Phys. Rev. C **80**, 044308 (2009).
[2] O. Perru *et al.*, Eur. Phys. J. A **28**, 307 (2006).
[3] D. Verney *et al.*, Braz. J. Phys. **34**, 979 (2004).
[4] O. Perru *et al.*, Phys. At. Nucl. **66**, 1421 (2003).
[5] G. Audi *et al.*, Chin. Phys. C **36**, 1157 (2012).
[6] D. Verney *et al.*, Phys. Rev. C **87**, 054307 (2013).
[7] J. A. Winger *et al.*, Phys. Rev. C **81**, 044303 (2010).
[8] F. Ibrahim *et al.*, Nucl. Phys. A **787**, 110 (2007).
[9] U. Köster *et al.*, Eur. Phys. J. A **15**, 255 (2002).
[10] K.-L. Kratz *et al.*, Z. Phys. A **340**, 419 (1991).

[11] J. S. Thomas *et al*., Phys. Rev. C **71**, 021302 (2005).
[12] J. S. Thomas *et al*., Phys. Rev. C **76**, 044302 (2007).
[13] E. Caurier and F. Nowacki, Acta Phys. Pol. B **30**, 705 (1999).
[14] E. Caurier, G. Martinez-Pinedo, F. Nowacki, A. Poves, and A. Zuker, Rev. Mod. Phys. **77**, 427 (2005).
[15] K. Sieja, F. Nowacki, K. Langanke, and G. Martinez-Pinedo, Phys. Rev. C **79**, 064310 (2009).
[16] D. Verney *et al*., Phys. Rev. C **76**, 054312 (2007).
[17] E. Caurier, A. Poves, and A. P. Zuker, Phys. Rev. Lett. **74**, 1517 (1995).
[18] P. Von Neumann-Cosel *et al*., Phys. Lett. B **443**, 1 (1998).
[19] O. Perru, Ph.D. thesis, Université Paris-Sud 11, 2004 (unpublished).
[20] J. Libert (private communication).
[21] J.-P. Delaroche, M. Girod, J. Libert, H. Goutte, S. Hilaire, S. Peru, N. Pillet, and G. F. Bertsch, Phys. Rev. C **81**, 014303 (2010).
[22] S. Hilaire and M. Girod, http://www-phynu.cea.fr/science_en_ligne/carte_potentiels_microscopiques/carte_potentiel_nucleaire_eng.htm.
[23] K. Sieja, T. R. Rodríguez, K. Kolos, and D. Verney, Phys. Rev. C **88**, 034327 (2013).