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Study of the N = 50 major shell effect toward ^{78}Ni at PARRNe*: Evidence of a weak-coupling structure in $^{83}_{32}Ge_{51}$

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Abstract. The γ-ray de-excitations following the β-decay of ^{83}Ga and the β-n decay of ^{84}Ga have been studied. The radioactive species were produced using the PARRNe on-line mass-separator installed at the IPN Orsay Tandem accelerator. Two γ-lines were attributed to ^{83}Ge with the aid of β-γ and γ-γ coincidences. The Z identification of the γ-lines was provided by time analysis of a buid-up/decay cycle. The excited levels of ^{83}Ge can be explained by the coupling of the single neutron state $\nu 2d_{5/2}$ to the first 2^+ excitation of the ^{82}Ge core.

PACS. 29.30.-h Spectrometers and spectroscopic techniques – 21.10.-k Properties of nuclei; nuclear energy levels – 23.20.Lv gamma transitions and level energies – 27.50.+e $59 \leq A \leq 89$

1 Introduction

Recently considerable evidence has been pointed out for the existence of shell gap reinforcements and disappearances far off stability, leading in certain cases to the statement that some well-known magic numbers would vanish while new ones would raise. Among the Mayer and Jensen "historical" magic numbers, *50* is known to retain its magic character for *protons* (Sn isotopes) from $N = 50$ to $N = 82$ [1]. On the other hand, probing the stiffness of the 50 *neutron* shell gap from $Z = 50$ down to $Z = 28$ still represents a vivid and extremely active field of investigation in present nuclear-structure research (see [2–4] and references therein). The conclusions of refs. [2] and [3] on a possible $N = 50$ shell effect weakening are contradictory. To illustrate why this question is addressed, let us consider for instance one of the most direct (but certainly not unique) pieces of evidence that a shell closure dominates the nuclear structure: the evolution in energy of the first 2^+ excited state of the even-even nuclei at the crossing of the corresponding magic number of nucleons. As can be seen in fig. 1 the $N = 50$ shell closure has definitely a strong influence, but the constant decrease of the 2^+_1 energy for the $N = 50$ isotones from $Z = 40$ to $Z = 32$, *i.e.*

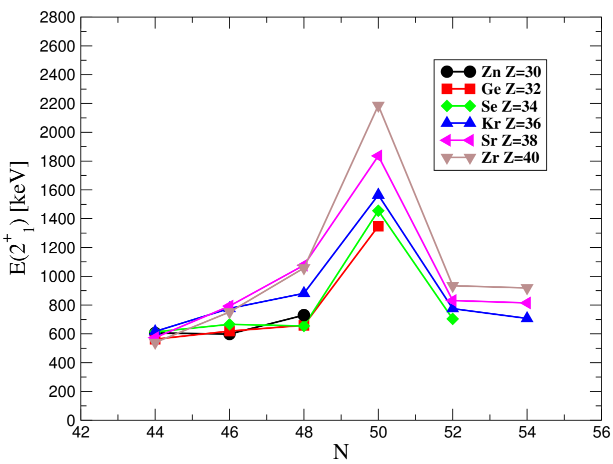

Fig. 1. Systematics of the experimentally observed $E2^+_1$ in the stable and neutron-rich nuclei near the $N = 50$ shell closure.

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as they become more and more proton deficient, is somewhat surprising. The question of knowing what remains from this influence in the vicinity of the expected double-shell closure ($Z = 28$, $N = 50$), is still open and obtaining more data on the structure of these hard-to-reach nuclei is certainly mandatory. We report here on one experiment aiming at feeding excited states in the very neutron-rich ${}^{83}_{32}Ge_{51}$ *via* the β-decay and β-n decay of the mother nuclei ${}^{83}_{31}Ga_{52}$ and ${}^{84}_{31}Ga_{53}$.

2 Experimental procedure and results

The Ga isotopes were obtained from the fission of ^{238}U nuclei at the PARRNe mass separator, installed at the Orsay Tandem accelerator. The 26 MeV deuteron beam delivered by the MP-Tandem hit a 5 mm thick graphite converter placed 110 mm upstream from the centre of the target. The fast incident neutrons produced in the break-up of the deuterons irradiated an UC$_x$ target heated up to 2200 °C [5,6]. The fission fragments released from the target were ionized with a MK5 ISOLDE-type ion source [7]. The ions were extracted at 30 kV, then magnetically mass separated and finally collected on a movable aluminized Mylar tape (see fig. 2). The production rates of the ^{83,84}Ga isotopes were of the order of 1 to 0.1 ion/s.

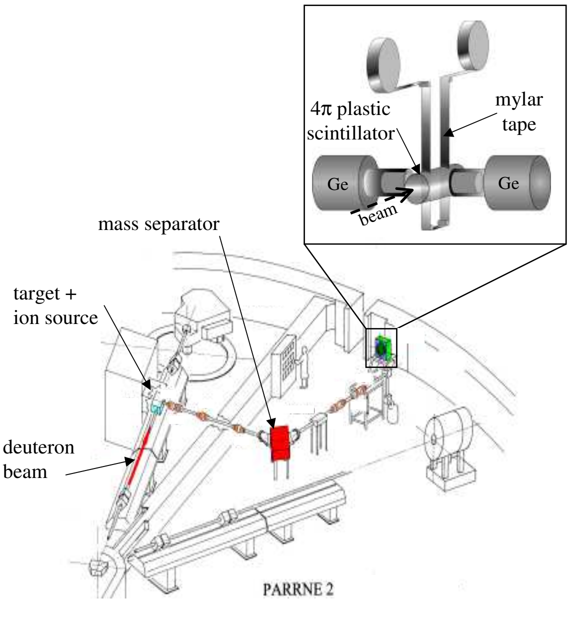

Fig. 2. Experimental set-up at the Tandem accelerator at Orsay. The two halls are separated with 1.5 m thick concrete wall to isolate the production place (with ^{238}U target and ion source), from the separation and detection place and therefore reduce the background. A more detailed scheme of the counting point is shown in the insert. The ions are collected on the Mylar tape through a hole in the plastic scintillator. The light generated by the interaction of β particles in the plastic is collected by means of a photomultiplier (not represented here) placed at the back of the plastic detector.

The β-detection system consisted of a 4π plastic scintillator surrounding the tape, providing an angular acceptance of $\approx 4\pi$ sr, and 2 large volume Ge detectors placed in a compact geometry providing an absolute total γ-efficiency of 3.6×10^{-3} at 1408 keV. With this set-up both β-γ and γ-γ coincidence events could be detected. The longer-lived isobar activities were cyclically evacuated by moving the tape every 2 seconds (1 second of build-up plus 1 second of decay). The data acquisition was running during the 2 s cycle and inhibited during the tape motion. An absolute time-stamping of every β or γ event was performed on an absolute time scale by use of a six-fold peak sensing ADC COMET-6X [8] associated with the OASIS data acquisition system. This allowed to choose any time window from 400 ps up to the whole 2 s duration of the build-up/decay time or any time binning in the off-line analysis. For instance, in our analysis, this window was set to 70 ns for prompt β-γ coincidences. The Z identification was provided by the analysis of the evolution in time of the γ-lines during the decay period.

Most of the peaks present in the $A = 83$ γ-spectra have been attributed to the activities of ^{83}Br ($T_{1/2} = 2$ h40), ^{83}Se ($T_{1/2} = 22.3$ min), ^{83m}Se ($T_{1/2} = 70.1$ s), ^{83}As ($T_{1/2} = 13.4$ s), ^{83}Ge ($T_{1/2} = 1.85$ s) [9]. Besides, in this mass region, γ-transitions belonging to the $A - 1$ nuclei are likely to be present in the γ spectra recorded for a given mass A due to β-n decay. As can be seen from fig. 3, excited levels of ^{83}Ge are populated from β-decay and excited levels of ^{82}Ge from β-n decay. Therefore, in the $A = 83$ γ spectrum, γ-lines corresponding to transitions in both ^{82}Ge and ^{83}Ge are present. Fortunately, the ^{82}Ge transitions are well known: a first detailed level scheme has been established by P. Hoff and B. Fogelberg in the analysis of the β-decay of ^{82}Ga at the OSIRIS fission prod-

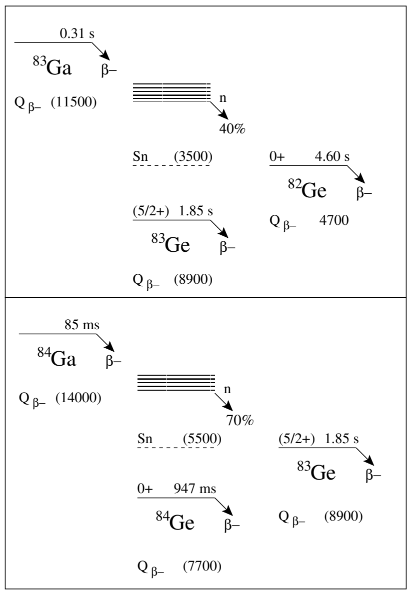

Fig. 3. Decay modes for ^{83}Ga and ^{84}Ga (taken from [9] and [10]).

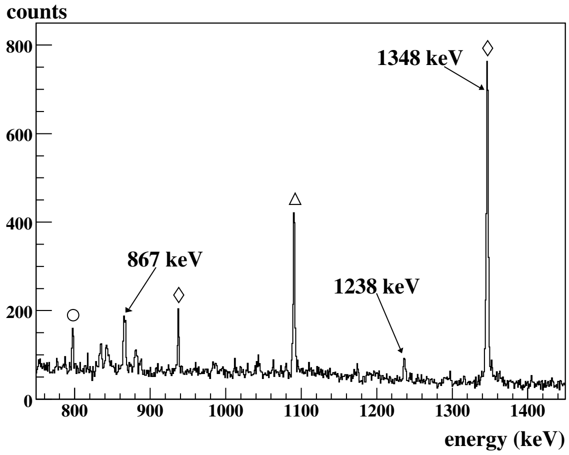

Fig. 4. Part of the γ spectrum for $A = 83$. The two peaks attributed to ^{83}Ge (867 keV and 1238 keV) are indicated as well as the $2^+ \to 0^+$ transition in ^{82}Ge at 1348 keV. Other peaks are transitions in ^{83}Br (○ at 799 keV), in ^{82}Ge (◇ at 938 keV) and in ^{83}As (△ at 1092 keV).

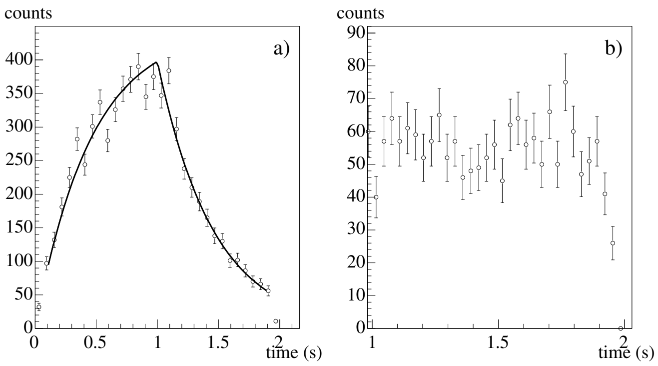

Fig. 5. a) β-gated time spectrum for the peak at 1348 keV recorded at $A = 83$, the fit result is $T_{1/2} = 317 \pm 7$ ms. The collection time is 1 s and the decay time is 1 s. b) Time spectrum of the γ background (obtained with the $A = 84$ γ spectrum).

uct mass separator (Studsvik) [11]. This level scheme has been confirmed and completed by J.C. Hill *et al.* at the TRISTAN mass separator at Brookhaven [12].

Let us consider the strongest line at the energy of 1348 keV in the part of the $A = 83$ γ spectrum shown in fig. 4. The time projection of the events in this 1348 keV γ-energy peak is represented in fig. 5a: one can recognize the growing part corresponding to the activity of the source while the ion beam is collected and the decaying part corresponding to the activity of the source without beam. A fit of the decaying part gives $T_{1/2} = 317 \pm 7$ ms which is in agreement with the known half-life of the mother nucleus ^{83}Ga ($T_{1/2} = 310 \pm 10$ ms [9]). This good agreement is explained by the fact that the shortest activity in the spectra necessarily originated from the decay of Ga. Indeed, it had been observed in previous production measurements [5], performed in identical experimental conditions, that the production yields of ^{78}Ga were ten times higher than those of the mother nuclei ^{78}Zn. Furthermore,

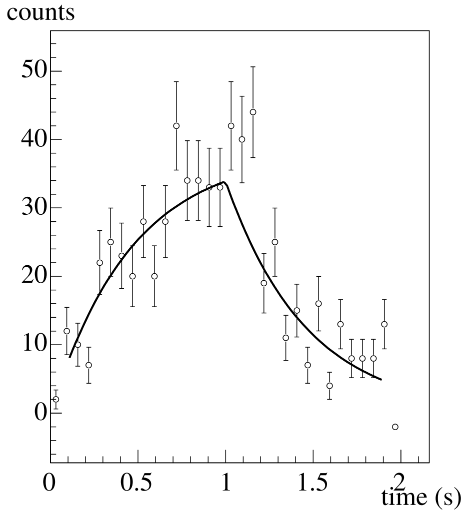

Fig. 6. Background-subtracted time spectrum for the γ-line at 1238 keV observed in the $A = 83$ spectrum. The fit gives a half-life $T_{1/2} = 319 \pm 24$ ms.

the activities of the longer-lived isobars give no noticeable contribution in the time behavior of the γ background as can be seen in fig. 5b. Then, the peak at 1348 keV can easily be attributed to the most intense transition in the ^{82}Ge level scheme, *i.e.* the $2^+ \to 0^+$ transition reported in refs. [11,12]. Incidentally, the presence of this peak in the spectra is the evidence that we successfully produced and collected ^{83}Ga. It was then used in order to monitor the Ga production in the target-ion source ensemble.

In the following, we will propose the γ-rays observed in this work and not reported prior to the present experiment, nor in the $A = 83$ activities nor in the $^{82}\mathrm{Ga} \to {}^{82}\mathrm{Ge}$ decay, as candidates to belong to the $^{83}\mathrm{Ga} \to {}^{83}\mathrm{Ge}$ decay. Two such γ-lines have been found: one at 867.4(8) keV and the other at 1238.2(5) keV. The experimental results reported in the present paper have already been the object of communications in various places [13,14].

The background-subtracted time spectrum of the 1238.2 keV γ-ray (fig. 6) exhibits a half-life $T_{1/2} = 319 \pm 24$ ms which is in agreement with the ^{83}Ga half-life. Therefore, there is no ambiguity in attributing the 1238.2 keV transition to the decay of ^{83}Ga. Since no 1238.2 keV γ-transition was previously reported in the level scheme of ^{82}Ge, this transition is very likely to belong to ^{83}Ge.

The case of the peak at 867.4 keV deserves a more detailed discussion since it happens to be very close in energy with two known γ-transitions: in ^{83}Br at 866.65 keV (from the β-decay of ^{83}Se, $T_{1/2} = 22.3$ min) and in ^{82}Ge at 867.46 keV (from the β-n decay of ^{83}Ga, $T_{1/2} = 310 \pm 10$ ms). However, it will be shown here from time and γ-γ spectrum analysis that this peak necessarily contains a contribution coming from a transition in ^{83}Ge. The half-life value of ^{83}Se being 22.3 min [9], it can be considered as infinite compared to our counting time. In the time projection of the γ-events which remain after background subtraction in the peak at 867.4 keV one observes two com-

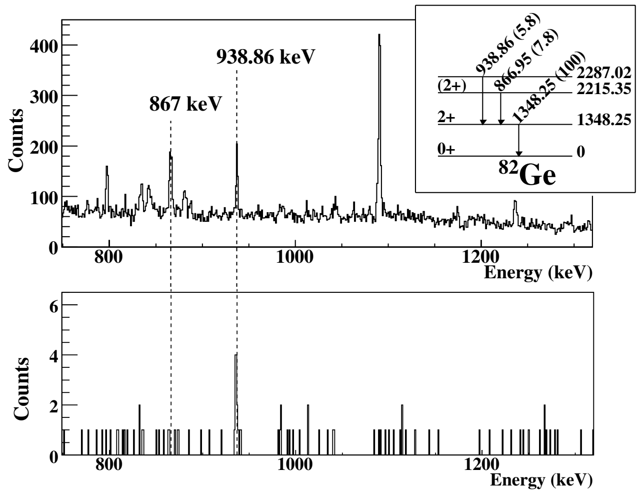

Fig. 7. Top: part of the γ spectrum $A = 83$. Bottom: same spectrum gated on the 1348 keV peak, only the γ-line at 938 keV is present. On the insert is shown a part of the level scheme of ^{82}Ge.

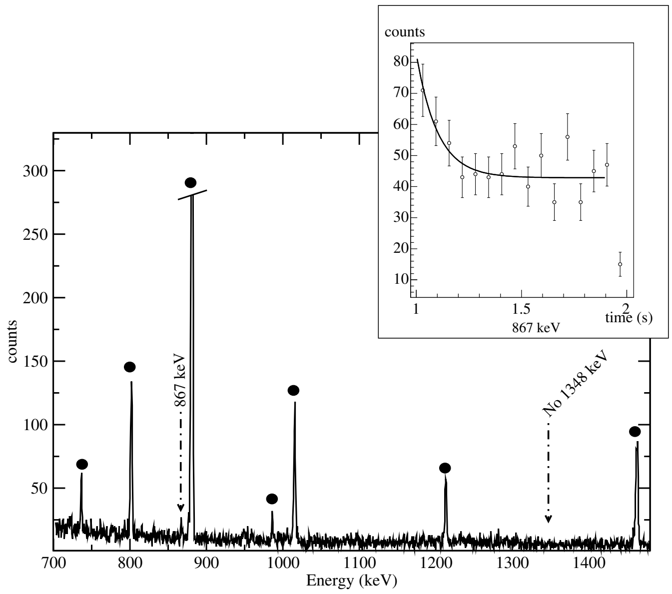

Fig. 8. Part of the β-gated spectrum recorded at $A = 84$. All the peaks marked by $\bullet$ belong to the decay of ^{84}Br. The presence of a 867 keV line together with the clear absence of the 1348 keV line is a strong argument in favor for assigning the 867 keV γ-ray as a transition in ^{83}Ge (see text). The time spectrum after background subtraction of that γ-ray is displayed in the insert. The fit gives a half-life value $T_{1/2} = 70 \pm 35$ ms.

ponents: one flat, corresponding to the ^{83}Se activity and one corresponding to a fast decay. The very low statistics for this peak makes a fit of the decaying part extremely difficult. However, a decay time higher than the value of the ^{83}Ga half-life is absolutely ruled out. This indicates clearly that part of the activity giving rise to the peak at 867.4 keV originates from the ^{83}Ga decay. In the β-decay scheme of ^{82}Ga to ^{82}Ge, the 867.46 keV transition is in coincidence with the 1348.07 keV transition [11]. In the

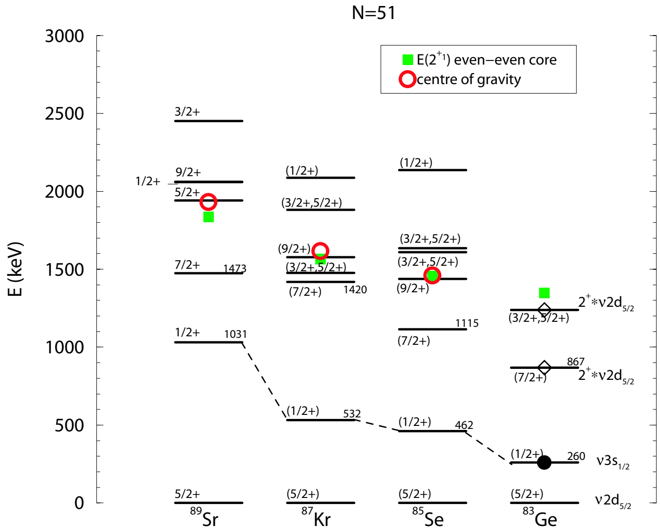

Fig. 9. Evolution of the energy of the proposed members of the $2_1^+ \otimes \nu 2d_{\frac{5}{2}}$ multiplet and evolution of the $\nu 3s_{\frac{1}{2}}$ quasi-particle state (connected with dashed lines) for the $N = 51$ isotonic chain. The state marked with $\bullet$ is from [4], those marked with $\diamond$ are from this work.

$A = 83$ γ-γ spectrum, if a gate is put on the 1348 keV peak, only a 938 keV line appears in coincidence whereas no peak is present at 867 keV (see fig. 7). As the intensity ($I = 13.4(8)$ [11] or $I = 7.8$ [12]) of the 867 keV transition in ^{82}Ge is larger than the one ($I = 5.8$) of the 938 keV, one can conclude that the 2287 keV level in ^{82}Ge is fed by the β-n decay of ^{83}Ga but not the 2215 keV level (see fig. 7). This indicates that the part of the 867 keV peak observed for $A = 83$ in our experiment corresponds to a transition which is not the one mentioned in the ^{82}Ge level scheme. Moreover, a 867 keV line is also observed in the γ spectrum corresponding to $A = 84$ as can be seen in fig. 8. In this case, it would be fed by the β-n decay of ^{84}Ga. The fact that no peak is present in this spectrum at 1348 keV provides another evidence for a 867 keV transition in ^{83}Ge. The fit of the time spectrum associated to this transition, as shown in the insert of fig. 8, gives a value of 70 ± 35 ms. This is in agreement with the half-life of ^{84}Ga which is $T_{1/2} = 85 \pm 10$ ms [10]. On the other hand, there is no evidence for a 1238 γ-line. As a conclusion, we attribute the 867.4 keV γ-line to a transition in ^{83}Ge.

From the ^{83}Ga decay study, two transitions are proposed to de-excite levels in ^{83}Ge. They allow us to place two excited levels (one at 867.4 keV and one at 1238.2 keV) in the ^{83}Ge level scheme for the first time. By this we assume that those levels are directly connected to the ground state. The existence of a very low-energy transition in coincidence with the 867 keV and 1238 keV is excluded above the value of our energy threshold (45 keV). Our two proposed levels are drawn in fig. 9 with the 260 keV level proposed in ref. [4] as $\frac{1}{2}^+$ having a neutron $3s_{\frac{1}{2}}$ quasi-particle nature. From considerations on systematics, the most reasonable hypothesis for the spin and parity of ^{83}Ga is $\frac{5}{2}^-$ due to its supposed $\pi 1f_{\frac{5}{2}}$ nature. Then, it is clear that such a $\frac{1}{2}^+$ state could not have been observed in our experiment since its direct feeding requires a first-forbidden unique ($\Delta J = 2$; $\Delta\pi = -$) transition characterized by a $\log ft$ value usually higher than 8.5. Such a transition was observed in the β-decay of the neighbour ^{85}As to feed the 461.9 keV level in ^{85}Se with $\log ft = 9.6$ from which it was deduced that this level was the $3s_{\frac{1}{2}}$ quasi-particle state [15]. Our statistics is obviously too scarce to allow the observation of an analogous transition.

At last and unfortunately, no new γ-line was found as a candidate to the $2^+ \to 0^+$ in ^{84}Ge because of low statistics.

3 Discussion

The simplest hypothesis concerning the nature of the two states which were observed in this experiment can be made by comparison with the neighbourless exotic $N = 51$ odd nuclei. Selected parts of their level schemes are shown in fig. 9 and compared to our proposed level scheme. The positive-parity levels in $^{89}_{38}Sr_{51}$ were soon understood as originating from the positive-parity neutron single-particle orbitals $2d_{\frac{5}{2}}$, $3s_{\frac{1}{2}}$, $2d_{\frac{3}{2}}$ and $1g_{\frac{7}{2}}$ situated above the $N = 50$ closed shell and their coupling to the 2^+_1 quadrupole first excited state of $^{88}Sr_{50}$ [16]. Such a structure is characteristic of the behaviour of a nucleus situated next to an effective strong shell closure. In particular, the coupling of the 51st neutron placed in the lowest-lying neutron orbital $2d_{\frac{5}{2}}$ to the 2^+_1 of the ^{88}Sr core gives rise to a multiplet of states $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{7}{2}^+$ and $\frac{9}{2}^+$. In a situation of weak coupling, the energy splitting of the multiplet is governed by a simple $6-j$ symbol $\begin{Bmatrix} J_c & j & J \\ j & J_c & k \end{Bmatrix}$ where J_c stands for the core angular momentum, j that for the odd particle and J is the total angular momentum [17]. Assuming as in [16] a quadrupole residual interaction between the core and the particle then we take $k = 2$ leading to a relative order $\frac{7}{2}^+$, $\frac{5}{2}^+$, a doublet $\frac{3}{2}^+/\frac{9}{2}^+$ and the $\frac{1}{2}^+$ pushed up. This is qualitatively what is observed in ^{89}Sr where the members of the $2^+ \otimes \nu 2d_{\frac{5}{2}}$ multiplet were the most securely identified. The discrepancy observed for the $\frac{3}{2}^+$ state is well understood as due to an interaction with the neutron single-particle state $\nu 2d_{\frac{3}{2}}$ [18]. Should $N = 50$ retain its magic property then such a weak-coupling structure should be found in the more exotic $N = 51$ odd isotones towards ^{78}Ni. An hypothetic assignation to the $2^+_1 \otimes \nu 2d_{\frac{5}{2}}$ multiplet can be inferred for states observed in $^{87}_{36}Kr_{51}$ from radioactivity [19], high-spin [20] and (d,p) direct reaction [21] experiments and in $^{85}_{34}Se_{51}$ from radioactivity [15] and high-spin [20] experiments. These results are summarized in fig. 9 where one sees that the order of the levels is qualitatively good with respect to what is expected in the framework of the weak-coupling scheme. In particular, the $\frac{7}{2}^+$ member appears to be systematically lower in energy than the other members. The centres of gravity of those multiplets are situated at less than

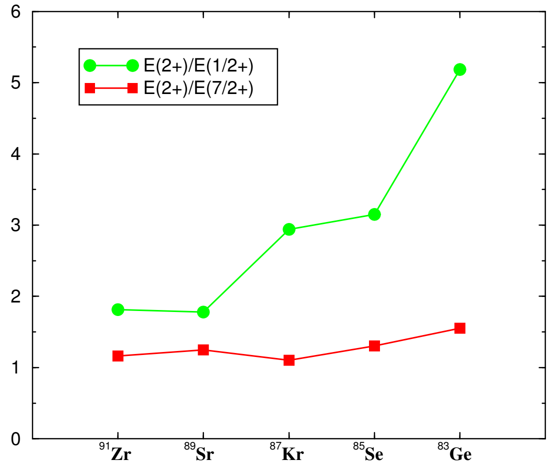

Fig. 10. Evolution of the ratios between the measured 2^+_1 energy of the semi-magic cores ^{90}Zr, ^{88}Sr, ^{86}Kr, ^{84}Se and ^{82}Ge and the measured energies of the first $\frac{1}{2}^+$ and $\frac{7}{2}^+$ of the corresponding odd $N = 51$ isotones.

100 keV from the observed 2^+_1 energy of their respective semi-magic cores (see fig. 9). For a reason which we do not understand well, the multiplet structure appears to be the purest in the most proton-deficient isotones. The case of ^{85}Se (provided our proposed identification for the states is correct) is particularly spectacular, the centre of gravity is situated at ≈ 1461 keV (the ambiguity on the identity of the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ states has no much influence on this value) while the 2^+_1 energy of ^{84}Se is 1454.42 keV. Then it is tempting to assign our two observed states of ^{83}Ge to the $2^+ \otimes \nu 2d_{\frac{5}{2}}$ multiplet. Assuming that the ground state of the mother nucleus ^{83}Ga has a $\pi 1f_{\frac{5}{2}}$ nature, then the lowest-lying states in ^{83}Ge which have, for most of them, a positive parity, are fed mainly through first-forbidden non-unique transitions ($\Delta J = 0, 1$; $\Delta\pi = -$). This leaves the possibility for the states that we observed to be $\frac{3}{2}^+$, $\frac{5}{2}^+$ or $\frac{7}{2}^+$. Considering the systematics, the state at 867 keV could well be the $\frac{7}{2}^+$ lowest-energy member of this multiplet. We suggest, then, that the second one at 1238 keV could be the $\frac{3}{2}^+$ or the $\frac{5}{2}^+$ member of the multiplet since its energy is very close to the one of the 2^+_1 state of ^{82}Ge (1348 keV). A further argument favouring our spin assignment is given by simply plotting the ratios between the energy of the 2^+_1 state in the even-even $N = 50$ cores and the energies of the first $\frac{1}{2}^+$ and $\frac{7}{2}^+$ states of the $N = 51$ isotones. It is clear from fig. 10 that while the evolution of the $E(2^+)/E(7/2^+)$ ratio has a smooth dependence in Z, the behaviour of the $E(2^+)/E(1/2^+)$ is much more erratic. The meaning of these curves should be straightforward: while the evolution of the energy of the $\frac{7}{2}^+$ state follows that of the centre of mass of the multiplet, the one of the $\frac{1}{2}^+$ state is not correlated, which confirms its non-belonging to the multiplet.

The main features in the structure of ^{83}Ge are then i) a decrease in energy of the members of the multiplet following naturally the decrease of the 2_1^+ state of the associated even-even core and ii) a decrease in energy of the first $\frac{1}{2}^+$ state which is *not* correlated to the previous one and should be understood as the fact that the two neutron orbitals $\nu 2d_{\frac{5}{2}}$ and $\nu 3s_{\frac{1}{2}}$ get closer for the $N = 51$ isotones as protons are removed. This last fact is of high interest and deserves a more detailed investigation in the future. There are at least two possible explanations: i) the splitting between $3s$ and $2d$ orbitals is diminishing, as if, when the nuclei become more neutron rich, the shape of the mean field would come back to that of the harmonic oscillator —this was already suggested a long time ago, *e.g.*, in ref. [22] but for nuclei much closer to the dripline than the one considered here; ii) a possible monopole drift: the monopole part of the residual proton-neutron interaction is attractive between the $1f_{\frac{5}{2}}$ proton orbital and the $2d_{\frac{5}{2}}$ neutron orbital, a decrease of the number of the $1f_{\frac{5}{2}}$ protons would result in a release of the $2d_{\frac{5}{2}}$ "upwards" leading to a closing relative to the $3s_{\frac{1}{2}}$, which is much less sensitive to such a residual interaction.

4 Conclusion

We have located two new excited states in the neutron-rich $^{83}_{32}Ge_{51}$ nucleus by studying the β-decay $^{83}Ga \rightarrow {}^{83}Ge$ using the PARRNe set-up installed at the Tandem accelerator of Orsay. Prior to this experiment no structural data were available for this nucleus which belongs to the region of the expected double-shell closure of ^{78}Ni. Recently, one excited state was observed in ^{83}Ge from the $^{2}H(^{82}Ge, p)^{83}Ge$ reaction [4]. The set of three excited levels represented in fig. 9 represents the most exotic set of data concerning the structure of the $N = 51$ isotones towards ^{78}Ni. By careful inspection of the known structure of the less exotic $N = 51$ isotones we propose a spin and parity $\frac{7}{2}^+$ for the level observed at 867 keV and $\frac{3}{2}^+$ or $\frac{5}{2}^+$ for the one at 1238 keV. Both states are interpreted as corresponding to members of the state multiplet originating from the coupling of the 2_1^+ state of the ^{82}Ge semi-magic core to the neutron single-particle state $2d_{\frac{5}{2}}$. Such structures were already identified in the less exotic $N = 51$ isotones for which an effective strong shell closure at $N = 50$ is averred. Then, we conclude that the shell closure at $N = 50$ still dominates the low-energy structure of this nucleus. Stated in another way, a weakening of the $N = 50$ shell effect, if it exists, has no noticeable effect on the low-energy structure of the nuclei having a Z as low as 32. It is important to underline that we made *no* explicite hypothesis concerning the nature of the 2_1^+ of ^{82}Ge except that it has a quadrupole nature. In particular, it is impossible from this study to rule out any contribution of proton core excitations across the $Z = 28$ gap in the 2_1^+ wave function of ^{82}Ge.

This paper reports on the first physics results obtained at the PARRNe facility. Soon, the new ALTO (Accélérateur linéaire auprès du Tandem d'Orsay) [23] facility at Orsay based on a 50 MeV electron linear accelerator as a driver to induce photofission, will provide a hundred times improved yields [24] and will offer the opportunity in a near future to undertake a detailed spectroscopy experimental program on those very neutron-rich nuclei in the vicinity of ^{78}Ni.

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