Shell structure evolution far from stability: experimental results

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Abstract. Shell structure evolution in nuclei situated at the extremes of neutron and proton excess are investigated using in-beam gamma spectroscopy techniques with radioactive beams at GANIL. A selection of results obtained very recently is presented: i) The reduced transition probabilities $B(E2;0^+ \rightarrow 2^+)$ of the neutron-rich $^{74}$Zn and $^{70}$Ni nuclei have been measured using Coulomb excitation at intermediate energy. An unexpected large proton core polarization has been found in $^{70}$Ni and interpreted as being due to the monopole interaction between the neutron $g_{9/2}$ and protons $f_{7/2}$ and $f_{5/2}$ spin-orbit partner orbitals. ii) Two proton knock-out reactions has been performed in order to study the most neutron-rich nuclei at the N=28 shell closure. Gamma rays spectra and momentum distribution have been obtained for $^{42}$Si and neighboring nuclei. Evidence has been found for a deformed structure at N=28 for Silicon, despite a relatively large Z=14 gap. iii) The in-beam gamma spectroscopy of $^{36}$Ca performed using neutron knock-out reactions revealed that N=16 is as large sub-shell closure as Z=16 in $^{36}$S. The uniquely large excitation energy difference of the first 2$^+$ state in these mirror nuclei turns out to be a consequence of their relatively pure neutron or proton 1p(d$_{3/2}$)-1h(s$_{1/2}$) nature.

1. Introduction
Shell structure predictions towards the neutron and proton drip-lines provide indispensable input to model the rapid neutron and proton capture for nucleosynthesis processes [1]. Furthermore, the evolution of shell structure far off the stability line has become a key topic of nuclear structure studies as it is intimately related to the monopole part of the residual nucleon-nucleon interaction and its origin in one-boson exchange potentials [2]. For instance, shell gap evolutions have been recently ascribed to the strongly attractive (repulsive) tensor force acting between protons and neutrons with opposite (similar) orientation of their intrinsic spin with respect to their angular momentum [3].

In the following, three recent examples of studies of shell structure evolution away from the valley of stability will be presented. These studies have been performed at GANIL and they are all based on in-beam gamma spectroscopy techniques used with reactions induced by secondary beams at intermediate energies. The three studies concern:

1. The evolution of the Z=28 shell effect in nuclei with neutron numbers beyond N=40.
2. The effectiveness of the N=28 shell effect in silicon nuclei.
3. The difference between the A=36 Ca isotope and its S mirror isotope.
The evolution of the Z=28 shell effect in nuclei with neutron numbers beyond N=40

Recently the Ni isotopes between the \( N = 28 \) and 50 shell closures have been the subject of extensive experimental and theoretical studies [6, 7, 8, 9, 10, 11, 12]. For \( 28 \leq N \leq 40 \) a parabola-like trend was found [10] in the B(E2;0\(^+\) \rightarrow 2\(^+\)) values which seemed to indicate a sub-shell closure at \( N = 40 \). On the other hand, the two-neutron separation energies exhibit a smooth decrease at \( N = 40 \) [8, 13] rather than a sharp drop. Beyond \( N = 40 \) and up to \( N = 48 \) a striking reduction in the 2\(^+\) excitation energies is observed for \(^{70}\)Ni(1259 keV) [14], \(^{72}\)Ni(1096 keV) [16], \(^{74}\)Ni(1028 keV) [17] and \(^{76}\)Ni(930 keV) [18] which could be due to increasing collectivity due to the neutron-proton tensor force. For that purpose, a direct measurement of the B(E2;0\(^+\) \rightarrow 2\(^+\)) value in the Ni and Zn isotopes have been carried out at GANIL, using Coulomb excitation at intermediate energies.

\(^{70}\)Zn\(_{44}\) and \(^{78}\)Ni\(_{42}\) were produced via reactions of a 60-A MeV \(^{76}\)Ge\(^{30+}\) beam with an average intensity of 1.2 eµA in a 500 µm-thick Be target. Two settings of the \textsc{Lise3} spectrometer [20] were used to select these isotopes. Mean rates of 2800 and 800 per second were obtained for the \(^{74}\)Zn and \(^{70}\)Ni isotopes, respectively. Another spectrometer setting was set to transmit the \( Q = 28^+ \) charge state of the primary beam at a rate of \( 10^4 \text{s}^{-1} \) in the same optical conditions. This aimed to confirm the known B(E2) value of \(^{76}\)Ge [19], which would strengthen confidence to our measurements for \(^{74}\)Zn and \(^{70}\)Ni. The nuclei produced were identified by means of their energy loss and time of flight measured in a “removable” Si detector placed downstream from the spectrometer at the entrance of the target chamber.

Two annular Si detectors were used in order to identify the deflected nuclei. The angular coverage of the silicon detector (from 1.5 to 6.1 degrees) in order to reduce as much as possible nuclear interaction with the target. A \(^{208}\)Pb target with 120 mg/cm\(^2\) thickness was located at the focal plane of \textsc{Lise3} and was surrounded by four segmented \textsc{Exogam} clover Ge detectors with a total photo-peak efficiency of \( \epsilon_\gamma = 5.0 \% \) at 1.3 MeV. The segmentation of the clover detectors allowed to reduce the Doppler broadening by 40\%, leading to an energy resolution (FWHM) of 75 keV at 1 MeV. The Doppler-corrected spectra for the 3 studied nuclei \(^{76}\)Ge, \(^{74}\)Zn and \(^{70}\)Ni are shown in Fig. 1. They exhibit photo-peaks associated with the Coulomb excitation of the 2\(^+\) energy level.

![Figure 1. Doppler-corrected γ-energy spectra obtained in the Ge clover detectors from the Coulomb excitation of the \(^{76}\)Ge, \(^{74}\)Zn and \(^{70}\)Ni isotopes.](image)

The measured total Coulomb excitation cross-section for \(^{76}\)Ge, was found to be 1.09(0.1)
b. By comparing the calculated cross-section to the experimental value, we find a B(E2) of 2720(250) e²fm⁴ for ⁷⁶Ge, which is in close agreement with the value of 2680(80) e²fm⁴ [19] obtained using a low-energy Coulomb excitation. Absolute B(E2) values are deduced in a similar manner for ⁷⁰Ni and ⁷⁴Zn and are found to be 860(170) e²fm⁴ and 1960(140) e²fm⁴, respectively.

The behavior of the B(E2; ⁰⁺ → ²⁺) values, as shown in Fig. 2, provides nuclear structure information on the existence of the N = 40 sub-shell closure and the evolution of collectivity in the Ni and Zn isotopic chains. In the Ni isotopic chain the πf₇/₂ orbital is separated from the remaining proton orbitals of the fp shell by the Z = 28 gap. In the Zn isotopic chain, valence protons in the πp₃/₂ and πf₅/₂ orbitals (above the Z = 28 gap) also add to polarization by proton-neutron interaction besides their direct contribution to the E2 strength. The large scale shell model (LSSM) reproduce the Ni and Zn B(E2) curves below mid-shell N = 34 within a fp model space [24, 25] while for N ≥ 34 the g₉/₂ neutron orbit is essential for a correct description [10, 25].

![Figure 2](image-url)  
**Figure 2.** Experimental B(E2; ⁰⁺ → ²⁺) values in units of e²fm⁴ in the Ni and Zn isotopic chains. Results on ⁷⁰Ni and ⁷⁴Zn nuclei are from the present study. Other values are taken from [19, 26]. The number of neutrons in the g₉/₂ orbital (written on top of each B(E2) curve) and the B(E2) values in Ni are calculated with the shell model of Ref. [10] (dashed line) or with the QRPA model of Ref. [12] (dotted line).

Beyond N = 40, the B(E2) values of the Zn isotopes continue to increase at least towards the g₉/₂ mid-shell (N ≃ 44). The results of the present work indicate also an increase of the B(E2) from ⁶⁸Ni to ⁷⁰Ni which is the result of the Z = 28 core polarization induced by the extra two neutron out the N = 40 shell closure. The amount of the proton core polarization of the ²⁺ state in ⁷⁰Ni was inferred through the evolution of the B(E2; J → J − 2) values along the ⁸⁺, ⁶⁺, ⁴⁺, ²⁺ components of the (νg₉/₂)² multiplet. In this approach the experimental B(E2; ⁸⁺ → ⁶⁺) = 19(4) [28], B(E2; ⁶⁺ → ⁴⁺) = 43(1) [29, 30] and the present B(E2; ²⁺ → ⁰⁺) = 172(34)e²fm⁴ are calculated as 17.3, 44.6 and 92.2 e²fm⁴ using an effective neutron charge eᵱ = 1.2 e. The good agreement for the high-spin states breaks down for the ²⁺ → ⁰⁺ transition which is a clear signature for an enhanced proton core polarization at low excitation energy.

The strong polarization in the Ni and Zn isotopes beyond N = 40 could be due to the attractive πf₅/₂ - νg₉/₂ monopole interaction [34, 35], ascribed to the tensor force of the in-medium nucleon-nucleon interaction [3]. This force also acts through the repulsive πf₇/₂ - νg₉/₂ interaction to reduce the apparent πf₅/₂ - πf₇/₂ spin-orbit splitting, provoking the crossing of the πf₅/₂ and the πp₃/₂ levels [34, 36]. Eventually the effective Z = 28 shell gap is decreased and enhanced ph excitations across the Z = 28 shell closure are generated. It is foreseen that this interaction will continue to weaken the Z = 28 gap with the complete filling of the νg₉/₂ at the doubly magic ⁷⁸Ni.  


3. The effectiveness of the N=28 shell effect in silicon nuclei

The aim of this study is to measure the energy of the first 2+ level in $^{42}$Si and to perform spectroscopy in the neighbors nuclei through in beam $\gamma$-spectroscopy using double fragmentation. This method has been already successfully applied to the spectroscopy of lighter nuclei around N=16 [38] whereas $^{44}$S was also studied but using a single fragmentation [39]. A first fragmentation in the SISSI device of a 4$\mu$A $^{48}$Ca beam at 60MeV/u produced a cocktail beam optimized for the production of nuclei around $^{44}$S. An average $^{44}$S production of 100 pps was obtained. These radioactive ions, selected by the alpha spectrometer were transported at the target point of the SPEG and identified event by event by their energy loss ($\Delta$E) in a Si detector located before the secondary target and their time-of-flight from the exit of the alpha spectrometer to the secondary target. The cocktail beam impinged the secondary Be target (185 mg/cm$^2$) and the nuclei produced in the second fragmentation were transmitted through the SPEG spectrometer with a $B_\rho$ value adjusted to maximize the collection of the $^{42}$Si. They were identified through their energy loss in an Ionization Chamber (IC) and their masse over charge (A/Q) ratio deduced from time-of-flight and $B_\rho$ measurement.

The secondary target was surrounded by the $4\pi$ gamma array ‘Chateau de Crystal’ consisting in 74 BaF$_2$ scintillators. The time resolution, around 1 nsec, allows to remove the neutrons and light charged particles emitted in the fragmentation process. The gamma efficiency and energy resolution have been checked with sources and were close to 50% and 10% at 1 MeV, respectively. The Doppler correction has been performed using the proper velocity of final fragments detected at the focal plan of SPEG. The spectrum extracted in the $^9$Be($^{44}$S,$^{42}$Si) reaction is displayed in figure 3.

![Figure 3. $\gamma$-ray spectrum obtained for the $^{42}$Si in the (2p) removal reactions.](image)

The $^{42}$Si spectrum exhibits a clear peak 765$\pm$20 keV with 23 counts which is attributed to the 2$^+\rightarrow0^+$ transition. The $^{40}$Si spectrum shows two peaks located at 624$\pm$10 MeV and 991$\pm$10 MeV. The $^{38}$Si spectrum exhibits a single peak located at 1081$\pm$8 MeV which agree with the known 2$^+\rightarrow0^+$ transition. We have display in figure 4 the energies of the 2$^+$ state in the Si isotopes, from N=18 to N=28. The case of the Ca isotopes is also displayed for comparison. For Si and Ca isotopes, the 2$^+$ excitation energy reaches a maximum at N=20 illustrating the N=20 spherical shell effect and the ‘magic’ character of the N=20. For the isotope $^{32}$Mg located in the island of inversion where intruder configurations dominate the ground state structure leading to a deformed nucleus, the 2$^+$ energy is known to drop at 885 keV. A similar drop is clearly observed for the $^{42}$Si at N=28. From this observation, we do conclude that $^{42}$Si is a collective nucleus which should be very deformed. From this similarity we are tempted to call $^{42}$Si a first nucleus of the isle of inversion around N=28. Shell model calculations and mean field
calculations so far also support a similar description of $^{42}$Si with an oblate deformation resulting from a reduction of the N=28 shell closure [41, 42, 43, 44].

![Graph](image)

**Figure 4.** Energies of the $2^+$ states measured in the Ca and Si isotopes from N=18 to N=28. The drop of the energy for the $^{42}$Si is a clear evidence of the absence of magicity in that nucleus.

4. The difference between the $^{A=36}$Ca isotope and its S mirror isotope

The so-called isle of inversion is currently understood [3] as due to the neutron-proton interaction between the $\nu d_{3/2}$ and the $\pi d_{5/2}$. This n-p interaction between the l=2 spin-orbit partners is also responsible of the large excitation energy of the $2^+$ states in $^{34}$Si and $^{36}$S. The aim of the study of $^{36}$Ca is primary to check if this interaction acts similarly in the $^{36}$S mirror nucleus. For that purpose an experiment was performed at GANIL in order to measure the excitation energy of the first $2^+$ state in $^{36}$Ca and to make a comparison with the mirror nucleus, $^{36}$S.

For this experiment the same technique of double step fragmentation (see previous section) [38] was used. From a $^{40}$Ca beam at around 95 $A\times$MeV, the secondary $^{37}$Ca beam was produced. The $^{37}$Ca beam was guided to the SPEG experimental area. There, it first passed through a detector for time-of-flight measurements. Then it impinged on the secondary target, a $^9$Be foil of 1072 $\mu$m thickness at an energy of around 60 $A\times$MeV. The identification of produced fragments after the target was done using the SPEG spectrometer as it was explained in the previous section. In order to measure the $\gamma$-ray energies, the same array of 74 BaF$_2$ scintillators was used. The doppler correction for the spectra was done assuming that the nucleon removal takes place in the middle of the secondary target. The spectra obtained for the two most proton rich nuclei $^{36}$Ca and $^{28}$S are shown in fig. 5. Using gaussian fits for the peaks, the energy of the $2^+$ state in $^{36}$Ca has been determined to be $E(2^+) = 3025(30)$ keV. The energy of the first $2^+$ state in $^{28}$S has been also measured for the first time to be $E(2^+) = 1525(30)$ keV. The result obtained for $^{36}$Ca indicates that the N=16 neutron gap in Ca is as large as the Z=16 proton gap in $^{36}$S and that the tensor monopole interaction between the neutron and proton $d$ orbits acts similarly when a proton and neutrons are exchanged.

When compared to the mirror nucleus $^{36}$S, one can see in figure 6, a relatively large excitation energy difference for the first $2^+$ states of $^{36}$Ca. This implies an MED (Mirror Energy Difference) of 266(30) keV which is one of the largest value observed so far in $T = 2$ mirror nuclei.
Figure 5. $\gamma$-ray spectra obtained for the proton-rich (a) $^{36}$Ca and (b) $^{28}$S isotopes

This is understood in a simple way as due to the combination of different effects. Because of parity non-conservation, 1p-1h proton excitations across $Z=20$ and 1p-1h neutron excitations across $N=20$ do not contribute to the first $2^+$ state in respectively $^{36}$Ca and $^{36}$S. In addition, because of the large $N=16$ and $Z=16$ gaps, the $2^+$ state in these two nuclei is therefore considered to be a relatively pure 1p($s_{1/2}$)-1h($d_{3/2}$) neutron or proton excitation. Consequently the difference in coulomb energy between the valence $s$ and $d$ orbits generates a large MED between these mirror nuclei.
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