Interprétation des B(E2)↑ pour des noyaux ayant N, Z ~ 40.
II. Fermeture de sous-couche et interaction p-n

Interpretation of the B(E2)↑ in N, Z~40 nuclei part II : Sub-shell closure and p-n interaction

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Résumé *: La comparaison des courbes expérimentales de B(E2: $0^+_1 \rightarrow 2^+_1$) avec celles calculées dans le cadre d'une approximation de la séniorité généralisée permet de valider, pour les isotopes de Ni, Zn, Ge et Se, l'hypothèse une fermeture de sous-couche neutrons à N=38 et non à 40 où elle est généralement supposée. Cette étude met aussi en évidence un phénomène s'inscrivant dans la phénoménologie de celui observé dans des isotopes de Mo, Ru et Zr, et interprété par P. Federman et S. Pittel comme une manifestation de l'interaction p-n.*

Introduction

On the basis of an approximation to the generalized seniority we have obtained (see previous contribution) several sets of theoretical B(E2)↑ curves, according to the proton and neutron valence spaces (VS). We confront here our results with the experimental curves in order to validate our hypothesis of a N=38 neutron sub-shell closure. This confrontation leads to interpret the B(E2)↑ evolution in the whole N~40 region as due to a p-n interaction effect.

I – From Ni to Se isotopes

I.a – Normalization

The single-j shell $f_{7/2}$ is involved, at sphericity, by particle number ranging between 20 and 28. The $\nu f_{7/2}$ and the $\pi f_{7/2}$ single-j shells are then, without any ambiguity, the only possible valence spaces in the $^{40\text{-}48}_{20}Ca$ isotopes. We have then used their experimental B(E2)↑ values (empty squares in figure 1) to normalize our calculations. We have deduced from their theoretical curve (cyan dotted line) that 10 units in calculations correspond to 1000 e^2fm^4 (see figure 1).

I.b – Case of the Ni and Zn isotopes

Figure 1 shows, in addition to the experimental Ca B(E2)↑ curve, the Ni and the Zn ones. Are also plotted two sets of calculated curves: in solid green lines the curves obtained with small VS for both proton and neutron; in dashed blue lines those obtained with large proton and small neutron valence spaces. The theoretical curves are labelled with the Z of the

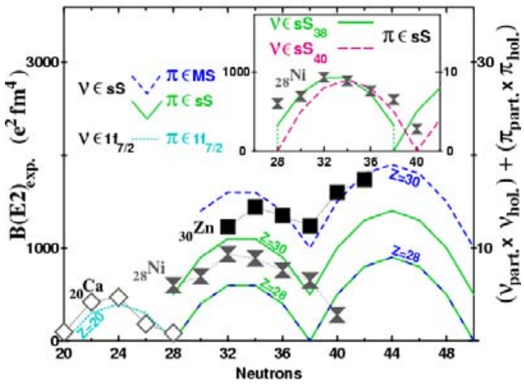

Figure 1: From [1] experimental Ca, Ni and Zn B(E2)↑ values (symbols) and calculated ones (for Z=20, 28 and 30) with different neutron and proton VS size.

calculations. The Z=28 green and blue curves are of course merged, the proton contribution being null when Z=28, whatever the proton valence space size is. Figure 1 makes evident a Ni experimental curve lying higher than expected, nearer the green Z=30 curve than the Z=28 one. In particular, the ^{56}Ni (doubly magic) B(E2)↑

value should be null, like it is for the ^{40,48}Ca. This is not the case and nearly all the Ni values have a greater amplitude than the Ca ones. Only the ^{68}Ni$_{40}$ B(E2)↑ value, considered as abnormally low in [2] (and induced the idea of a N=40 sub-shell closure for Ni), is in agreement with the seniority calculations as well as the Ca experimental values. For N between 28 and 38, the Ni B(E2)↑ values are all increased, as if there were two more protons in a Ni core. Moreover, one can see in the inset of figure 1 the perfect agreement — along the four central points, — of the Ni experimental profile and the one calculated with a N=38 neutron sub-shell closure (s.S 38) which has been arbitrarily shifted up to underline the agreement and the constancy of the enhancement. This implies a proton cause : when due to neutrons, it should evolve with N. The slight disagreements at N=28 and N=38 are the only variations which can be related to a neutron effect [3]. Concerning our hypothesis of a N=38 sub-shell closure, the curve obtained with a N=40 subshell closure (s.S$_{40}$) exhibits indeed a profile which does not allow to reach the quality of the previous agreement (with s.S$_{38}$). It is worth noting that the assumption of a N=40 sub-shell closure gives a null theoretical ^{68}Ni$_{40}$ B(E2)↑ value, lower than the experimental one. The hindering of the quadrupole excitation, assumed within a N=40 sub-shell closure hypothesis in [4], goes then in the wrong direction to explain a ^{68}Ni data which is lower and not higher than expected. The decrease of the B(E2)↑ in the ^{66,68}Ni is really misleading, it dissimulates a N=38 sub-shell closure and a proton contribution enhancement for N below 40.

In the Zn isotopes the agreement is emphazised by the experimental minimum at N=38. As in the Ni isotopes, the proton contribution is modified for some N values. The Zn experimental curve evolves from near the green Z=30 calculated curve (small proton and neutron VS) for light isotopes to the blue one (large proton VS) for N between 34 and 42. The change of the proton VS between the light Zn isotopes and the heavy ones can be interpreted as the vanishing of the proton subshell closure.

I.b – Case of the Ge and Se isotopes

The proton valence space also evolves between the light and the heavy Ge isotopes. The Ge B(E2)↑ curve (see figure 2) starts

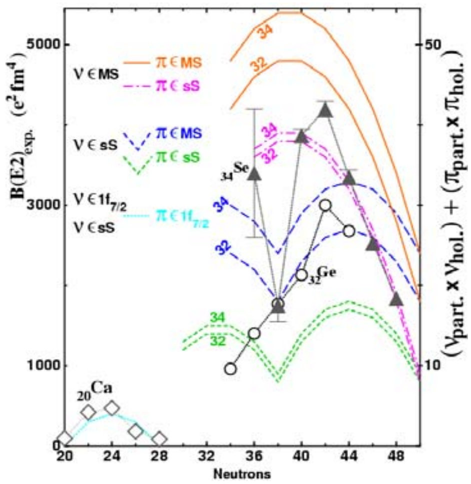

Figure 2: From [1] experimental Ca, Ge and Se B(E2)↑ curves (symbols) and calculated ones with different proton and neutron valence spaces.

below the green Z=32 curve calculated with small proton and neutron VS (the agreement is reached at N=36), and joins from N=38 the blue Z=32 curve calculated with a large proton and a small neutron VS . One can note the experimental value at N=42, at midpoint of the blue Z=32 and the magenta (large neutron and small proton VS) curves which can indicate an inversion of the proton and neutron VS size at this point. Such changes are seen also in the Se B(E2)↑ curve, its values mainly correspond to those obtained with large neutron and small proton VS (magenta), but lie for N=38 at mid point of the blue and green Z=34 curves (i.e. beetween small and large proton VS) and for N=42 on the way to the orange curve, above the magenta one (i.e beetween small and large proton VS).

The Ge and Se appears to lie in a transitional region, where alternatively the proton and the neutron have a large valence space, but never together. One can note that the Ge and Se B(E2)↑ curves have a maximum and are deformed both at N=42, as pulled up to the higher values of the next (Z=32 or 34) calcu-lated curves.

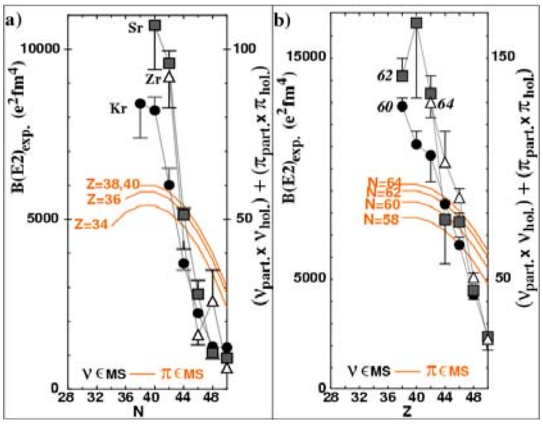

Figure 3: a) From [1] Kr, Sr and Zr experimental B(E2)↑curves (symbols) and calculated ones with the]28,50] major shell for proton and neutron VS. b) N=58-64 experimental B(E2)↑curves (from [1], symbols) and calculated ones with the]50,82] major shell for proton VS and the]28,50] one for neutron VS.

From Ni up to Se the distortion of the experimental curves is continuously amplified by Z. All this calls to mind a proton-neutron interaction effect which can be strong enough [5, 6, 7] to reduce (and even eradicate) the Z=40 subshell gap in the heavy (N>60) Zr, Mo and Ru isotopes and promote protons and neutrons into high orbitals. The great similarity between the isotopic $_{36}$Kr, $_{38}$Sr and $_{40}$Zr B(E2)↑ curves of figure 6a) and those of the isotonic chains of figure 6b) – in which F. Federman and S. Pittel saw a p-n effect— leads us to involve the pn interaction for the B(E2)↑evolution in the N, Z ~ 40 region.

II - Anchors of our interpretation of the Ni and Zn B(E2)↑ difference

Our interpretation of the N ~ 40 B(E2)↑ curves is built firstly on a neutron subshell closure at N=38. A spacing at N=38 has been obtained, even at sphericity, in [8] between the $1f_{5/2}$ and $2p_{1/2}$ orbitals, as shown in the insets of figure 4. One can note that such a single-particle level spectrum offers in addition the possibility for a second energy spacing, at N=40.

We also involve in our interpretation the p-n interaction. It is worth noting that the $1f_{7/2}$ (below 28), the $1f_{5/2}$ (below 38) and the $1g_{9/2}$ (above 40) orbitals and can allow the pn

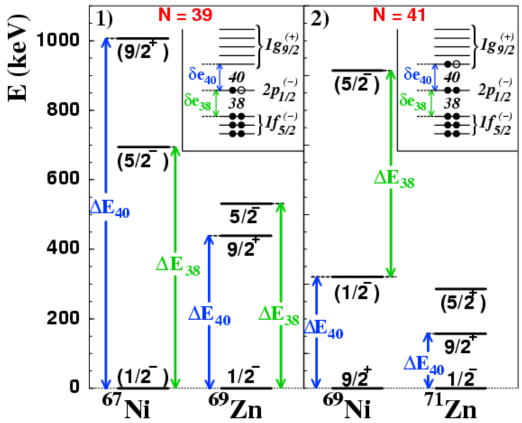

Figure 4: Experimental excitation energies from [11] of the first three states in 1) $^{67}Ni_{39}$ and $^{69}Zn_{39}$, 2) $^{69}Ni_{41}$ and $^{71}Zn_{41}$. Insets: neutron single-particle level order from [8] and schematic ground states neutron occupation for the Ni and Zn isotopes with 1) N=39 and 2) N=41.

interaction to start in these nuclei [2], since allowing the necessary large overlap between the proton and neutron orbitals [9]. The N=40 spacing, if existing for the Ni isotopes only, could complete our interpretation of the difference in the B(E2)↑ curve for ^{66,68}Ni and ^{68,72}Zn. Added to the Z=28 gap, two consecutive spacings between $\nu 1f_{5/2}$ and $\nu 1g_{9/2}$ would represent an insuperable obstacle for the pn interaction, unable to act after N=38 in the Ni isotopes as it does in the Zn isotopes.

A first sign of the presence of a N=38 neutron subshell closure followed by a N=40 energy spacing in the Ni isotopes is given by the ^{68}Ni B(E2)↑ value which lies exactly between the two curves of the figure 1 inset as an intermediate or transitional point would. Moreover, recent lifetime measurements [10] has given lower $^{58-64}$Ni B(E2)↑ values than in [1] with which however they are incompatibles. But, when confirmed, such values — in agreement with a N=38 sub-shell closure (without requiring the extra proton contribution) — added to the values at N=28 and 38, that are in agreement with a N=40 subshell closure, would extend the transitional behavior to the whole Ni isotopic series.

The most convincing sign of the presence of a N=38 neutron subshell closure in both the Ni and Zn isotopes, followed by, in the Ni isotopes only, a N=40 energy spacing, is given by the energies of the two first excited states in the Ni and Zn odd isotopes with N=39 (drawn in figure 4a) and 41 (figure 4b). We have called in figure 4 ΔE_{38} and ΔE_{40} the excitation energy differences related respectively to δe_{38}, the spacing at N=38 between $1f_{5/2}$ and $2p_{1/2}$, and to δe_{40}, the spacing at N=40 between $2p_{1/2}$ and $1g_{9/2}$. One can see on figure 4 that δe_{38} and δe_{40} are both present in the odd-Ni isotopes: ΔE_{38} and ΔE_{40} are so large that the ^{67,69}Ni excitation spectra, with only 2 excited states along 1MeV (900keV for ^{69}Ni) have twice smaller density than in their corresponding odd Zn isotopes. Indeed, in ^{69}Zn ΔE_{38} is 100keV smaller and ΔE_{40} is twice smaller than in ^{67}Ni. In ^{71}Zn the $1g_{9/2}$ orbital is so close to $2p_{1/2}$ that $1f_{5/2}$ (too far) is not anymore involved in the first excited states; ΔE_{38} can not anymore be deduced.

III - Predictions for ^{70}Ni and ^{74}Zn

According to the presence of a spacing at N=40, the ^{70}Ni B(E2)↑ value should lie around 400e^{2}fm^4, following the sS_{40} curve of the figure 4 inset. On another hand, in ^{70}Ni two neutrons are occupying $\nu 1g_{9/2}$. The pn interaction could be restarted and eradicate the N=40 subshell closure, making from the N=38 subshell closure the lower limit of the ^{70}Ni neutron valence space. In that case, the ^{70}Ni B(E2)↑ value should lie around 800e^{2}fm^4, following the sS_{38} curve of the inset, or even above it if the proton promotion is also restarted. Our predictions for the ^{70}Ni B(E2)↑ was then that it could take two values according the between two possibilities.
For ^{74}Zn the prediction was more simple. Indeed, in $^{66\text{-}72}$Zn the pn interaction is already found strong enough to suppress the Z=40 proton subshell closure. The B(E2)↑ value in the heavier even Zn isotopes is expected to increase up to N=44 then to decrease, following the blue Z=30 curve of figure 1.
These predictions were very recently validated by the experimental, as shown in figure 5. This definitively establishes the N=38 subshell closure in the Ni isotopes.

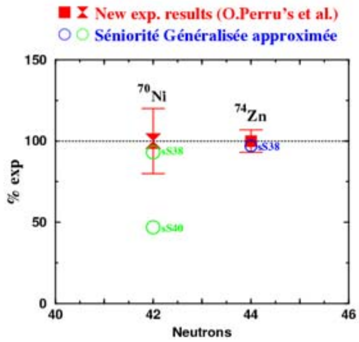

Figure 5: In percentage of the recent results (thesis of O. Perru) in ^{70}Ni and ^{74}Zn (red symbols), our predicted theoretical values.

Conclusions

The Ni and Zn B(E2)↑ curves are analyzed using calculations performed within the seniority scheme. They are shown to follow a N=38 subshell closure behavior with deviations interpreted as coming from a proton contribution enlarged by the pn interaction. The low B(E2)↑ value in ^{68}Ni is explained by the Z=28 gap which, added to the N=38 and a N=40 subshell spacings, prevents the pn interaction to promote protons over the Z=28 gap (as it does in $^{56\text{-}66}$Ni) together with (as in $^{64\text{-}72}$Zn) neutrons over the N=40 energy spacing. The predictions we have made from this scenario were recently confirmed, validating the Ni and Zn subshell structure we have described here.

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