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On the Nature of the Intruder Bands in the Neutron-Rich Silver Nuclei

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Abstract. Through the entire silver isotopic chain, from ^{97}Ag to ^{125}Ag, in each of these nuclei, a strongly pronounced sequence of positive-parity states is observed. At the neutron deficient edge of the isotopic chain, close to doubly magic ^{100}Sn, the spectrum is well understood in the framework of the single-j^{-3} coupling scheme. However, silver spectra start to look bizarre when few neutrons are being added. This has been attributed to an unreasonably strong $Q \cdot Q$ residual interaction. Alternatively, the excited states in the medium-mass silver nuclei were explained by a number of interacting particle-core models. In this study, a systematics of the available experimental data is presented. It presents an evidence for a strong correlation between the Ag excited states and the underlying Cd core, supporting the collective nature of the low-lying positive-parity states, superimposed on $\pi g_{9/2}^{-3}$ excitations.

1 Introduction

The neutron-rich silver nuclei represent an interesting laboratory for testing of different theoretical models. Being three proton holes away from the magic thin nuclei, they present an excellent ground for testing of the Nuclear Shell model [1]. Indeed, in the past, the $j-1$ anomaly has been initially interpreted as a manifestation of the $\pi g_{9/2}^{-3}$ coupling scheme [2], which is a straight forward application of the spherical shell model. However, neither the experimental (j)-$(j-1)$ multiplet splitting nor the electromagnetic transition strengths have been effectively reproduced within this approach suggesting that collective degrees of freedom might also play a role at the low energies. Indeed, the neutron (50,82) mid-shell silver nuclei have a relatively large number of valence particles, which is a prerequisite for development of quadrupole deformation. Isotopes of the neighbouring Cd and Pd elements with similar number of valence bosons [3], for example, are known to exhibit a more vibration-like or even transitional structure.

In search for collective effects in the low-energy part of the silver spectra, a number of model calculations have been performed in the past, with Axially symmetric Rotor-plus-Particle Model [4], Traixial-Rotor-plus-Particle Model, [5], and Three-Valence-Particle-Cluster-plus-Vibrational Core model [6] being only few of them. Recently, the structure of neutron mid-shell $^{111,113}\mathrm{Ag}_{64,66}$ nuclei was analysed within the IBFM-1 model [7].

In general, these collective models give a better description of the low-lying positive-parity excited states, supporting the idea of enhanced collectivity in the medium-mass silver nuclei.

2 Silver Isotopic Chain

As discussed above, the structure of the low-lying excited states in the odd-A medium-mass silver nuclei can be understand in the framework of particle-core coupling models. Depending on the particular realization, the palladium (particle-core coupling) or the cadmium nuclei (hole-core coupling) can be used as cores. These nuclei share some common features. They are slightly deformed, but even the neutron mid-shell Pd and Cd isotopes [8] do not have the typical "good" rotors behavior. Indeed, the neutron mid-shell cadmium nuclei are among the best examples of harmonic vibrators [9], while the palladium isotopes develop significant γ instability [10, 11].

In Ag isotopic chain, the collective effects seems to emerge already at low energies. As shown in Figure 1, the $7/2^+$ state appears above $9/2^+$ in the beginning of the (50,82) neutron shell, as it can be expected from the j^{-3} seniority scheme [13]. In the mass region, close to the ^{100}Sn, the core E_{2^+} energy is approximately 1.4 MeV. When approaching the neutron mid shell, however the cores energy E_2^+ decreases to less than 500 keV. As a result, the $9/2^+$ and $7/2^+$ states swap their places, and the $7/2^+$ becomes the lowest-lying positive parity state. There, the seniority scheme brakes due to a strong $Q \cdot Q$ residual

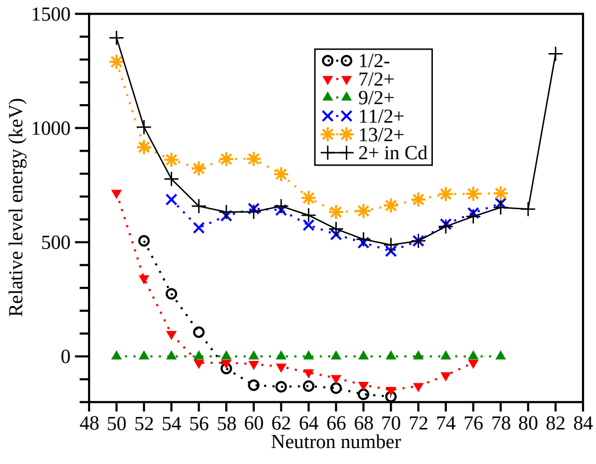

Figure 1. Yrast states in Ag nuclei, as a function of the neutron number, are compared to the E_{2^+} in the even-even Cd isotones. All Ag level energies are relative to the $9/2^+$ level. The figure is reproduced from [1], by including new data from [12] and [7].

Table 1. Level energies, in keV, in Z=47 (Ag) isotopes, compared to the even-even Z=48 (Cd) and Z=46 (Pd) nuclei . With few exceptions, all level energies are taken from ref. [17]. The level energies of ^{97}Ag are from [14], those of ^{117}Ag – are from [15]. The level energies for ^{119}Ag are taken from [12] and [16]. ^{121}Ag data is from [12].

	Ag	Ag	Ag	Cd	Pd
N	$E_{9/2^+}$	$E_{7/2^+}$	ΔE	E_{2^+}	E_{2^+}
50	0	716	716	1395	1415
52	0	343	343	1004	863
54	0	98	98	776	666
56	28	0	-28	658	556
58	53	25	-28	632	556
60	126	93	-33	633	512
62	133	88	-45	658	434
64	130	60	-70	618	374
66	139	43	-95	558	349
68	167	41	-126	513	333
70	176	29	-147	488	340
72	129+x	0+x	-129	506	379
74	83	0	-83	569	438
76	27	0	-27	613	590

interaction [2, 6]. In this mass region, the $j-1$ anomaly was not reproduced by single-j shell, nor by a large scale shell model calculations [1], where the modern jj45pna interaction was used. However, empirical j^{-3} calculations still describe, to certain extent, the structure of the silver spectra.

However, some correlations between the Ag spectra and the even-even cadmium cores have been observed [1]. Details on the low-energy positive-parity states in the odd-mass silver isotopes are presented in Table 1. The $7/2^+$ and $9/2^+$ level energies are listed for all presently known silver isotopes. The ΔE energy gap between $7/2^+$ and $9/2^+$ is also calculated and shown in Figure 2 as a function E_2^+ in the even-even Pd and Cd isotones. Indeed, the data clearly shows that there is a correlation between the $(7/2^+, 9/2^+)$ doublet splitting and the core's 2^+ level energy. This correlation is well pronounced when the cadmium E(2^+) is taken as a core. When the palladium nuclei are considered, the overall trend is the same, except for the A$\sim$110 region where enhanced γ instability is present [11].

More about particle-core coupling scheme can be learned from the electromagnetic transition rates for which the precise knowledge of excited states lifetimes, gamma-decay mixing and branching ratios, as well as electron conversion coefficients, is essential. However, little lifetime data is available for the silver nuclei. In fact, there are lifetimes for few states in $^{105-111}$Ag. The $9/2^+ \to 7/2^+$ mixing ratio is known only for the respective transition in ^{105,107}Ag. Thus, based on these scarce data, the following observations can be made. In general,

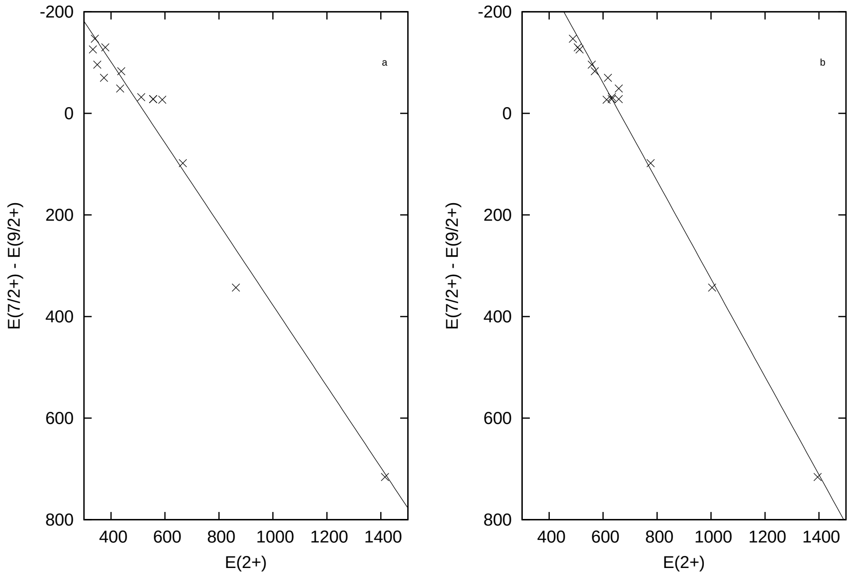

Figure 2. $9/2^+ - 7/2^+$ level energy gap in Ag as a function of E(2^+) in the neighbouring palladium (left) and cadmium (right) nuclei.

the $M1$ component is hindered by two orders of magnitude with respect to the Weisskopf estimates, but the $E2$ component in these nuclei suggests existence of strong collective component. There are two main mechanisms that can generate hindered $M1$ transitions - transitions between $\Delta l = 2$ states, or l-forbidden transitions, and transitions within a j^{-3} seniority multiplet. Extensive lifetime data is needed in order to disentangle between the two scenarios.

To further test the particle-core coupling concept, $R = 1/(T_{1/2}E^5)$ ratio was calculated for the $9/2^+ \rightarrow 7/2^+$ transitions in the silver nuclei, where data is available, and compared to the $2^+ \rightarrow 0^+$ in the Cd cores. In the weak coupling limit, a strong correlation between the transitions in the odd-mass and the even-mass core nuclei is expected to emerge. The results are presented in Table 2. In general, the order of magnitude is the same for all nuclei presented in the table. However, there are fine effects which might be related to the number of valence particles. Indeed, the cadmium isotopes do not show such a dependence, while R for the palladium nuclei smoothly increases with the neutron number when approaching the (50,82) mid shell. This effect seems to be stronger pronounced in the silver isotopes, where the odd- $g_{9/2}$ proton(s) enhance the core polarization. Nevertheless, given that the magnitude of the ratio in the silver isotopes is similar to that of the neighbouring even-even nuclei, we may conclude that the $7/2^+$ and $9/2^+$ states have significant contribution of 0^+ and $2+$ core states, respectively.

Table 2. $R = 1/(T_{1/2}E^5)$ calculated for ^{105,107}Ag and the neighbouring cadmium and palladium nuclei. Here, $T_{1/2}$ is the partial half-life in picoseconds and the gamma transition energy E is in MeV.

neutrons	56	57	58	59	60	61	62	63	64
Cd	1.3		1.4		1.2		1.5		
Ag			2.7		4.2				
Pd			1.9		2.4		2.8		3.11

3 N=47 Nuclei

It is interesting to note that the excitation pattern observed in the N=47 isotonic nuclei has some similarities with the silver spectra. The precise $9/2^+$ and $7/2^+$ level energies are given in Table 3 and compared to the 2^+ level energies of the N=48 nuclei. The $\Delta E = E(7/2^+) - E(9/2^+)$ level energy difference is plotted in Figure 3 as a function of the $E(2^+)$ N=48 core energy. At low energies, their level schemes are dominated by positive-parity states arising from $\nu g_{9/2}$ intruder orbit and, when the number of neutrons is close to the neutron sub-shell closure at N=40, the $9/2^+$ level is the lowest-lying positive-parity state. For those nuclei, the $7/2^+$ state appears above $9/2^+$. Deeper in the proton shell,

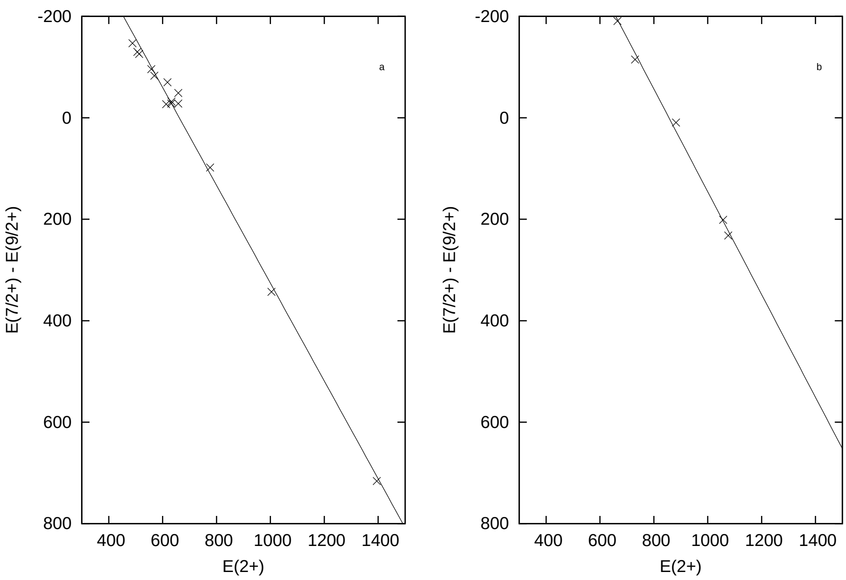

Figure 3. Evolution of the $E(7/2^+) - E(9/2^+)$ energy gap as a function of the core $E(2^+)$ in the Z=47 and N=47 chains.

when the deformation start to emerge, the two levels swap their places, as it is in the Z=47 isotopic chain.

Table 3. Level energies in the N=47 isotopes, compared to the neigbouring even-even isotones

nucleus	$E(9/2^+)$	$E(7/2^+)$	ΔE	core	$E(2^+)$
$^{87}_{40}$Zr$_{47}$	0	201	201	$^{88}_{40}$Zr$_{48}$	1057
$^{85}_{38}$Sr$_{47}$	0	232	232	$^{86}_{38}$Sr$_{48}$	1076
$^{83}_{36}$Kr$_{47}$	0	9.4	9.4	$^{84}_{36}$Kr$_{48}$	882
$^{81}_{34}$Se$_{47}$	294	103	-191	$^{82}_{34}$Se$_{48}$	665
$^{79}_{32}$Ge$_{47}$	391	186	-205	$^{80}_{32}$Ge$_{48}$	659
$^{77}_{30}$Zn$_{47}$	115	0	-115	$^{78}_{30}$Zn$_{48}$	730

4 Conclusion

In the last half-a-century, the silver isotopes have been a subject of extensive studies. They are close to the magic thin nuclei where shell model effects are expected to dominate. Indeed, the single-orbit j^{-3} seniority concept works well at the edges of the isotopic chain. Some features of this coupling scheme seems to survive towards the middle of the isotopic chain. On the other side, there is a clear correlations between the low-lying part of the Ag energy spectra and the even-even core nuclei, which is typical for the particle-core coupling mechanisms. Hence, it seems that in the silver nuclei two completely orthogonal regimes coexists in a very unconventional way.

Acknowledgements

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