Scientific synthetic report 2011 - 2013 - project IDEI-0153: 'ADVANCED STUDIES ON STRUCTURE AND DYNAMICS OF EXOTIC NUCLEI'

I. Coexistence phenomena in exotic neutron-rich A~100 nuclei

The structure of neutron-rich nuclei in the A~100 mass region relevant for the r-process as well as reactor decay heat manifests drastic changes in some isotopic chains and often sudden variations of particular nuclear properties have been identified.

Neutron-rich Sr and Zr nuclei indicate rapid transition from spherical to deformed shape with a possible identification of the sudden onset of quadrupole deformation increasing the neutron number from N = 58 to N = 60. The structure and dynamics of ^{96}Sr and ^{98}Zr have been investigated in the frame of the *complex* Excited Vampir (EXVAM) beyond-mean-field approach using a large model space and a realistic effective two-body interaction.

Intense studies based on *complex* MONSTER (VAMPIR) model have been dedicated to the renormalisation of the effective two-body interaction in a large model space, including above the ^{40}Ca core $1p_{1/2}$, $1p_{3/2}$, $0f_{5/2}$, $0f_{7/2}$, $2s_{1/2}$, $1d_{3/2}$, $1d_{5/2}$, $0g_{7/2}$, $0g_{9/2}$, and $0h_{11/2}$ oscillator orbits for both protons and neutrons in the valence space.

The effective two-body interaction is constructed from a nuclear matter G matrix based on the Bonn A potential. In order to enhance the pairing properties the G matrix was modified by three short-range Gaussians in the T=1 and T=0 channel. In addition the isoscalar interaction was modified by monopole shifts for all T=0 matrix elements of the form $\langle 0g_{9/2}0f;IT=0|\hat{G}|0g_{9/2}0f;IT=0\rangle$involving protons and neutrons occupying the $0f_{5/2}$ and the $0f_{7/2}$ orbitals. The Coulomb interaction between the valence protons was added [1].

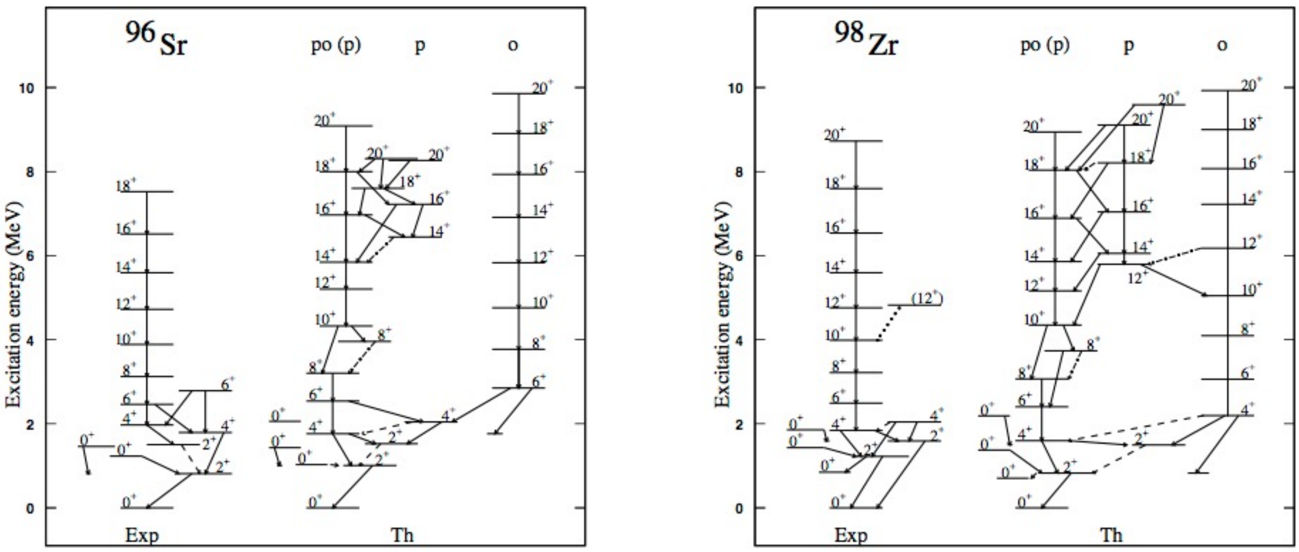

Fig.1 Theoretical EXVAM spectrum of ^{96}Sr and ^{98}Zr compared to experimental data.

We calculated the lowest positive-parity states up to spin 20^+ in ^{96}Sr and ^{98}Zr [1]. For each nucleus the calculated states have been organized in bands based on the B(E2;ΔI = 2) values connecting them. The theoretical lowest bands of ^{96}Sr and ^{98}Zr are compared to the experimental data in Figure 1.

Table I: Structure of wave functions for 0^+ states

	^{96}Sr			^{98}Zr		
I[$\hbar$]	spherical	prolate	oblate	spherical	prolate	oblate
0_1^+	36%	20%	44%	12%	43%	45%
0_2^+	57%	18%	25%	84%	12%	4%
0_3^+		69%	31%	1%	57%	42%
0_4^+	4%	6%	90%	2%	10%	88%

The states building the *po*(*p*)-band in each nucleus are characterised by strong prolate-oblate mixing at low spins and variable prolate mixing at intermediate and high spins. At intermediate and high spins prolate and oblate bands coexist in both nuclei. A particular situation is found for the 0^+ states: the lowest projected EXVAM configuration is spherical in both nuclei. In ^{96}Sr the second 0^+

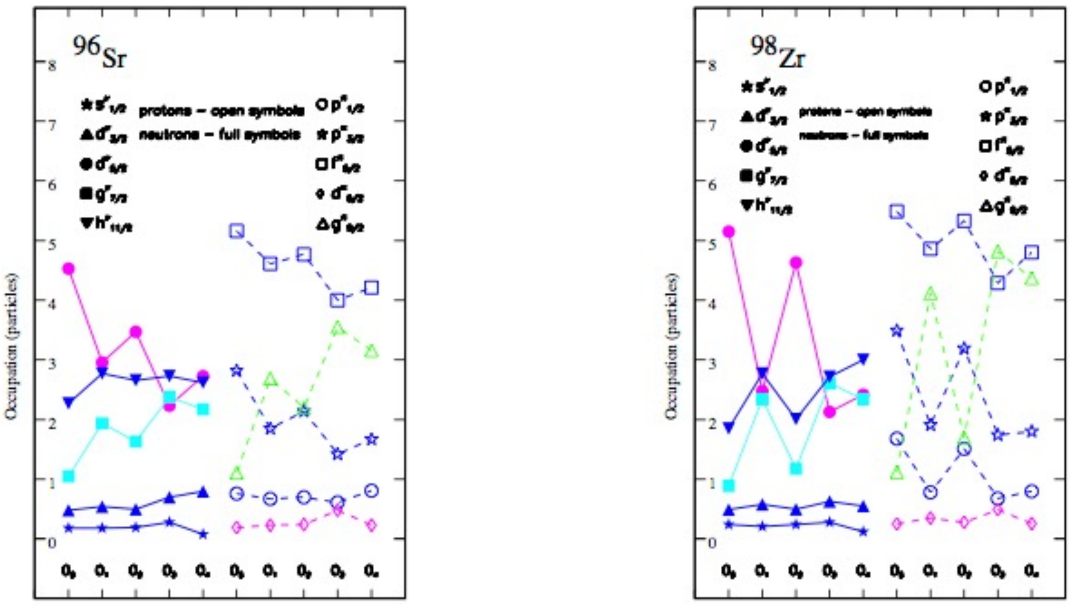

Fig.2 Occupation of valence spherical orbitals for 0^+ states in ^{96}Sr and ^{98}Zr

configuration is oblate deformed in the intrinsic system, the third one is prolate. In ^{98}Zr the second configuration is prolate, the third is oblate. The structure of the lowest four 0^+ states in terms of spherical, prolate, and oblate content is presented in Table I. Support for the mixing of

configurations with different intrinsic deformations in the structure of the wave functions for the 0^+ states is offered by the strong $\rho^2(E0)$ values found theoretically and experimentally in both nuclei.
In Figure 2 we present the occupation of valence single-particle orbitals for the spherical 0^+ EXVAM configuration (the first state in the row for each nucleus) and for the lowest four 0^+ states in ^{96}Sr and ^{98}Zr, respectively.
The occupation of the $1d_{5/2}$ neutron orbital is essential for the spherical 0^+ EXVAM configuration. The occupation of the $0g_{9/2}$ proton orbital is significantly changing from the intrinsically oblate deformed configurations to the prolate deformed ones in both nuclei.
The evolution of the structural changes is correlated with the faster alignment of the neutrons with respect to the protons corroborated with the variation of theoretical gyromagnetic factors [2]. The variable configuration mixing of the wave functions is revealed in the evolution of the spectroscopic quadrupole moments and in- and inter-band B(E2) strengths [2,3]. Strong oblate-prolate mixing at low spins is supported by the recent experimental results on quadrupole moments and B(E2) strengths. The EXVAM scenarios for the triple shape coexistence: spherical, oblate and prolate specific for the 0^+ states is confirmed and used in the literature for the interpretation of the experimental results in the neighbouring nuclei.

II. Gamow-Teller beta decay of ^{102,104} Tc

The Gamow-Teller (GT) β decay of neutron-rich A~100 nuclei is not only relevant to nuclear structure, but is of high interest in nuclear technology. The estimation and control of the heat emitted by the decay of fission products requires certain still missing useful information, such as a knowledge of the decay properties of specific nuclei that contribute to the heating of the reactor during and after operation. The Gamow-Teller strengths distributions and the accumulated strength for the decay of ^{102}Tc to ^{102}Ru and ^{104}Tc to ^{104}Ru are self-consistent investigated for the first time in the frame of *complex* Excited Vampir model in a large model space and using a realistic two-body interaction.

Table II: Spectroscopic quadrupole moments (in *efm²)* of ^{102}Ru and ^{104}Ru states

^{102}Ru	^{104}Ru	
2^+-states	2^+-states	4^+-states
-19.2	-28.0	34.3
23.7	42.0	-17.0
-14.7	54.4	71.1
30.1	-44.0	-82.9
3.9	50.1	-7.6

We calculated the lowest 1^+ states in ^{102}Tc, the lowest 3^+ states in ^{104}Tc, and the positive-parity states up to spin 4^+ in ^{102}Ru and ^{104}Ru [4]. The experimental data indicate 3 orders of magnitude difference in the β-decay half-lives of the two Tc isotopes. The mixing of different deformed configurations obtained self-consistently in the frame of *complex* Excited Vampir model, which dominate the structure of both even-even parent and odd-odd daughter nucleus give a scenario in good agreement with the experimental data obtained using Total Absorption Gamma Spectrometer (TAGS) [4]. The obtained results indicate that the structure of the wave function for the lowest 1^+ state of ^{102}Tc manifest a strong mixing of differently deformed prolate and oblate configurations in the intrinsic system. Altogether the prolate components represent 53% of the total amplitude and the oblate components make 47% in the structure of the wave function while the wave function for the lowest 3^+ state of ^{104}Tc is dominated (99%) by a single prolate deformed configuration. The wave functions of the daughter states with significant Gamow-Teller strength manifest significant oblate-prolate mixing and the corresponding spectroscopic quadrupole moments are presented in Table II [5].

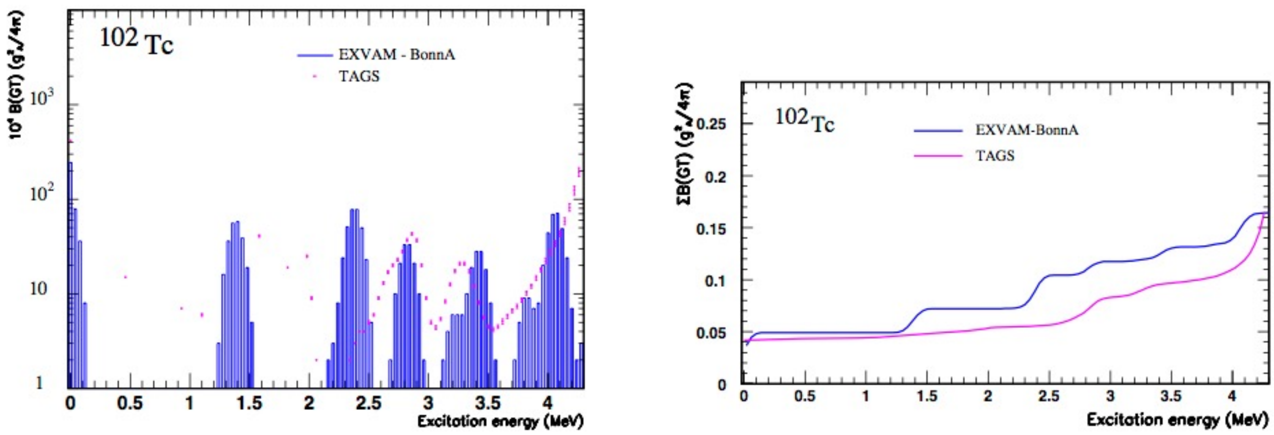

Fig.3: The Gamow-Teller strength distribution and the corresponding accumulated strength for ^{102}Tc obtained within the *complex* Excited Vampir model compared with TAGS results[4,5].

The Gamow-Teller strength distribution and the corresponding accumulated Gamow-Teller strength for the decay of the 1^+ parent state in ^{102}Tc to the calculated 0^+ and 2^+ daughter states in ^{102}Ru is presented in Figure 3 compared with TAGS results. The GT strength for the decay to the 1^+ states in ^{102}Ru is negligible. The Gamow-Teller strength distribution and the accumulated GT strength for the decay of the 3^+ parent state in ^{104}Tc to the calculated 2^+ and 4^+ daughter states in ^{104}Ru (the 3^+ states do not have a significant contribution) is compared with TAGS results in Figure 4. The strong Gamow-Teller β-decay branches indicate essential contribution from the $g^{\pi}{}_{9/2}\, g^{\nu}{}_{7/2}$, $d^{\pi}{}_{5/2}\, d^{\nu}{}_{3/2}$ and $d^{\pi}{}_{5/2}\, d^{\nu}{}_{5/2}$ matrix elements. Smaller contributions are obtained from $p^{\pi}{}_{1/2}\, p^{\nu}{}_{3/2}$ and $p^{\pi}{}_{3/2}\, p^{\nu}{}_{1/2}$ matrix elements. In the case of the decay of ^{104}Tc to ^{104}Ru the same matrix elements are relevant, but all of them are relatively small and the cancellations produce the final small strength for each Gamow-Teller contributing state. We have to mention that the best theoretical results based on other models are one order of magnitude outside the experimental data. The strong mixing of prolate and oblate projected configurations in the parent state as well as in the daughter states is responsible for the significant difference in the GT decays of ^{102} Tc and ^{104} Tc.

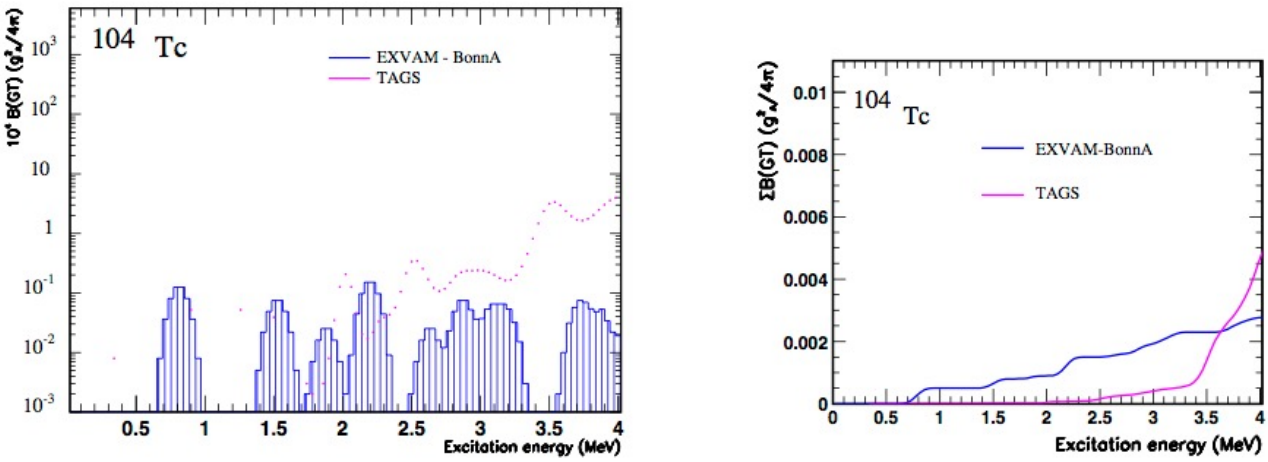

Fig. 4: The Gamow-Teller strength distribution and the corresponding accumulated strength for ^{104}Tc obtained within the *complex* Excited Vampir model compared with TAGS results [4,5]

Also the deformation of the main configurations in the structure of the wave functions is smaller in the first case where the number of neutrons in the daughter nucleus has the critical value N = 58 while in the second case the larger deformation is determined by N = 60 in the ^{104}Ru daughter nucleus. This results give support to our predictions concerning the role of the critical number of neutrons N=58 for the structure and dynamics of neutron-rich nuclei with A~100 exemplified for ^{96} Sr and ^{98} Zr isotopes [5]. Our results are relevant predictions for the next experiments at FAIR, Germany, RIKEN, Japan and MSU, SUA.

III. Two-body correlations relevant for the structure and dynamics of proton-rich medium mass nuclei

The properties of proton-rich nuclei in the A~70 mass region are not only relevant to nuclear structure, but are of high interest as micro-laboratory for high precision tests of the Standard Model. Shape coexistence and mixing, isospin mixing, competition between neutron-proton and like-nucleon pairing correlations are characteristic features of nuclei near the N=Z line in the A~70 mass region. We studied shape coexistence effects on Coulomb Energy Differences (CED) for A=66 analogs [6] and two-body correlations in T=0 and T=1 channel relevant for the competition between the superallowed Fermi and Gamow-Teller (GT) β decay in the A=70 isovector triplet [7], using *complex* Excited Vampir model, in a relatively large model space using a realistic effective interaction (starting from a nuclear matter G-matrix based on the Bonn A potential).
We investigated the possible shape coexistence phenomena in positive parity states up to spin 8^+ in ^{66}As and ^{66}Ge studying the influence of some particular two-nucleon correlations on the low energy spectra [6]. The theoretical results regarding the anomalous behaviour of CED with the spin evolution are in good agreement with the experimental data. It was revealed the essential effect of

the mixing of differently deformed configurations on the anomalies in the behaviour of the CED for A~70 analogs. The comparison of our results with the available data are presented in Figure 5 [7].

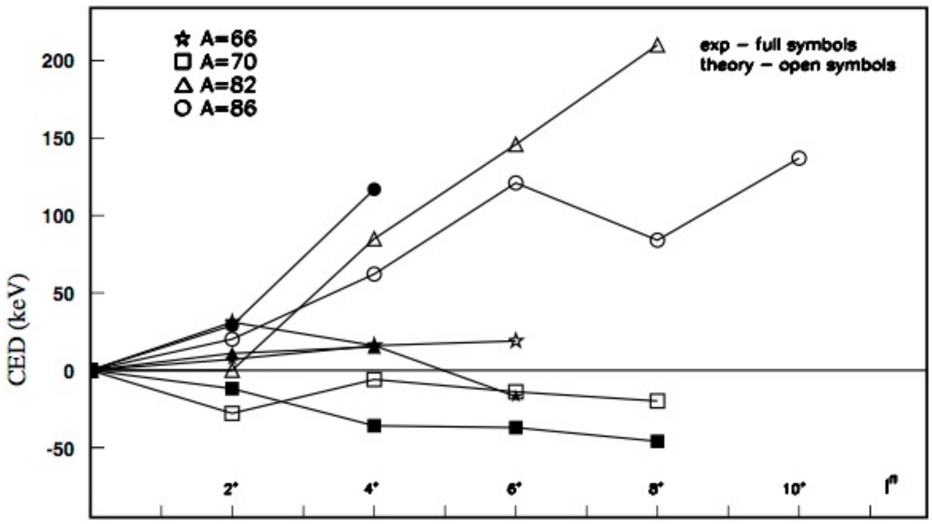

Fig.5: CED obtained within the *complex* Excited Vampir model compared to data [6].

We analysed the pair structure of ^{70}Kr and ^{70}Br, members of the A = 70 isovector triplet who manifest CED anomalies [7]. The motivation is connected with the possible competition of the superallowed Fermi and Gamow-Teller (GT) β decay of ^{70}Kr to ^{70}Br as a signature of the isoscalar proton-neutron pairing correlations. It is suggested in the literature that in medium mass nuclei an enhancement of the Gamow-Teller β decay of the ground state of an even-even Z = N + 2 nucleus to the lowest I = 1 $^{+}$ state in the daughter odd-odd N = Z nucleus would be expected as a fingerprint of the neutron-proton T = 0 condensate in the odd-odd system.

Using the same Hamiltonian as for the CED studies [6] we constructed the lowest 8 0^{+} states in ^{70}Kr and the lowest 14 0^{+} states and the lowest 10 1^{+} states in ^{70}Br [7]. The lowest 1^{+} states indicate a completely different structure in terms of oblate-prolate mixing with respect to the 0^{+} states. The EXVAM results for the Gamow-Teller β decay of the ground state of ^{70}Kr indicate that the strength is distributed over many states, the GT branch to the lowest 1^{+} state is very weak, while for the second and the third 1^{+} states the strength is stronger.

The pair structure analysis of the lowest three 0^{+} states in the parent ^{70}Kr and the daughter ^{70}Br nucleus, involved in the superallowed Fermi beta decay, and the lowest three 1^{+} states in ^{70}Br manifesting strong B(GT) branches are illustrated in Figures 6 and 7. Contrary to the scenario proposed in the literature the maximum number of pairs has been obtained for the yrast 1^{+} state characterised by negligible B(GT) strength. We have to mention that from the experimental study performed at GSI-Darmstadt on the Gamow-Teller β decay of the T = 1 0^{+} ground state of ^{62}Ge into excited states of the odd-odd N = Z ^{62}Ga nucleus absence of the neutron-proton T = 0 condensate was inferred from the weak B(GT) observed for the transition to the first 1^{+} state.

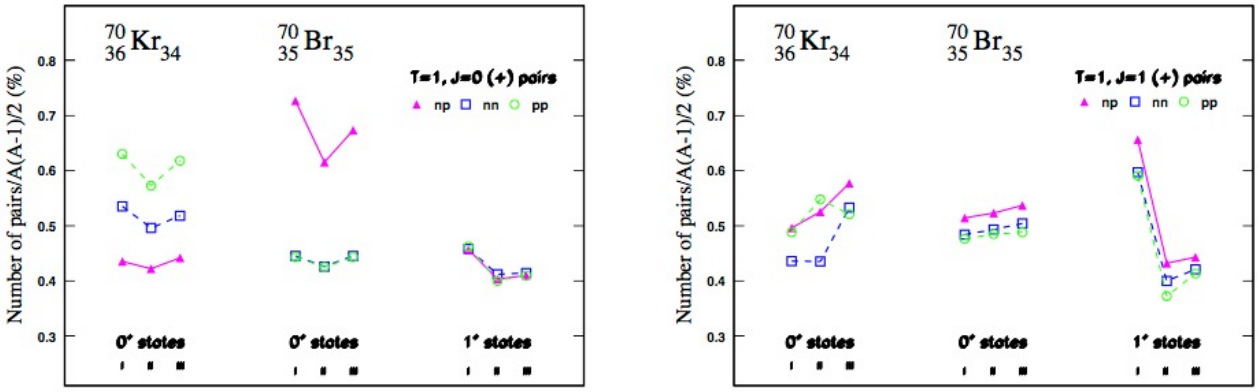

Fig.6. The number of nn, pp, and np pairs with T = 1, $J^\pi = 0^+$ and $J^\pi = 1^+$ of the lowest 0^+ states in ^{70}Kr and the lowest 0^+ and 1^+ states in ^{70}Br given in percent of the sum rule [7].

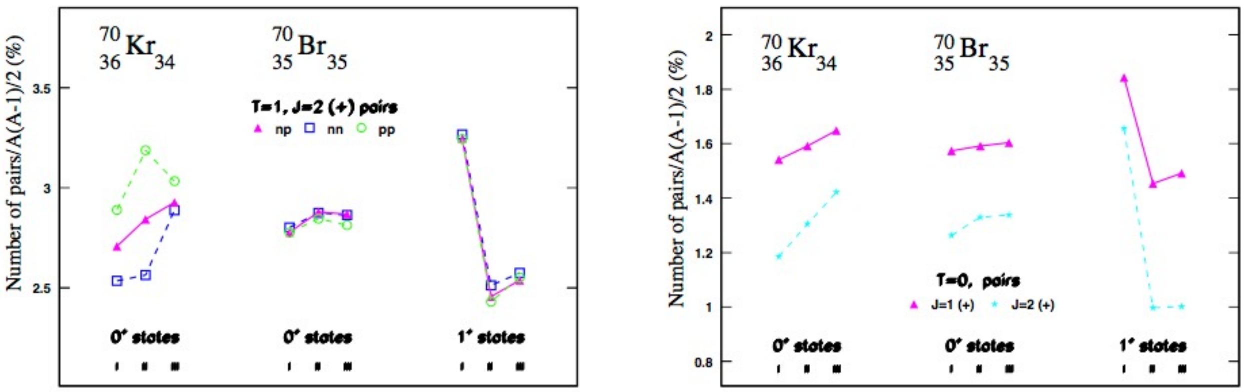

Fig.7. The same as in Fig.6 but for T = 1, $J^\pi = 2^+$ and T = 0, $J^\pi = 1^+$ and $J^\pi = 2^+$, respectively [7].

The *complex* Excited Vampir beyond-mean-field model self-consistently describes the anomalies identified in the behaviour of the Coulomb energy differences for the A=70 analogs based on a strong oblate-prolate mixing specific for each nucleus. Our analysis did not find support for the suggested scenario concerning the enhancement of the B(GT) strength in the Gamow-Teller β decay of the ground state of the even-even Z=N+2 parent to the lowest 1^+ state in the odd-odd N=Z ^{70}Br daughter nucleus as a fingerprint for the neutron-proton T=0 condensate.

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[1] A. Petrovici, Phys. Rev. C 85, 034337 (2012).
[2] A. Petrovici, K.W. Schmid, A. Faessler, AIP Conf. Proc. 1498, 38 (2012).
[3] A. Petrovici, K.W. Schmid, A. Faessler, J. Phys.: Conf. Ser. 413, 012007 (2013).
[4] D. Jordan, A. Petrovici et al, Phys. Rev. C 87, 044318 (2013).
[5] A. Petrovici, EPJ Web of Conf. 63, 01012 (2013).
[6] G. de Angelis, A. Petrovici et al, Phys. Rev. C 85, 034320 (2012).
[7] A. Petrovici, Rom. J. Phys. 58, 1120 (2013).

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