Exotic structure and decay of medium mass nuclei near the drip lines

A Petrovici\textsuperscript{1,2}, K W Schmid\textsuperscript{2} and A Faessler\textsuperscript{2}

\textsuperscript{1}National Institute for Physics and Nuclear Engineering, R-077125 Bucharest, Romania
\textsuperscript{2}Institut für Theoretische Physik, Universität Tübingen, D-72076 Tübingen, Germany

E-mail: spetro@nipne.ro

Abstract. Nuclei at or near the \(N=Z\) line are of particular interest as micro-laboratory for fundamental effects. The simulation of many astrophysical objects requires the knowledge of properties and decay rates of nuclei near the drip lines. The structure and dynamics of proton-rich \(A \approx 70\) nuclei and neutron-rich \(A \approx 100\) nuclei are influenced by shape coexistence and mixing. A realistic description of shape coexistence phenomena requires beyond-mean-field approaches. Results concerning the self-consistent description of exotic phenomena including anomalies in mirror energy differences of proton-rich nuclei, triple shape coexistence in neutron-rich \(N=58\) Sr and Zr isotopes as well as Gamow-Teller \(\beta\)-decay strength distributions, half-lives, and \(\beta\)-delayed neutron emission probabilities of neutron-rich nuclei in the \(A \approx 100\) mass region obtained in the frame of the \textit{complex} Excited Vampir model using realistic effective interactions in large model spaces are presented.

1. Introduction

The interest for the investigation of medium mass nuclei near the drip lines goes beyond the frontier of nuclear structure and dynamics. 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 \(A \approx 70\) mass region. Nuclei at or near the \(N=Z\) line are of particular interest as micro-laboratory for high precision tests of fundamental effects which requires particularly high accuracy of the nuclear structure models [1].

The isotopic chain of neutron-rich zirconium nuclei offers an example of rapid transition from spherical to deformed shape with a possible identification of the sudden onset of quadrupole deformation between \(N=58\) and 60. The rapid neutron-capture process involving neutron-rich nuclei in the \(A \approx 100\) region remains as one of the most challenging problem in nuclear astrophysics [2]. The \(\beta\)-decay properties of some specific nuclei that are important contributors to the reactor decay heat are also required. Previous theoretical investigations revealed the difficulty of describing in a unitary way the experimental data at low and high spins as well as the Gamow-Teller (GT) \(\beta\)-decay properties of these nuclei. The realistic description of shape coexistence phenomena in proton-rich \(A \approx 70\) nuclei and neutron-rich \(A \approx 100\) nuclei requires beyond-mean-field approaches. We shall present results on exotic phenomena in these nuclei obtained within the \textit{complex} Excited Vampir variational approach with symmetry projection before variation. We use a large model space and a realistic effective nucleon-nucleon interaction obtained starting from a nuclear matter G-matrix based on Bonn A potential. In the next section the \textit{complex} Excited Vampir variational procedure will be briefly described and the effective
Hamiltonian will be defined. In Section 3 results concerning shape coexistence phenomena specific for the A≈70 mass region will be presented. Particular features of neutron-rich A≈100 nuclei influenced by shape coexistence and mixing will be discussed in Section 4.

2. Theoretical framework

Shape coexistence phenomena characterizing the structure and dynamics of proton-rich A≈70 nuclei and neutron-rich A≈100 nuclei are investigated within the complex Excited Vampir model which successfully explained the structure and weak decays of the nuclei dominated by shape coexistence in the A≈70 mass region [3-7]. Many predictions that emerged have been experimentally confirmed. The complex Excited Vampir model uses Hartree-Fock-Bogoliubov (HFB) vacua as basic building blocks which are only restricted by time-reversal and axial symmetry. The underlying HFB transformations are essentially complex and do mix proton- with neutron-states as well as states of different parity and angular momentum. The broken symmetries (nucleon numbers, parity, total angular momentum) are restored by projection techniques and the resulting symmetry-projected configurations are used as test wave functions in chains of successive variational calculations to determine the underlying HFB transformations as well as the configuration mixing. The HFB vacua account for arbitrary two-nucleon correlations and thus simultaneously describe like-nucleon as well as isovector and isoscalar proton-neutron pairing. Unnatural parity correlations are also included. Furthermore, the complex Excited Vampir model (EXVAM) allows the use of rather large model spaces and realistic effective interactions.

For nuclei in the A≈70 mass region we use a 40Ca core and include the 1p1/2, 1p3/2, 0f5/2, 0f7/2, 1d5/2 and 0g9/2 oscillator orbits for both protons and neutrons in the valence space. We start with an isospin symmetric basis and then introduce the Coulomb shifts for the proton single-particle levels resulting from the 40Ca core by performing spherically symmetric Hartree-Fock calculations using the Gogny-interaction D1S in a 21 major-shell basis [4].

For nuclei in the A≈100 mass region we use a rather large model space above the 40Ca core built out of 1p1/2, 1p3/2, 0f5/2, 0f7/2, 2s1/2, 1d3/2, 1d5/2, 0g7/2, 0g9/2, and 0h11/2 oscillator orbits for both protons and neutrons in the valence space. The corresponding single-particle energies had been adjusted in complex Monster (Vampir) calculations for odd mass nuclei in the A≈100 mass region [8]. This rather large model space allows the realistic description of the Gamow-Teller β-decay properties of neutron-rich nuclei in this region.

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 (0.707 fm) Gaussians for the isospin T = 1 proton-proton, neutron-neutron, and neutron-proton matrix elements. The isoscalar spin 0 and 1 particle-matrix elements are enhanced by an additional Gaussian. In addition, the isoscalar interaction was modified by monopole shifts including all T = 0 matrix elements of the form \langle 0g9/2f;IT = 0|G|0g9/2f;IT = 0 \rangle involving protons and neutrons occupying the 0f5/2 and the 0f7/2 orbitals. The Coulomb interaction between the valence protons was added.

3. Coexistence phenomena in proton-rich A≈70 nuclei

Coexistence phenomena at low, intermediate, and high spins have been predicted in the frame of the variational approaches of the Vampir model family [3-7] and later identified experimentally. Low-lying isomeric 0+ states based on a strong mixing of projected configurations with large or small prolate and oblate deformations in the intrinsic system have been predicted for some Ge, Se, and Kr isotopes. Small spectroscopic quadrupole moments for the lowest 2+ and 4+ states of these nuclei and collective B(E2;ΔI = 2) values as well as significant B(E2) strengths for the transitions connecting states of the same spin and parity represent fingerprints of strong oblate-prolate mixing. The rapid variation of the deformation with the number of nucleons and
excitation energy, the shape coexistence and mixing, the competition of T=0 and T=1 pairing correlations may have important effects on the mirror energy differences which are expected to be determined by the isospin mixing induced by the interplay of all these facts.

Anomalies in the mirror energy differences are experimentally identified in this mass region ([9, 10] and references therein) for nuclei supposed to manifest shape mixing at low spins [7].

Figure 1. The theoretical EXVAM spectrum for $^{70}$Se compared to the available data.

Figure 2. The theoretical EXVAM spectrum for $^{70}$Br compared to the available data.

Figure 3. The mirror energy differences obtained within the complex Excited Vampir model is compared to data [10].

The anomalous negative trend for the A=70 nuclei can be explained based on the strong competition and mixing between configurations of oblate and prolate deformation in the intrinsic system. In $^{70}$Br the ground state is dominated by prolate components, while for $^{70}$Se the calculations predict a predominantly oblate ground state. In $^{70}$Br the oblate (prolate) components represent 36% (64%), 41% (59%), 41% (58%), 20% (80%) of the total amplitude of the wave function for the lowest 0$^+$, 2$^+$, 4$^+$, and 6$^+$, respectively, while in $^{70}$Se the corresponding amplitudes amount to 57% (42%), 59% (41%), 64% (36%), and 39% (61%). In figure 1 and 2 we present the low-spin spectra of $^{70}$Se and $^{70}$Br, respectively, compared to data. In $^{70}$Se the calculated spectroscopic quadrupole moment for the yrast 2$^+$ state, 4.5 $efm^2$, is in agreement with recent experimental data [11], whereas for the spins 4$^+$ and 6$^+$ we found 11.5 $efm^2$ and -17.5 $efm^2$, respectively. In $^{70}$Br the corresponding calculated values are: -6.4 $efm^2$, -9.8 $efm^2$, and -39.7 $efm^2$ [10].
The experimental energy differences for the A=66 analogs $^{66}$As and $^{66}$Ge show a slightly positive trend up to spin 4$^+$ becoming slightly negative for 6$^+$ [10]. The predominantly prolate states in the $^{66}$As - $^{66}$Ge pair show smooth changes of the prolate-oblate mixing for increasing spin. In $^{66}$As the oblate (prolate) components amount to 16% (84%), 29% (70%), 18% (81%), and 4% (95%) for the lowest 0$^+$, 2$^+$, 4$^+$, and 6$^+$ states, whereas for the analog states in $^{66}$Ge the corresponding amplitudes are 20% (80%), 38% (61%), 32% (66%), 9% (91%). The EXVAM mirror energy differences manifest a slightly positive trend.

A positive trend is observed for the $^{82}$Nb - $^{82}$Zr and for $^{86}$Tc - $^{86}$Mo nuclei, which is reproduced by our calculations. The situation is different for the A=82 and A=86 analogs where it was found that one prolate component strongly dominates the structure of the yrast states representing more than 90% of the total amplitude [5]. In figure 3 the mirror energy differences obtained within the complex Excited Vampir using the Bonn A potential and the Coulomb interaction for the mirror nuclei $^{66}$Ge - $^{66}$As, $^{70}$Se - $^{70}$Br, $^{82}$Zr - $^{82}$Nb, and $^{86}$Mo - $^{86}$Tc are compared to the available data. We conclude that the oblate-prolate shape mixing strongly perturbs the isospin symmetry, altering the excitation energies of the levels in the nuclei of the same isospin multiplet which is reflected in the mirror energy differences behaviour. The overall trend of the mirror energy differences is reasonably well reproduced by the complex Excited Vampir model even if we take into account only the isospin mixing determined by the Coulomb interaction [5, 10].

4. Coexistence phenomena in neutron-rich A≈100 nuclei

The structure of neutron-rich nuclei in the A ≈ 100 mass region relevant for the astrophysical r-process manifests drastic changes in some isotopic chains and often sudden variations of particular nuclear properties have been identified [12-21]. Reliable predictions concerning the properties of neutron-rich nuclei along the r-process path are required from robust nuclear structure models to explain the observational data in the frame of the astrophysical models.

4.1. Sape coexistence and shape evolution in neutron-rich A≈100 nuclei

For neutron-rich nuclei in the region the N=58 is considered a critical number of neutrons. Since the onset of deformation is supposed to take place for N ⩾ 58 we investigated the structural changes and the evolution of deformation with increasing spin aiming at a unitary description of the lowest few 0$^+$ states and the low, intermediate, and high spins in $^{96}$Sr and $^{96}$Zr. We studied the properties of the positive parity states up to spin 20$^+$ in the frame of the complex Excited Vampir model including in the many-nucleon bases up to 12 EXVAM configurations [8].

A particular situation is found for the 0$^+$ states: the lowest projected EXVAM configuration is spherical in both nuclei (the quadrupole deformation parameter amounts to $\beta_2 \approx 0.03$). In $^{96}$Sr the second 0$^+$ configuration is oblate deformed in the intrinsic system ($\beta_2 = -0.32$), the third one is prolate ($\beta_2 = 0.37$) and all three orthogonal configurations are situated in an energy interval of 375 keV. In $^{96}$Zr the second configuration is prolate ($\beta_2 = 0.37$), the third is oblate ($\beta_2 = -0.30$) and the separation energy between the spherical one and the third one is 323 keV. For each nucleus we constructed the lowest 10 0$^+$ orthogonal EXVAM configurations and the result of the diagonalization of the residual interaction between them in terms of spherical, prolate, and oblate content in the structure of the lowest four 0$^+$ states is presented in table 1. The occupation of the 1d$_{5/2}$ neutron orbital is essential for the spherical 0$^+$ EXVAM configuration.

The theoretical lowest bands of $^{96}$Sr and $^{96}$Zr are compared to the experimental spectra in figure 4 and 5, respectively. The labels of the bands indicate the prolate (p) or oblate (o) intrinsic quadrupole deformation for the dominant projected EXVAM configurations underlying the states of the corresponding bands. The states building the po(p)-band in each nucleus are characterized by strong prolate-oblate mixing at low spins and variable prolate mixing at intermediate and high spins. The almost pure oblate states belonging to the most right band in the theoretical spectrum are feeding the second 4$^+$ (2$^+$) state in $^{96}$Sr ($^{98}$Zr) that manifests
maximum o-p mixing as it is illustrated in table 2. The shape evolution with increasing spin and excitation energy is suggested by the amount of mixing in the structure of the wave functions illustrated in table 3 for $^{98}$Zr. 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.

Figure 4. The theoretical EXVAM spectrum for $^{96}$Sr is compared to the available data [13, 15, 18].

Figure 5. The theoretical EXVAM spectrum for $^{98}$Zr is compared to the available data [13, 15, 18].

Table 1. The structure of the wave functions for the lowest $0^+$ states.

| I[h] | $^{96}$Sr | $^{98}$Zr |
|------|----------|----------|
|      | 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%      | 5%      | 42%     |
| $0^+_4$ | 4%      | 6%      | 90%     | 2%       | 10%      | 88%     |

Table 2. The o-p mixing of the lowest $2^+$ and $4^+$ states.

| I[h] | $^{96}$Sr | $^{98}$Zr |
|------|----------|----------|
|      | o-mixing | p-mixing | o-mixing | p-mixing |
| $2^+_1$ | 58(5)% | 34(2)% | 31% | 60(8)% |
| $2^+_2$ | 33(2)% | 65% | 63(1)% | 36% |
| $4^+_1$ | 36(6)% | 56(1)% | 10% | 83(7)% |
| $4^+_2$ | 52(5)% | 43% | 85(1)% | 13(1)% |
Table 3. The amount of mixing for the states of the lowest bands of $^{98}$Zr.

| $I^+[h]$ | o-mixing | p-mixing |
|----------|----------|----------|
| 6$^+_1$  | 2%       | 90(5)(1)%|
| 6$^+_2$  | 80(14)%  | 4(2)%    |
| 8$^+_1$  | 3%       | 89(7)(2)%|
| 8$^+_2$  | 84(4)(2)%| 4(4)(2)% |
| 10$^+_3$ | 43(26)(24)(7)% |
| 10$^+_2$ | 74(8)(2)% | 13(1)(1)%|
| 12$^+_3$ | 75(8)(4)% | 55(30)(7)%|
| 12$^+_2$ | 67(16)%  | 59(37)(2)%|
| 14$^+_3$ | 65(8)%   | 19(4)(2)%|
| 16$^+_3$ | 56(33)(4)(3)(2)(1)% |
| 16$^+_2$ | 51(42)(5)(1)% | 9(1)% |
| 16$^+_1$ | 89%      | 19(4)(2)%|
| 18$^+_3$ | 49(28)(21)(1)% |
| 18$^+_2$ | 68(14)(14)(2)% | 1% |
| 18$^+_1$ | 98%      | 87(5)(3)(2)(2)(1)% |
| 20$^+_3$ | 91(4)(3)(1)% |
| 20$^+_2$ | 98(1)%   |
| 20$^+_1$ | 99%      |

The experimental B(E2) values for the transitions connecting the lowest 0$^+$ and 2$^+$ states in $^{96}$Sr support the idea of strong shape mixing. The retardation of the 2$^+_1 \rightarrow 0^+_1$ transition is induced from the strength B(E2) = 340(209) $e^2 fm^4$ deduced from the measured lifetime of 7(4) ps [12]. Recent preliminary results indicate for this lifetime 4.1 ps [20]. The EXVAM result is B(E2) = 795 $e^2 fm^4$. Lifetimes for the 12$^+ \rightarrow 10^+ \rightarrow 8^+$ cascade in $^{96}$Sr and 12$^+ \rightarrow 10^+ \rightarrow 8^+ \rightarrow 6^+$ cascade in $^{98}$Zr have been measured [15]. By a simultaneous fit to several levels, assuming that they form a rotational band characterized by a common quadrupole moment the reported value is $Q_0 = 220(15) \text{ efm}^2$ in $^{96}$Sr and $Q_0 = 200(10) \text{ efm}^2$ in $^{98}$Zr. The theoretical results indicate significant fragmentation of the E2 strength decaying a given state due to the high density of states obtained at intermediate and high spins in both nuclei as it is illustrated in table 4 for $^{98}$Zr. The quadrupole deformation parameter in both nuclei amounts to $\beta_2 \simeq 0.3$ for the po(p) band. For the intermediate spins the states building the o-band in both nuclei indicate smaller deformation for the underlying oblate configurations. The $\beta_2$ parameter varies between -0.19 and -0.23 in $^{96}$Sr for the spins 8$^+$, 10$^+$, 12$^+$, while in $^{98}$Zr even smaller values have been obtained for the corresponding spins: between -0.17 and -0.13. Other preliminary experimental results give support to the theoretical o-p mixing: the spectroscopic quadrupole moment of the 2$^+_1$ state in $^{96}$Sr is equal 0 [20], while the calculated value is $Q^{spec}(2^+_1) = 9.5 \text{ efm}^2$ using the effective charges $e_p = 1.3$ and $e_n = 0.3$. The shape evolution within the bands is illustrated by the spectroscopic quadrupole moments for $^{98}$Zr presented in table 5.
Table 4. $B(E2; I \rightarrow I-2)$ values (in $e^2 fm^4$) for the lowest bands of $^{98}$Zr (EXVAM). Strengths for secondary branches are given in parentheses.

| $I[\hbar]$ | po(p)    | $p$     | $o$  |
|-----------|----------|---------|------|
| 2$^+$     | 1140 (198) (161) | 1305 (28) (18) (15) |
| 4$^+$     | 2072 (620)    | 1593 (56)   |
| 6$^+$     | 2558 (101)    | 1662       |
| 8$^+$     | 1802 (942) (153) | 1572 (123) |
| 10$^+$    | 1430 (719)    | 1314 (119) (100) |
| 12$^+$    | 2300 (216)    | 731 (345) (212) | 663 (621) (307) |
| 14$^+$    | 2428 (123)    | 1840 (392)  | 1094 (494) |
| 16$^+$    | 1360 (832) (190) | 548 (246) (1421) | 602 (250) |
| 18$^+$    | 863 (1416) (207) | 1347 (808) (713) | 1115 |
| 20$^+$    | 409 (1958)    | 347 (185) (1972) | 1313 |

The angular momentum alignment indicates that maximum contribution in the direction of the total angular momentum is brought by $0h_{11/2}$ neutrons and $0g_{9/2}$ protons. The particularities of the $I^\pi \geq 8^+$ states are reflected by the g-factor values that are larger in $^{96}$Sr ($\simeq 0.24$) with respect to the corresponding values in $^{98}$Zr ($\simeq 0.14$), both corroborated by the faster alignment of the valence neutrons occupying the $0h_{11/2}$ orbital. For the $I^\pi \geq 10^+$ states along the $o$-band the g-factors are slightly larger than 0.5 (0.44) in $^{96}$Sr ($^{98}$Zr) supporting the role of the $0g_{9/2}$-proton alignment. In figures 4 and 5 are indicated by dashed-dotted lines some M1 transitions connecting states of the same spin. The strongest calculated strengths amount to $B(M1; 8^+_3 \rightarrow 8^+_1) = 1.292 \mu_N^2$ in $^{96}$Sr and $B(M1; 8^+_2 \rightarrow 8^+_1) = 1.600 \mu_N^2$ in $^{98}$Zr where the states are ordered according to the excitation energy.

Table 5. Spectroscopic quadrupole moments $Q^p_2$ (in $efm^2$) for the lowest bands of $^{98}$Zr.

| $I[\hbar]$ | po(p)    | $p$     | $o$  |
|-----------|----------|---------|------|
| 2$^+$     | -36.6    | 7.1     |
| 4$^+$     | -89.6    | 54.7    |
| 6$^+$     | -115.5   | 76.7    |
| 8$^+$     | -126.7   | 70.7    |
| 10$^+$    | -130.1   | 58.2    |
| 12$^+$    | -129.1   | -98.5   | 55.6 |
| 14$^+$    | -126.1   | -121.2  | 30.5 |
| 16$^+$    | -126.6   | -123.0  | 60.8 |
| 18$^+$    | -124.2   | -134.4  | 74.9 |
| 20$^+$    | -125.6   | -135.4  | 68.9 |

In summary, we found triple shape coexistence specific for the $0^+$ states and evolution of the shape coexistence and mixing with increasing spin and excitation energy for the positive parity states up to spin $20^+$ in the N = 58 Sr and Zr isotopes within the complex Excited Vampir...
model using a realistic effective interaction in a large model space. The lowest four $0^+$ states are described as a variable mixing of spherical, prolate, and oblate deformed Excited Vampir configurations. The oblate-prolate mixing characterizes the low-spin states. At intermediate and high spins prolate and oblate bands coexist in both nuclei. The comparison to the available data indicates rather good agreement.

The situation is changed for the $^{104,106}$Zr isotopes where the oblate minima are much higher in energy and the lowest bands are built on prolate strongly deformed configurations [22] in agreement with recent data [17, 21]. Our investigations indicated that the ground states of $^{104}$Zr and $^{106}$Zr are dominated (99%) by a prolate deformed configuration. In $^{104}$Zr beginning with spin $6^+$ the yrare states manifest significant mixing of two or three prolate deformed projected configurations whereas for spins $10^+$, $12^+$, and $14^+$ even for the lowest band the states manifest some mixing. In $^{106}$Zr significant mixing of different prolate deformed configurations was found starting with spin $10^+$.

4.2. Gamow-Teller $\beta$-decay of neutron-rich $A \approx 100$ nuclei

Aiming at a unitary description of the structure and dynamics of neutron-rich nuclei in the $A \approx 100$ mass region we extended our investigations to the Gamow-Teller $\beta$-decay of the even-even and odd-odd isotopes studying the strength distributions, $\beta$-decay half-lives, and $\beta$-delayed neutron emission probabilities. A completely self-consistent description of the Gamow-Teller $\beta$-decay properties of $^{104}$Zr and $^{106}$Zr nuclei involved the calculation of the lowest 50 $1^+$ states in the odd-odd $^{104,106}$Nb nuclei [23]. The calculated $1^+$ states are all situated within 6.2 MeV excitation energy in $^{104}$Nb and 6.0 MeV in $^{106}$Nb. In both nuclei the states manifest strong mixing of differently deformed configurations in the intrinsic system. The Excited Vampir configurations are strongly or moderately deformed and more than 75% manifest prolate deformation. Some states are dominated by strong prolate-oblate mixing. The theoretical results for the GT accumulated strength for the decay of the ground state of $^{104}$Zr and $^{106}$Zr are presented in figure 6 and 7, respectively. The strong GT $\beta$-decay branches for both $^{104}$Zr and $^{106}$Zr nuclei indicate essential contribution from the $g_{9/2}^\pi g_{7/2}^\nu$, $d_{5/2}^\pi d_{3/2}^\nu$, and $d_{5/2}^\pi d_{3/2}^\nu$ matrix elements.

Figure 6. The Gamow-Teller accumulated strength for the decay of $^{104}$Zr.

Figure 7. The Gamow-Teller accumulated strength for the decay of $^{106}$Zr.
was changed recently to 870(50)(30) ms [25]. The Excited Vampir result obtained calculating the lowest 50 $^1_+$ in $^{104}$Nb is 2040 ms. Recent experimental data [25] for the half-life of $^{106}$Zr indicate 260(20)(30) ms, while the Excited Vampir result is 230 ms involving the lowest 50 $^1_+$ in $^{106}$Nb. Of course, the theoretical results on the Gamow-Teller strength distributions could be changed, more for the high-excitation energy region, by the higher-lying configurations not included in the complex Excited Vampir many-nucleon basis. The probability of $\beta^-$delayed neutron emission ($P_n$) was calculated taking into account the GT contributions from the $^1_+$ states with excitation energy larger than $S_n$. The experimental results indicate for $P_n$ an upper limit of 1% for the decay of $^{104}$Zr and an upper limit of 7% for the decay of $^{106}$Zr [25]. The Excited Vampir $P_n$ value based on the lowest 50 $^1_+$ states is smaller than 1% for $^{104}$Zr decay and amounts to 2% for $^{106}$Zr. Of course, these results are strongly dependent on the $^1_+$ states higher in energy than $S_n$ and require a much larger EXVAM basis than the presently involved one.

![Figure 8](image-url)

**Figure 8.** The Gamow-Teller strength distribution for the decay of $^{104}$Tc obtained within the complex Excited Vampir model compared to TAGS data [27, 28].

Some of the neutron-rich $A \simeq 100$ nuclei play a key role in the safe operation of nuclear reactors being important contributors to the decay heat. 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 [27]. In the following we shall present some results on the Gamow-Teller $\beta$-decay properties of $^{102}$Tc to $^{102}$Ru and of $^{104}$Tc to $^{104}$Ru within the complex Excited Vampir model compared to recent results of the total absorption gamma spectrometer (TAGS) measurements [27, 28]. We calculated the lowest $^1_+$ states in $^{102}$Tc and the positive-parity states up to spin $4^+$ in $^{102}$Ru. For the description of the involved states in $^{102}$Ru we included in the Excited Vampir many-nucleon basis up to 26 EXVAM configurations. The dimension of the many-nucleon EXVAM basis for the $^1_+$ states in $^{102}$Tc was 7. The final solutions have been obtained diagonalizing the residual interaction between the considered Excited Vampir configurations for each spin. 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. In $^{104}$Tc the results indicate completely different structure properties. The $^3_+$ parent state is dominated by one prolate component which represents more than 99% of the total amplitude. The $^2_+$ and $^4_+$ daughter states in $^{104}$Ru manifest variable prolate-oblate mixing. For the states with significant GT strength the contribution of the prolate configurations to the structure of the $^2_+$ states varies from 82% to 9%, while the prolate mixing of the $^4_+$ states varies from 96% to 8%. The deformation of the states is reflected by the spectroscopic quadrupole moments. The $^2_+$ states with significant Gamow-Teller strength contribution display quadrupole moments varying from -43.99 $efm^2$ to 54.44 $efm^2$ (we used as effective charges $e_p = 1.3$, $e_n = 0.3$). The Gamow-Teller strength distribution
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 to TAGS results in figure 8. The strong Gamow-Teller $\beta$-decay branches indicate essential contribution from the $g_9^2/2g_7^{1/2}$, $d_5^2/2d_3^{1/2}$, and $d_5^2/2d_5^{1/2}$ matrix elements. Smaller contributions are obtained from $p_1^2/2p_3^{1/2}$ and $p_0^2/2p_4^{1/2}$ matrix elements. In the case of $^{104}$Tc to $^{104}$Ru decay all matrix elements are relatively small and the cancellations produce the final small strength for each Gamow-Teller contributing state. 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 $\beta$-decay properties of $^{102}$Tc with respect to $^{104}$Tc. 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 is the critical $N = 58$ [8], while in the second case the larger deformation is determined by the $N = 60$ neutrons in the $^{104}$Ru daughter nucleus.

In conclusion, the complex Excited Vampir results concerning the influence of shape coexistence and mixing on the structure and dynamics of neutron-rich nuclei in the $A \approx 100$ mass region are in rather good agreement with the available data. Of course the theoretical results could be changed by the higher-lying configurations not included in the complex Excited Vampir many-nucleon basis so far. Also changes in the renormalization of the effective interaction could influence the shape mixing in the structure of the wave functions as well as the corresponding electromagnetic and Gamow-Teller $\beta$-decay properties.

Acknowledgments

This work was supported by the Romanian National Authority for Scientific Research, CNCS - UEFISCDI - project number PN-II-ID-PCE-2011-3-0153 and the CERN-ISOLDE contract 6/2012, and the DFG (Germany) under the project FA67/36-1.

References

[1] Petrovici A 2010 J. Phys. G: Nucl. Part. Phys. 37 064036
[2] Cowan J J, Thielemann F -K and Truran J W 1991 Phys. Rep. 208 267
[3] Petrovici A, Schmid K W and Faessler A 2000 Nucl. Phys. A 665 333
[4] Petrovici A, Schmid K W, Radu O and Faessler A 2008 Phys. Rev. C 78 044315
[5] Petrovici A, Schmid K W, Radu O and Faessler A 2008 Phys. Rev. C 78 064311
[6] Petrovici A, Schmid K W, Andrei O and Faessler A 2009 Phys. Rev. C 80 044319
[7] Petrovici A 2009 ISOLDE Workshop and Users meeting 2009
[8] Petrovici A 2012 Phys. Rev. C 85 034337
[9] Nara Singh B S et al 2007 Phys. Rev. C 75 061301
[10] de Angelis G et al 2012 Phys. Rev. C 85 034320
[11] Ljungvall J et al 2008 Phys. Rev. Lett. 100 102502
[12] Mach H et al 1991 Nucl. Phys. A 523 197
[13] Lhersonneau G et al 1994 Phys. Rev. C 49 1379
[14] Hamilton J H et al 1995 Prog. Part. Nucl. Phys. 35 635
[15] Urban W et al 2001 Nucl. Phys. A 689 605
[16] Campbell P et al 2002 Phys. Rev. Lett. 89 082501
[17] Hua H et al 2004 Phys. Rev. C 69 014317
[18] Wu C Y et al 2004 Phys. Rev. C 70 064312
[19] Simpson G S et al 2006 Phys. Rev. C 74 064308
[20] Clémente E et al 2010 CERN-INTC 2010-009/INTC-P-216-ADD-108/01/2010
[21] Sumikama T et al 2011 Phys. Rev. Lett. 106 202501
[22] Petrovici A, Schmid K W and Faessler A 2011 J.Phys.:Conf. Series 312 092051
[23] Petrovici A, Schmid K W and Faessler A 2011 Prog. Part. Nucl. Phys. 66 287
[24] Rinta-Antila S et al 2007 Eur. Phys. J. A 31 1
[25] Pereira J et al 2009 Phys. Rev. C 79 035806
[26] Schmitt A, Kaffrell N and Trautmann N 1980 Jahresbericht 1979 34
[27] Algora A et al 2010 Phys. Rev. Lett. 105 202501
[28] Jordan D, Tain J L and Algora A private communication.