Competition of proton and neutron pair breakings: High-spin structures of $^{124-127}$Te isotopes

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Abstract.
In the present work recently available experimental data for high-spin states of four nuclei, $^{124}$Te, $^{125}$Te, $^{126}$Te, and $^{127}$Te have been interpreted using state-of-the-art shell model calculations. The calculations have been performed in the 50-82 valence shell composed of 1$g_{7/2}$, 2$d_{5/2}$, 1$h_{11/2}$, 3$s_{1/2}$, and 2$d_{3/2}$ orbitals. We have compared our results with the available experimental data for excitation energies and transition probabilities, including high-spin states. The results are in reasonable agreement with the available experimental data. The wave functions, particularly, the specific proton and neutron configurations which are involved to generate the angular momentum along the yrast lines are discussed.

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1. Introduction

Neutron rich nuclei in the vicinity of Sn ($Z = 50$) are important in many ways, viz. abundance of isomeric states, a possible candidate of neutrinoless double beta decay ($^{124}$Sn), astrophysical interest etc [1, 2, 3, 4]. The high-seniority states in the case of Sn isotopes with triple pair breaking (seniority $v=6$), has been reported in the literature [5]. This region is also important to test nuclear models for the correct prediction nuclear spectroscopic properties. Beyond Sn many experimental works have recently been done to investigate the nuclear structure properties of Te and Xe isotopes.

Recently Astier et al.[6] populated $^{124-131}$Te isotopes as fission fragments in two fusion-fission reactions $^{18}$O + $^{208}$Pb and $^{12}$C + $^{238}$U induced by heavy ions, using Euroball array. In this experiment high-spin level schemes extended up to 6 MeV (for even-Te) and 5 MeV (for odd-Te). The yrast excitations in $A = 126 - 131$ Te isotopes from deep inelastic $^{130}$Te+$^{64}$Ni reactions were reported in ref. [7]. In this work, the information especially on yrast excitations in the odd-A $^{127,129,131}$Te isotopes is discussed. Both single-particle and collective aspects of the level spectra are analyzed there.

High-spin states of $^{136}$Xe, $^{137}$Cs, $^{138}$Ba, $^{139}$La and $^{140}$Ce are populated by Astier et al [8] for $N = 82$ isotones. In the frame work of shell model we have interpreted these experimental data successfully for these nuclei in ref. [9]. In this mass region previously one of us have analyzed experimentally observed slow $E3$ transition in $^{136}$Cs [10] which was populated at ISOLDE facility at CERN and also for the high-spin states of $^{136}$Cs [11] which were populated by XTU Tandem accelerator at Legnaro and Vivitron accelerator of IRes, Strasbourg. $B(E2)$ transition trends have recently been studied by I. O. Morales et al [12] in tin isotopes using generalized seniority approach.

The aim of the present work is to discuss shell model results of newly populated high-spin states of $^{124-127}$Te isotopes [6]. This work will add more information to the work by Astier et al [6] on Te isotopes, where shell model result of only for $^{128-131}$Te isotopes were reported.

This work is organized as follows: comprehensive comparison of shell-model results and experimental data are given in Section 2. In Section 3, transition probabilities are compared with the available experimental data. Finally, concluding remarks are drawn in Section 4.

2. Shell model results and discussions

The shell-model calculations for the Te isotopes have been performed in the 50-82 valence shell composed of the orbits $1g_7/2$, $2d_5/2$, $1h_{11/2}$, $3s_{1/2}$, and $2d_{3/2}$. We have performed calculations with SN100PN interaction due to Brown et al [13]. This interaction has four parts: neutron-neutron, neutron-proton, proton-proton and Coulomb repulsion between the protons. The single-particle energies for the neutrons are -10.6089, -10.289, -8.717, -8.694, and -8.816 MeV for the $1g_7/2$, $2d_5/2$, $2d_{3/2}$, $3s_{1/2}$, and $1h_{11/2}$ orbitals, respectively,
and those for the protons are 0.807, 1.562, 3.316, 3.224, and 3.605 MeV. The results shown in this work were obtained with the code NuShellX \cite{14}. In the present work we have employed truncation for neutrons orbitals. For $^{124,126}$Te, we filled completely $\nu g_{7/2}$ orbital and put minimum 4 particles in $\nu d_{5/2}$ orbital. In the case of $^{125,127}$Te, we slightly relaxed truncation by filling completely $\nu g_{7/2}$ orbital and putting only minimum 2 particles in $\nu d_{5/2}$ orbital.

2.1. Analysis of spectra

The comparisons of calculated and experimental spectra for $^{124-127}$Te isotopes are shown in Figs. 1, 3, 5, 7.

2.1.1. $^{124}$Se: The spin sequence of the calculated positive parity energy levels are the same as in the experiment, however the energy levels $2^+, 4^+, 6^+, 8^+, 10^+, 12^+, 14^+, 14^+_2, 15^+, 16^+_1$ are 124, 316, 451, 939, 1108, 1284, 1410, 1373, 1338, and 1594 keV lower than in the experiment, respectively. The calculated energy levels in the shell model are compressed as compared to the experimental ones. This is because of the truncation while filling the neutrons in the model space, which we discuss in the details of calculation. In the case of negative parity energy levels, model predicts the $7^-$ (847 keV) lower than in the experiment. The calculated $11^-$ level is 105 keV lower than the $9^-$. The order of the calculated negative energy levels are the same as in the experiment. There is 586 keV energy difference between the levels $9^-_1$ and $9^-_2$ in shell model while this difference is very small (61 keV) in the experiment. The energy levels $9^-_1, 9^-_2, 11^-$, and $12^-$ are 981, 456, 1198 and 980 keV lower, than in the experiment, respectively.

From the analysis of the wave functions it is possible to identify which nucleon pairs are broken to obtain the total angular momentum of the calculated states. The two components for neutrons and protons are $I_n$ and $I_p$, respectively. These components are coupled to give the total angular momentum of each states. In the figs. 2 (a) -(d), we have shown results of positive parity states of $^{124}$Se. The dominant component (46%) of the $10^+$ state predicted at 2044 keV comes from the neutron pair breaking ($I_n = 10$), the two protons being paired ($I_p=0$). The $12^+$ and $14^+_1$ states are due to breaking of both neutrons and protons pairs. The states $12^+$ and $14^+_1$ are collective states. The $14^+_2$ state at 3383 keV has mainly from $I_p=6$ (with $I_n=8-12$). Here, the two angular momenta are fully aligned and the proton pair are broken. The above three families are drawn with three different colors, the magenta color is for breaking of neutron pairs, the green color is for that of protons and blue color is for many components with various values of $I_n$ and $I_p$.

The negative parity states are shown in figs. 2 (e) -(h). The dominant component (49 %) of 7$^-$ comes from the neutron pair breaking ($I_n = 7$), the two protons being paired ($I_p=0$). Similarly the 13$^-$ (at 3247 keV) and 15$^-$ (at 3717 keV) are also from the neutron pairs breaking of $I_n=13$ and 15, respectively. Here, the two protons are paired ($I_n=0$). The 11$^-$ (at 2789 keV) shows many components. Thus unlike the positive
Figure 1. Comparison of calculated and experimental excitation spectra for \(^{124}\text{Te}\) using SN100PN interaction.
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Figure 2. Decomposition of the total angular momentum of selected states of $^{124}$Te into their $I_n \otimes I_p$ components. The percentage above 10% are written inside the squares, drawn with an area proportional to it. Percentage below 5% are not written.

parity, the negative parity states are not coming from the proton pair pair breaking.

2.1.2. $^{125}_{52}$Te: The $1/2^+$ is a ground state while isomeric $11/2^-$ state is at 145 keV in the experiment. For this isotope shell model fails to predict the ground state. It is $11/2^-$ in the calculation and the next level is $3/2^+$ at 129 keV. The $3/2^+$ energy level in the shell model calculation is higher by 94 keV than in the experiment. After these two positive parity levels the order of the calculated positive parity energy levels are the same as in the experiment but the calculated value of the levels beyond $7/2^+$ are lower than in the experiment. The calculated $7/2^+$ level is higher by 49 keV than in the experiment. The calculated energy levels $11/2^+$, $15/2^+$, $23/2^+$, $27/2^+$ and $31/2^+$ are 59, 143, 680, 778, and 751 keV lower than in the experiment, respectively. The calculated $11/2^-$ level is 145 keV lower than experiment. The sequence of experimental $25/2^-$, $25/2^-27/2^-27/2^-1$ levels is predicted as $25/2^-$, $27/2^-25/2^-27/2^-$ in shell model. There is very small energy difference (16 keV) between $25/2^-$ and $27/2^-$ in shell model while this energy difference is 703 keV in experiment. Overall the spin sequence of the calculated negative energy levels are the same with the experimental data. The energy difference between calculated and experimental levels are greater at higher spins.

In figs. 4 (a) -(d) the components of negative parity states of $^{125}$Te are given. The $21/2^-$ state is predicted at 1440 keV comes from the proton pair breaking ($I_p = 6$), this has one odd neutron in the $h_{11/2}$ orbit. The major components (41%) of the $27/2^-$ (2112 keV) state comes from the neutron pair breaking ($I_n = 27/2$), the two protons being paired ($I_p = 0$). The $29/2^-$ (2730 keV) state comes from the proton breaking ($I_p = 6$). The $31/2^-$ (2780 keV) state displays many components with various values of
Figure 3. Comparison of calculated and experimental excitation spectra for $^{125}$Te using SN100PN interaction.
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Figure 4. Decomposition of the total angular momentum of selected states of $^{125}$Te into their $I_n \otimes I_p$ components. The percentage above 10% are written inside the squares, drawn with an area proportional to it. Percentage below 5% are not written.

$I_n$ and $I_p$. The components of positive parity states are shown in figs. 4 (e) - (h). The $15/2^+$ state predicted at 1426 keV comes from the neutron breaking ($I_n = 15/2$), the two protons being paired ($I_p = 0$). The major component of $23/2^+$ increases to 51% with the neutron pair breaking ($I_n = 23/2$). The $27/2^+$ state exhibits many components with various values of both $I_n$ and $I_p$ (similar results are obtained for $31/2^+$ state at 3310 keV).

2.1.3. $^{126}_{52}$Te: The calculated $2^+$, $4^+$ and $6^+$ levels are 118, 254 and 213 keV lower than in the experiment. The spin sequence of the positive parity energy levels are the same with the experiment, excluding 4137 keV experimental level to which no spin and parity has been assigned yet. The calculated energy levels $8^+_1$, $10^+_1$, $12^+_1$, $13^+_1$, $14^+_1$, $14^+_2$, $15^+_1$, $16^+_1$, and $16^+_2$ are 823, 821, 925, 993, 1021, 953, 959, 1229 and 1254 keV lower than in the experiment, respectively. The unassigned spin and the parity of the energy levels at 4137 keV can not be definitely assigned with the shell model because of the large energy difference between calculated and experimental levels.

The lowest negative parity energy level is $5^-$, both in the calculation and experiment. The calculated $5^-$ level is 371 keV lower than in the experiment. The energy levels $6^-$ and $7^-$ are interchanged in shell model and the energy difference between these two pair is 43 keV in shell model, while it is 343 keV in the experiment. The spin sequence of the calculated negative parity levels are the same as in the experiment, but energies are lower than in the experiment. In the shell model the energy difference between $11^-$ and $12^-$ levels are 158 keV while this difference is 412
Figure 5. Comparison of calculated and experimental excitation spectra for $^{126}\text{Te}$ using SN100PN interaction.
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Figure 6. Decomposition of the total angular momentum of selected states of $^{126}$Te into their $I_n \otimes I_p$ components. The percentage above 10% are written inside the squares, drawn with an area proportional to it. Percentage below 5% are not written.

keV in the experiment. There is one unassigned level at 2811 keV between the $5^-$ and $6^-$ in the experiment. Shell model predicts this level at 1915 keV ($4^-$) which is not shown in figure 5 because of the small difference in energies. The energy difference between the pair of $5^-$ and $6^-$ levels is 147 keV in shell model while this difference is 620 keV in the experiment. The levels $13^-_1$, $13^-_2$, $15^-_1$, and $17^-_1$, are 917, 824, 1077, and 1154 keV lower than in the experiment, respectively.

In figs. 6 (a) -(h) the components of positive and negative parity states of $^{126}$Te are given. The $12^+$ state is due to the neutron pair breaking. For these isotopes, the $10^+$ (2151 keV) has major component (55%) from the neutron pair breaking ($I_n = 10$), the two protons being paired ($I_p = 0$). Similar feature exhibits the $12^+$ state with major component (36%) from the neutron pair breaking ($I_n = 12$), the two protons being paired ($I_p = 0$). The $14^+_2$ state at 3679 keV has mainly from $I_p=6$ (with $I_n=8\text{-}12$). Here, also the two angular momenta are fully aligned and the proton pair being broken. The $14^+_1$ state at 3515 keV have mixed components.

The negative parity states show the same trend as in $^{124}$Te. The major components for $7^-$(2037 keV), $13^-$ (3668 keV) and $15^-$ (4034 keV) increases while $11^-$ (3263 keV) state component becomes more mixed. From $^{126}$Te to $^{128}$Te, the same trend is reported in ref. [6]. This shows that the reasonable truncation is used in the calculation.
2.1.4. \(^{127}\text{Te}\): The shell model predicts \(3/2^+\) level at 117 keV which is the experimental ground state. The spin sequence of the positive parity energy levels beyond \(7/2^+\) are exactly the same energies and are lower than in the experiment. The \(7/2^+\) level in shell model is higher by 96 keV than in the experiment. The tentative \(11/2^+\) level at 1289 keV in the experiment is confirmed by shell model as a \(11/2^+\) level. The \(15/2^+\) level in shell model is lower by 263 keV than in the experiment. The energy levels 23/2\(^+\), 27/2\(^+\), 29/2\(^+\), and 31/2\(^+\) are 448, 516 773, and 748 keV lower than in the experiment, respectively.

Shell model predicts \(11/2^-\) as the ground state which is the lowest negative parity energy level at 88 keV in the experiment. The order of the calculated energy levels up to \(21/2^-\) is the same as in the experiment, the \(23/2^-\) - \(21/2^-\) are interchanged in shell model. The \(23/2^-\) level is 437 keV lower, and the \(21/2^-\) is higher by 131 keV than the experiment. The energy difference between \(19/2^-\) and \(19/2^-\) is 369 keV in shell model, while this difference is 81 keV in the experiment. The energy levels \(27/2^-\), \(27/2^-\), \(29/2^-\), \(31/2^-\), \(31/2^-\), \(33/2^-\), and \(35/2^-\) are 815, 692, 792, 739, 854, 716 and 868 keV lower than in the experiment, respectively.

In figs. 8 (a) -(d) the components of negative parity states of \(^{127}\text{Te}\) are given. The \(21/2^-\) state (46 %) predicted at 1662 keV comes from breaking of the proton pair \((I_p = 6)\), this has one odd neutron in the \(h_{11/2}\) orbit. The major components (55\%) of the \(27/2^-\) (2192 keV) state comes from the neutron pair breaking \((I_n = 27/2)\), the two protons being paired \((I_p = 0)\). The \(31/2^-\) (3031 keV) state exhibits many components with various values of both \(I_n\) and \(I_p\) (similar results are obtained for \(29/2^-\) state at 3054 keV).

The components of positive parity states are shown in figs. 8 (e) -(h). The \(15/2^+\) state (51\%) predicted at 1407 keV comes from the neutron pair breaking \((I_n = 15/2)\), the two protons being paired \((I_p = 0)\). Similarly, for \(23/2^+\) state (53\%) predicted at 1865 keV comes from the neutron breaking \((I_n = 23/2)\), the two protons being paired \((I_p = 0)\). The \(27/2^+\) state (2614 keV) exhibits many components with various values of both \(I_n\) and \(I_p\). Similar results are obtained for \(29/2^+\) state at 2919 keV. For the positive parity states trends are similar as we move from \(^{125}\text{Te}\) to \(^{127}\text{Te}\). However in the case of \(^{129}\text{Te}\), the \(29/2^+\) state (3422 keV) is due to the proton pair breaking \((I_p = 6)\) \(^{[6]}\), while this state in \(^{127}\text{Te}\) at 2919 keV has mixed components.

3. Transition probability analysis

The comparison of the transition probabilities with the experiment data is given in Table 1. The three set of effective charges are used in the calculation. The overall calculated values of \(B(E2;2^+\rightarrow 0^+_1)\) transition probabilities are in good agreement with the experimental ones with \(e_\pi = 1.47e\) and \(e_\nu = 0.64e\). The three set of results indicating that \(E2\) transition probability is very much sensitive on effective charge of neutrons. The \(B(E2;6^+_1\rightarrow 4^+_1)\) values for \(^{126,128,130,132}\text{Te}\) are in good agreement with experimental value, while \(B(E2;10^+_1\rightarrow 8^+_1)\) for \(^{126}\text{Te}\) is slightly lower and for \(^{128}\text{Te}\) is
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| Isotope | Calculated Energies (keV) | Experimental Energies (keV) |
|---------|--------------------------|----------------------------|
| $^{127}$Te | 4816 $(35/2^-)$ | |
| | 4422 $(33/2^-)$ | |
| | 4241 $(31/2^-)$ | |
| | 4029 $(31/2^+)$ | |
| | 3823 $(31/2^-)$ | 3948 $(35/2^-)$ |
| | 3793 $(29/2^-)$ | 3706 $(33/2^-)$ |
| | 3692 $(29/2^+)$ | |
| | 3352 $(27/2^-)$ | 3387 $(31/2^-)$ |
| | 3130 $(27/2^+)$ | |
| | 3007 $(27/2^-)$ | 3054 $(29/2^-)$ 3031 $(31/2^-)$ |
| | 2660 $(27/2^-)$ | |
| | 2416 $(23/2^-)$ | 2192 $(27/2^-)$ |
| | 2313 $(23/2^+)$ | 2086 $(21/2^-)$ 1979 $(23/2^-)$ |
| | 1955 $(21/2^-)$ | |
| | 1856 $(21/2^-)$ | |
| | 1670 $(15/2^-)$ | 1662 $(21/2^-)$ 1613 $(19/2^-)$ |
| | 1545 $(19/2^-)$ | |
| | 1464 $(19/2^-)$ | |
| | 1289 $(11/2^-)$ | 1244 $(19/2^-)$ |
| | 1202 $(11/2^+)$ | |
| | 781 $(7/2^-)$ | 786 $(15/2^-)$ |
| | 685 $(7/2^+)$ | 618 $(15/2^-)$ |
| | 88 $(11/2^-)$ | |
| | 0 $(3/2^-)$ | 0 $(11/2^-)$ |

**Figure 7.** Comparison of calculated and experimental excitation spectra for $^{127}$Te using SN100PN interaction.
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Figure 8. Decomposition of the total angular momentum of selected states of $^{127}$Te into their $I_n \otimes I_p$ components. The percentage above 10% are written inside the squares, drawn with an area proportional to it. Percentage below 5% are not written.

higher. The calculated $B(M4; 11/2^-_1 \rightarrow 3/2^+_1)$ for $^{127}$Te is 16.21 W.u. ($g_s^{\text{eff}} = g_s^{\text{free}}$) and 7.95 W.u. ($g_s^{\text{eff}} = 0.7g_s^{\text{free}}$), corresponding experimental value is 3.6 W.u. For $^{130}$Te the calculated $B(M2; 7^-_1 \rightarrow 6^+_1)$ value is 0.00139 W.u. ($g_s^{\text{eff}} = g_s^{\text{free}}$), while corresponding experimental value is 0.013(3) W.u. We have also calculated $B(E2; 7/2^+_1 \rightarrow 3/2^+_1)$ value for $^{127}$Te, however experimental data for this transition is not available.

4. Summary

We have performed shell model calculation for recently available experimental data for $^{124}$Te, $^{125}$Te, $^{126}$Te and $^{127}$Te isotopes. This work will add more information in [6] where high spin states of $^{124-131}$Te isotopes are populated and shell model results on $^{128-131}$Te isotopes reported.

The broad conclusions from present work is following:

- The yrast states of the four $^{124-127}$Te isotopes are very well described by shell model.
- From the components of the wave functions, particularly the two values of $I_n$ and $I_p$ it is possible to identify which nucleon pairs are broken to obtain the total angular momentum of the calculated particular high-spin states.
- The electric transition probabilities are in reasonable agreement with the experimental data with $e_\pi = 1.47e$ and $e_\nu = 0.64e$.
- High-spin states in nuclei $Z \sim 50$ is expected from breaking of neutron/proton pairs. Experimentally it is difficult to detect the de-excitation of these high-spin states through long-lived isomers. For theory it is an ideal test of the two-body matrix elements of the residual interactions to reproduce these states.
### Table 1

Experimental and calculated $B(E2)$, $B(E3)$, $B(M2)$ and $B(M4)$ values in W.u. for different transitions. Experimental results are taken from ref. [15].

| Nucleus | Transition | Expt. | Calc. I | Calc. II | Calc. III |
|---------|------------|-------|---------|----------|-----------|
|         | $e_\pi = 1.5e$, $e_\nu = 0.5e$ | $e_\pi = 1.47e$, $e_\nu = 0.64e$ | $e_\pi = 1.5e$, $e_\nu = 1.41e$ |
| $^{124}$Te | $B(E2; 2^+_1 \rightarrow 0^+_1)$ | 31.1 (5) | 12.27 | 15.25 | 40.59 |
|         | | 97.529 (4) | 18.27 | 22.98 | 57.69 |
| $^{125}$Te | $B(E2; 3/2^+_1 \rightarrow 1/2^+_1)$ | 11.9(24) | 0.59 | 0.736 | 2.37 |
|         | | 4.8(24) | 9.88 | 12.30 | 32.78 |
| $^{126}$Te | $B(E2; 2^+_1 \rightarrow 0^+_1)$ | 25.4 (7) | 11.12 | 14.00 | 38.65 |
|         | | 34.16 | 16.52 | 20.59 | 55.22 |
|         | $B(E2; 6^+_1 \rightarrow 4^+_1)$ | 17.8(6) | 17.09 | 20.89 | 53.12 |
|         | | 2.50(19) | 0.14 | 0.19 | 0.67 |
| $^{127}$Te | $B(E2; 7/2^+_1 \rightarrow 3/2^+_1)$ | N/A | 6.10 | 7.50 | 19.31 |
| $^{128}$Te | $B(E2; 2^+_1 \rightarrow 0^+_1)$ | 19.62(18) | 10.42 | 13.01 | 35.02 |
|         | | 9.7(6) | 5.51 | 6.40 | 14.00 |
|         | $B(E2; 10^+_1 \rightarrow 8^+_1)$ | 1.40(12) | 2.88 | 3.76 | 11.23 |
| $^{130}$Te | $B(E2; 2^+_1 \rightarrow 0^+_1)$ | 15.1(3) | 8.04 | 9.75 | 29.14 |
|         | $B(E2; 6^+_1 \rightarrow 4^+_1)$ | 6.1(3) | 3.63 | 4.07 | 7.96 |
| $^{131}$Te | $B(E3; 23/2^+_1 \rightarrow 19/2^+_1)$ | 0.0151(20) | 0.0044 | 0.0072 | 0.031 |
| $^{132}$Te | $B(E2; 6^+_1 \rightarrow 4^+_1)$ | 3.3(2) | 2.61 | 2.75 | 4.30 |
|         | $B(E2; 19/2^+_1 \rightarrow 15/2^+_1)$ | 2.56(14) | 2.55 | 2.44 | 2.48 |

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