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Proton-Induced Nuclear Reactions on Tellurium Isotopes (^{125}Te, ^{126}Te) at Intermediate Energies (10-100 MeV) Using Code COMPLET

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Abstract

Theoretical nuclear model predictions were carried out using computer code COMPLET to calculate the excitation function of ^{125}Te(p,xn)^{124,123,121}I, x=2,3,5 and ^{126}Te(p,xn)^{125,124,123}I, x=2-4 reaction channels respectively. The aim of this study is to investigate proton-induced nuclear reactions on Tellurium isotopes (^{125}Te, ^{126}Te) at intermediate energies (10-100MeV) using COMPLET code and EXFOR database based on compound nucleus and pre-equilibrium stage of nuclear reactions. The calculated pre-equilibrium and compound nucleus excitation functions are discussed and compared with the experimental data taken from EXFOR database and indicated a considerable positive and strong correlation as $0.7 \leq R < 1$ for all six reaction channels. There is a good agreement between theoretical cross-sections and experimental data from the EXFOR data center. This work also demonstrates that for each reaction channels, the low-energy ranges are dominated by the compound nucleus reaction mechanism, whereas the high-energy ranges are dominated by the pre-equilibrium reaction mechanism.

Keywords: COMPLET; cross-section; exciton; level density; tellurium isotope.

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1. Introduction

Excitation functions of proton induced nuclear reactions on stable isotopes of Tellurium are of great practical importance in the production of different radioisotopes of iodine via (p,xn) reactions [1]. Nuclear reactions those induced by proton particles on tellurium isotopes at intermediate energies (10-100MeV) have significance in various fields including nuclear medicine, industrial applications, and fundamental nuclear physics [2,6].

Data including model prediction on excitation functions [7] concerning nuclear reactions induced by intermediate energy protons hold significant importance across various fields including space and environmental sciences (for understanding and mitigating radiation effects in space environments), medical sciences (for ensuring the efficacy and safety of medical procedures), activation technology particularly in accelerator-based nuclear waste transmutation(to optimize waste management strategies and energy production processes) [8,11].

At intermediate excitation energies, reactions induced by nucleons and light-charged projectiles are found to proceed through the equilibrium (EQ) and pre- equilibrium (PE) mode reactions [12].

Understanding reaction mechanisms requires evaluating reaction cross-section data, and comparative studies using experimental data and theoretical predictions are crucial. In this regard, nuclear reaction model-based computer codes can swiftly help to predict unknown reaction cross-sections and thus improve computer code predictions. Studies of proton induced nuclear reactions help better understand the reaction mechanisms and test the validity of various available and newly evolving computer codes. Additionally, because of the intense competition between the PE and EQ modes of reactions at intermediate excitation energies, the processes of PE and EQ particle(s) emission are crucial for understanding and describing the reaction mechanisms in proton-induced nuclear reactions.

The equilibrium mode of reaction mechanism dominates in the low energy region (generally below 20 MeV). In the equilibrium mode of reactions, the projectile is captured by the target nucleus, and shared its energy with nucleons, losing their identity and forming a single excited complex system that eventually leads to a fully equilibrated compound nucleus. The equilibrium emissions of nuclear reactions are usually treated using statistical models like Hauser-Feshbach and Weisskopf-Ewing formalism. The Pre-equilibrium mode of reaction mechanism becomes increasingly crucial at a relatively high energy region (above ≈20 MeV) and particle emissions occur before the compound nucleus fully equilibrated and are usually treated using non-statistical models like exciton model, and geometry-dependent hybrid model [13].

Tellurium isotopes, particularly ^{125}Te and ^{126}Te, hold significance in nuclear physics and various scientific applications due to their unique nuclear properties. ^{126}Te is one of the most common stable isotopes of tellurium and with its abundant and stable properties, is widely used in nuclear medicine and semiconductor manufacturing, particularly in the synthesis of cadmium telluride (CdTe) semiconductor materials for solar cells and radiation detectors. ^{125}Te, despite its shorter half-life, it is used in nuclear medicine and environmental monitoring. According to IAEA, it is commonly employed as a tracer for studies on environmental processes including sedimentation and groundwater movement because of its tendency to produce gamma radiation that may be picked up by sensitive detectors [14].

Nuclear reactions that can be generated through laboratory accelerators offer the most nuclear data in terms of both volume and variety. For a large range of energies, it is both economically and practically impossible to measure the necessary cross section for every isotope in the periodic table; hence, estimates are typically required from nuclear reaction models. Subsequently, the computation of nuclear reaction models is crucial to the assessment of nuclear data.

Several studies on proton induced reactions on tellurium isotopes using theoretically predicted and experimentally measured reaction cross sections have been done [15,17] in attempts to explain these reaction mechanisms. To the best of our knowledge, no such computation employing Code COMPLET has been published in any literature for these particular reactions.

To explain the compound nucleus and pre-equilibrium emission of particles in reactions, to test nuclear models used in Code COMPLET, and to explain the underlying physics, one must have a priori knowledge of the excitation functions. The pre-equilibrium and compound nucleus processes caused by intermediate energy proton projectiles (10-100 MeV) were investigated [18,21].

The present study was undertaken with three aims: The first one is to compute the theoretical prediction of the compound nucleus model and pre-equilibrium model for proton-induced reactions on (^{125}Te and ^{126}Te) within 10-100MeV in order to enhance the quality of the available data from EXFOR. The second one is to investigate the dominance reaction processes within the designated energy regions. The third one is to validate how the theoretical result agrees with the experimental value.

2. Materials and Methods

2.1. Stimulation Techniques Using Computer Code COMPLET

To investigate the behavior of reaction processes, to check the prediction power of theoretical models, and to validate how the theoretical result agrees with the experimental value from EXFOR, nuclear model calculations were performed using the code COMPLET by adjusting nuclear model input parameters [22].

The code COMPLET was used to calculate the cross-section of ^{125}Te (p,xn)^{124,123,121}I, x=2,3,5 and ^{126}Te(p,xn)^{125,124,123}I, x=2- 4 reaction channels within 10-100MeV energy ranges.

2.2. Computer Code COMPLET

Code COMPLET is a versatile computational tool designed to handle various reaction mechanisms including compound nucleus and pre-equilibrium reactions induced by different types of particles, such as protons, neutrons, and heavy ions, widely used in nuclear physics research for simulating nuclear reactions and predicting reaction cross-sections [23]. When experimental data are unavailable or measurement of reaction cross-sections is impractical due to experimental challenges, the code COMPLET, an improved version of ALICE-91, is crucial. The code employed Weisskopf-Ewing model for the statistical part and geometry dependent hybrid model of M.Blann for the pre-equilibrium emission [24]. To generate the theoretical cross section data, parameters such as exciton number, level density parameter, atomic mass and charge of target nucleus and proton projectile were entered into the code COMPLET. In pre-equilibrium emission calculations, the initial exciton number and level density parameters are very essential quantities [25]. The nuclear level density influences the shape and the height of the calculated excitation functions [26,27].

2.3. Experimental Results

The experimental data for the reaction ^{125}Te(p,2n)^{124}I, ^{125}Te(p,3n)^{123}I, and ^{125}Te(p,5n)^{121}I are taken from authors Reference [28] and ^{126}Te(p,2n)^{125}I, ^{126}Te(p,3n)^{124}I, and ^{126}Te(p,4n)^{123}I are taken from [29], which are available in EXFOR [30].

2.4. Data Analysis Procedure

In this study, data were properly and systematically organized in table (Tables 1-6), graphically described using Origin and spreadsheet software, and analyzed using Pearson's correlation coefficient by quantifying the relationship between experimental and theoretical data.

$$R = \frac{\sum_i^N (XTi-<XT>)(XEi-<XE>)}{(N-1)(SXT)(SXE)} \quad (1)$$

Where, R is the correlation coefficient and unit less, N is the number of the theoretical and experimental data, $<XT>$ and $<XE>$ are the mean theoretical and experimental reaction cross-sections, XTi and XEi are the theoretical and experimental total cross-sections of the value, SXT and SXE are the standard deviations of the theoretical and experimental total cross-sections respectively.

$$<XT> = \frac{1}{N}\sum_{i=1}^N (XTi),\ SXT = \sqrt{\frac{1}{N-1}\sum_{i=1}^N (XTi-<XT>)} \quad (2)$$

$$<XE> = \frac{1}{N}\sum_{i=1}^N (XEi),\ SXE = \sqrt{\frac{1}{N-1}\sum_{i=1}^N (XEi-<XE>)} \quad (3)$$

The value of R is in between -1 and 1. Where, 1 is the total positive linear correlation, 0 is no linear correlation, and -1 is total negative linear correlation. If $0 < R < 0.3$, the correlation is weak and positive, $0.3 \le R < 0.7$, describes a moderate correlation and $0.7 \le R < 1$, the correlation is strong and positive [31].

3. Results and Discussion

The experimental data with their uncertainties from EXFOR and the theoretical data for the mentioned six reaction channels from code COMPLET are presented in table (Tables 1-6) and in graph (figures 1-6) and discussed below. To get the desired theoretical outcome from code COMPLET for these reactions, calculation of the reaction cross-sections being done more than once by varying an input parameter factor. The theoretical calculations were done by taking the initial exciton $n = 3$ with configurations (2p+1h) and the level density parameter, $a = \frac{A_{CN}}{10}$.

3.1. Determination of Cross-Sections of the Reactions

3.1.1. Cross-Sections of the $\mathbf{125}\boldsymbol{Te}\ (\boldsymbol{p}, \mathbf{2}\boldsymbol{n})\ \mathbf{124}\boldsymbol{I}$ Reaction

At 10.6 MeV, neither model can estimate the cross section. Both models overestimate the reaction; the cross-section grows rapidly with energy, and the pre-compound model predicts values that are lower than the compound model from 13.3 MeV to 18.5 MeV, with a peak at 18.5 MeV. Compounds show a rapid fall in cross-section above 25.1 MeV, reaching almost zero (0.01 mb) at 45.2 MeV, while the pre compound shows a more gradual drop in cross-section that remains relatively bigger. Strong and positive correlations are found between the theoretical and experimental excitation functions, with values of R = 0.9674 for the compound nucleus and R = 0.9881 for the pre-equilibrium. The compound model shows reasonable agreement with the experimental data in the low-energy range. In medium - high energy range, both models predict close to zero cross-sections, failing to match the experimental data, which still shows finite values.

Table 1: Measured and calculated cross-sections for the reaction $^{125}Te(p,2n)^{124}I$

Proton energy (MeV)	**Total cross-section (mb)**		
	Expt. data	**Theo. compound**	**Theo. pre-compound**
10.3	1±0.45	67.46	59.47
11.3	238.9±107.51	331.10	288.40
12.2	412.5±185.63	588.60	506.80
13.9	605.4±272.43	784.60	671.60
14.6	778.1±350.15	921.20	785.00
15.8	733.5±330.08	1,019.00	868.00
16.6	956.7±430.52	1,096.00	933.30
17.6	1045.3±470.39	1,159.00	987.50
19.1	888.6±399.87	1,144.00	996.30
20.3	701.7±315.77	959.30	886.30
23.1	671.3±302.09	332.20	521.80
25.9	268.8±120.96	133.30	413.30
28.2	165.2±74.34	30.53	345.80
30.6	203.1±91.40	10.84	316.30
32.7	149±67.05	3.81	295.00
36.1	104.5±47.03	0.51	269.30
38.4	162.8±73.26	0.19	255.40
41.3	92.9±41.81	0.04	235.70
45.4	85±38.25	0.01	213.50
60.8	86.3±38.84	0.00	143.10
70.8	61.4±27.63	0.00	115.40
80.7	57.1±25.70	0.00	90.49
90.5	40±18	0.00	86.05
100	36.1±16.25	0.00	72.75

$\boldsymbol{Exciton\ number\ (n) = 3\ and\ Level\ density (a) = \frac{A_{CN}}{10}}$

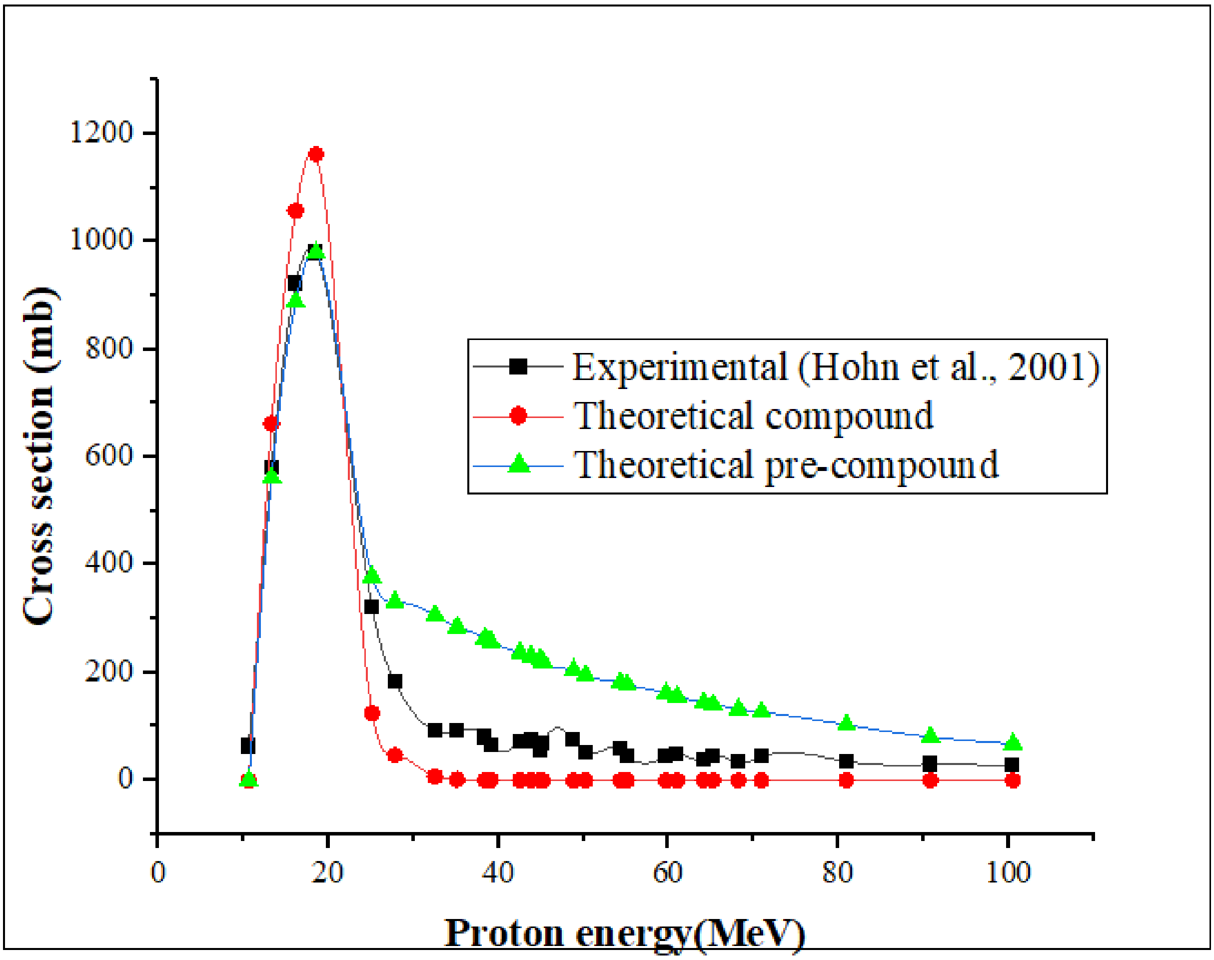

Figure 1: Experimental and theoretical excitation functions for ^{125}Te (p,2n)^{124}I

3.1.2. Cross-Sections of the $125Te\ (p,3n)124I$ *Reaction*

Both models show increasing cross-sections with energy, but the compound model shows a more rapid increase from 21.5 MeV to 26.1 MeV. After 31.5 MeV the compound model shows a steep drop in cross-sections, continues to decrease to almost zero (0.03 mb) at 59.7 MeV and higher energies and the pre compound model shows cross section decline much more gradual and maintaining relatively higher values compared to the compound model. The correlation of the theoretical & experimental excitation functions is strong and positive with the values of R = 0.8862 for compound nucleus & R = 0.955 for pre-equilibrium. Pre-compound model shows better agreement with experimental data, especially at medium and high energies. The compound model predicts higher cross-sections at low energies but becomes negligible as energy increases.

Table 2: Experimental and theoretical excitation functions for $^{125}Te(p,3n)^{123}I$

Proton energy (MeV)	Total cross-section (mb)		
	Expt.data	**Theo.compound**	**Theo.pre-compound**
21.5±0.5	38±6	85.89	52.66
23.3±0.5	292±47	514.00	301.20
26.1±0.5	674±108	1,097.00	623.70
31.5±0.4	885±142	1,041.00	642.10
38.8±0.3	484±77	147.50	307.90
39.5±0.3	291±47	102.00	288.00
43.8±0.2	251±40	21.61	242.50
44.9±0.2	134±21	14.50	235.50
45.3±0.2	172±28	9.71	229.00
48.8±0.5	206±33	2.83	212.50
50.2±0.5	101±16	1.26	203.00
54.3±0.4	164±26	0.24	192.20
55.1±0.4	84±13	0.16	188.30
59.7±0.3	82±13	0.03	173.60
61±0.3	172±28	0.01	166.60
64.1±0.2	64±10	0.00	155.50
68.2±0.2	60±10	0.00	143.60

$$\textit{Exciton number } (n) = 3 \textit{ and Level density}(a) = \frac{A_{CN}}{10}$$

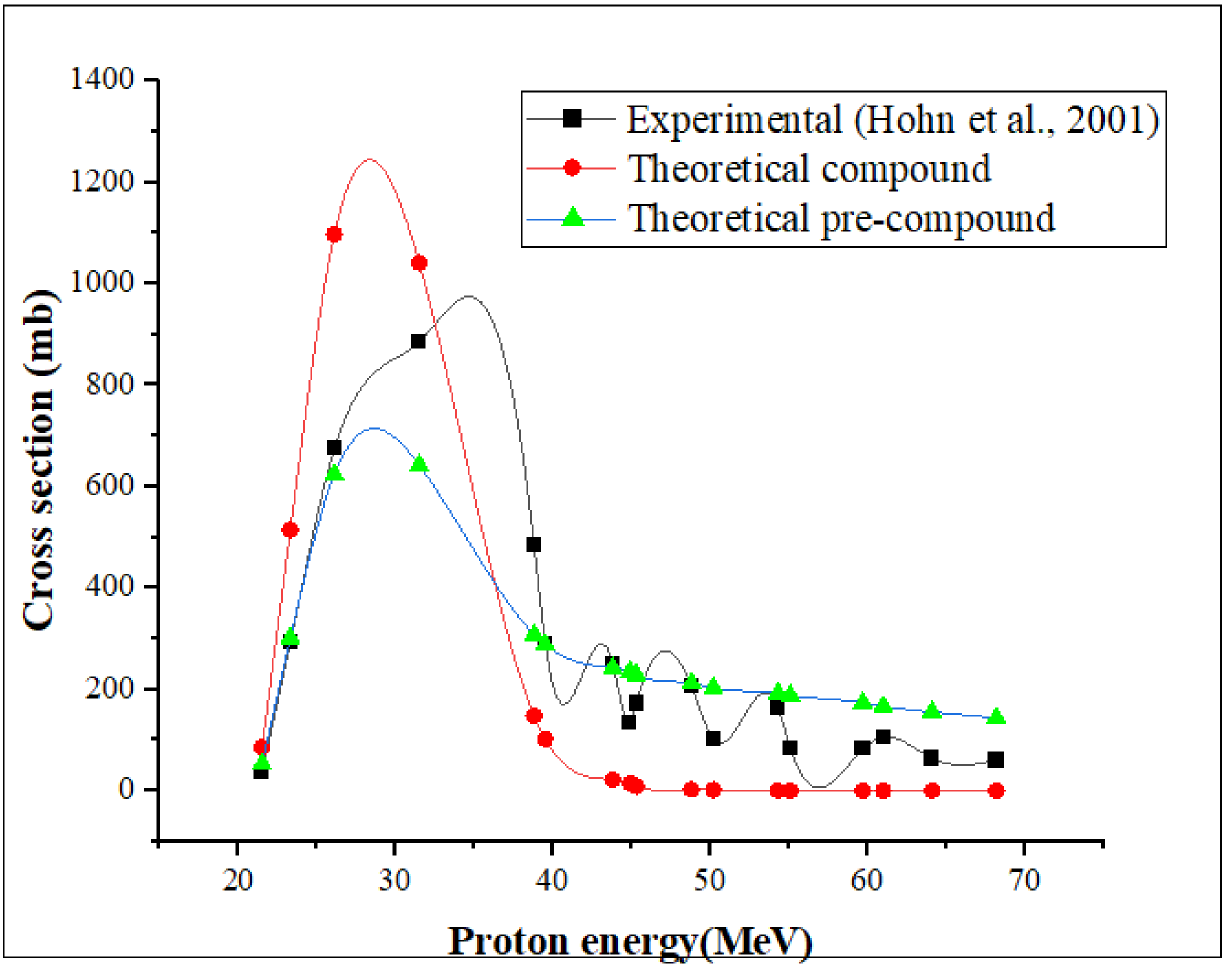

Figure 2: Experimental and theoretical excitation functions for $^{125}Te(p,3n)^{123}I$

3.1.3. Cross-Sections of the $125Te\ (p, 5n)\ 121I$ Reaction

The cross section increases with energy for both models but at a slower rate in pre-compound, peaks at 54.3 MeV. The prediction begins to drop at 61.0 MeV for both models. The compound model decreases rapidly beyond 65 MeV, essentially reaching zero at higher energies (above 80 MeV). The model predicts negligible cross-sections, especially at 80.9 MeV and higher whereas the pre-compound model predicts a gradual decline in cross-sections with increasing energy but maintains non-zero values even at high energies. The correlation of the theoretical & experimental excitation functions is strong and positive with the values of R = 0.8007 for compound nucleus & R = 0.9257 for pre-equilibrium. The pre-compound model provides a better approximation at higher energies (above 70 MeV), while the compound model offers more realistic predictions at lower-to-medium energies. Both models, however, fail to fully capture the experimental trends.

Table 3: Measured and calculated cross-section for the reaction $^{125}Te(p,5n)^{121}I$

Proton energy (MeV)	Total cross-section (mb)		
	Expt. data	Theo.compound	Theo.pre-compound
43.8±0.4	46±6	75.82	21.93
48.8±0.3	290±38	522.90	141.60
54.3±0.3	434±56	729.90	198.30
61±0.2	443±58	304.60	141.00
65.2±0.2	236±31	131.70	116.40
70.9±0.5	223±29	39.15	101.10
80.9±0.4	126±16	2.49	85.00
90.8±0.3	96±12	0.14	73.96
100.5±0.2	80±10	0.01	63.79

$$\textit{Exciton number}\ (n) = 3\ \textit{and Level density}(a) = \frac{A_{CN}}{10}$$

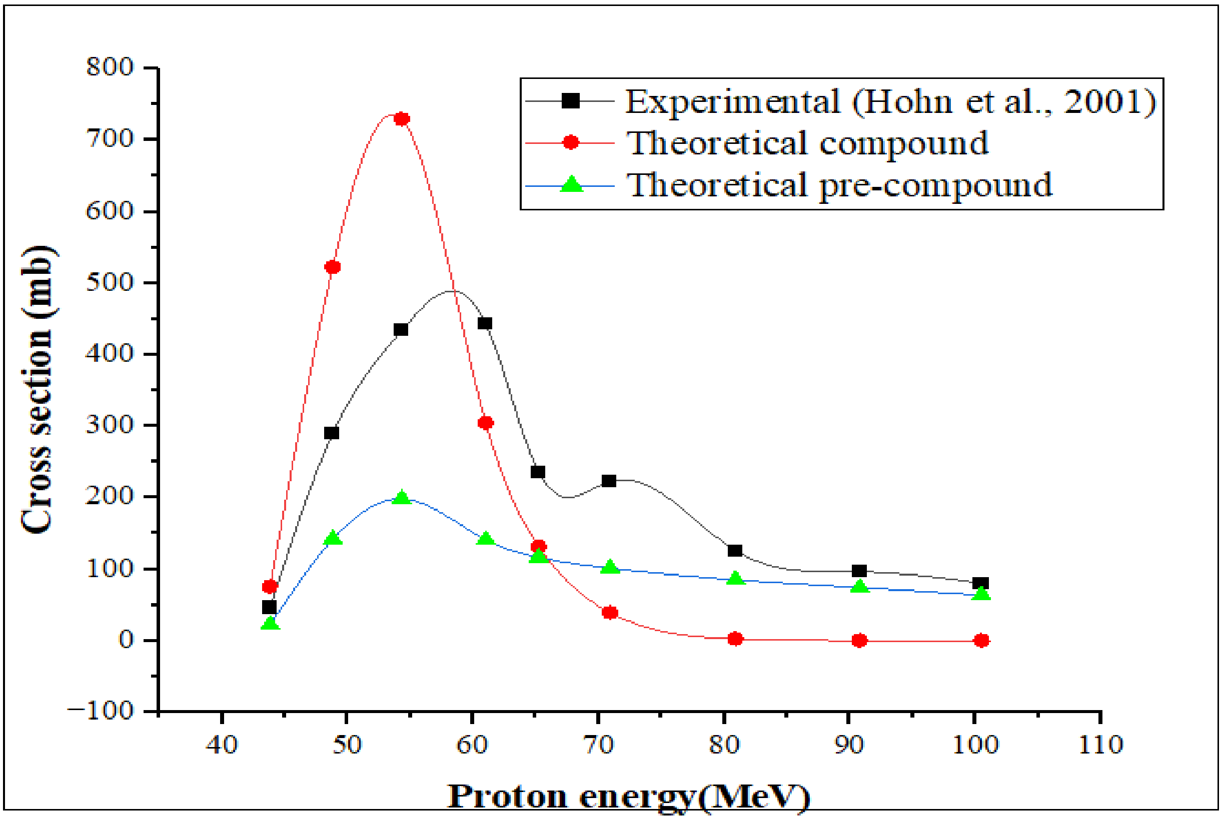

Figure 3: Experimental and theoretical excitation functions for $^{125}Te(p,5n)^{121}I$

3.1.4. Cross-Sections of the $126Te(p,2n)125I$ Reaction

Both models predict increasing cross-sections with energy, with the compound model generally predicting higher values, reach their peak at 17.6 MeV for compound followed by a steady decline and becoming negligible (near zero) at 41.3 MeV and beyond. And at 19.1MeV for pre compound followed by a gradually decreases and maintains meaningful values at higher energies, though the decline is still significant as energy increases respectively. The correlation between the experimental and the theoretical values of nuclear reaction cross-section was positive and strong with a value of R = 0.9564 for compound nucleus & R = 0.9733 for pre-equilibrium. Pre-compound model shows better agreement with the experimental data, particularly at high and medium energies, while the compound model tends to underperform at higher energies.

Table 4: Measured and calculated cross-section for the reaction $^{126}Te\,(p,2n)^{125}I$

Proton energy (MeV)	**Total cross-section (mb)**		
	Expt. data	**Theo.compound**	**Theo.pre-compound**
10.3	1±0.45	67.46	59.47
11.3	238.9±107.51	331.10	288.40
12.2	412.5±185.63	588.60	506.80
13.9	605.4±272.43	784.60	671.60
14.6	778.1±350.15	921.20	785.00
15.8	733.5±330.08	1,019.00	868.00
16.6	956.7±430.52	1,096.00	933.30
17.6	1045.3±470.39	1,159.00	987.50
19.1	888.6±399.87	1,144.00	996.30
20.3	701.7±315.77	959.30	886.30
23.1	671.3±302.09	332.20	521.80
25.9	268.8±120.96	133.30	413.30
28.2	165.2±74.34	30.53	345.80
30.6	203.1±91.40	10.84	316.30
32.7	149±67.05	3.81	295.00
36.1	104.5±47.03	0.51	269.30
38.4	162.8±73.26	0.19	255.40
41.3	92.9±41.81	0.04	235.70
45.4	85±38.25	0.01	213.50
60.8	86.3±38.84	0.00	143.10
70.8	61.4±27.63	0.00	115.40
80.7	57.1±25.70	0.00	90.49
90.5	40±18	0.00	86.05
100	36.1±16.25	0.00	72.75

$$\boldsymbol{Exciton\ number\ (n) = 3\ and\ Level\ density(a) = \frac{A_{CN}}{10}}$$

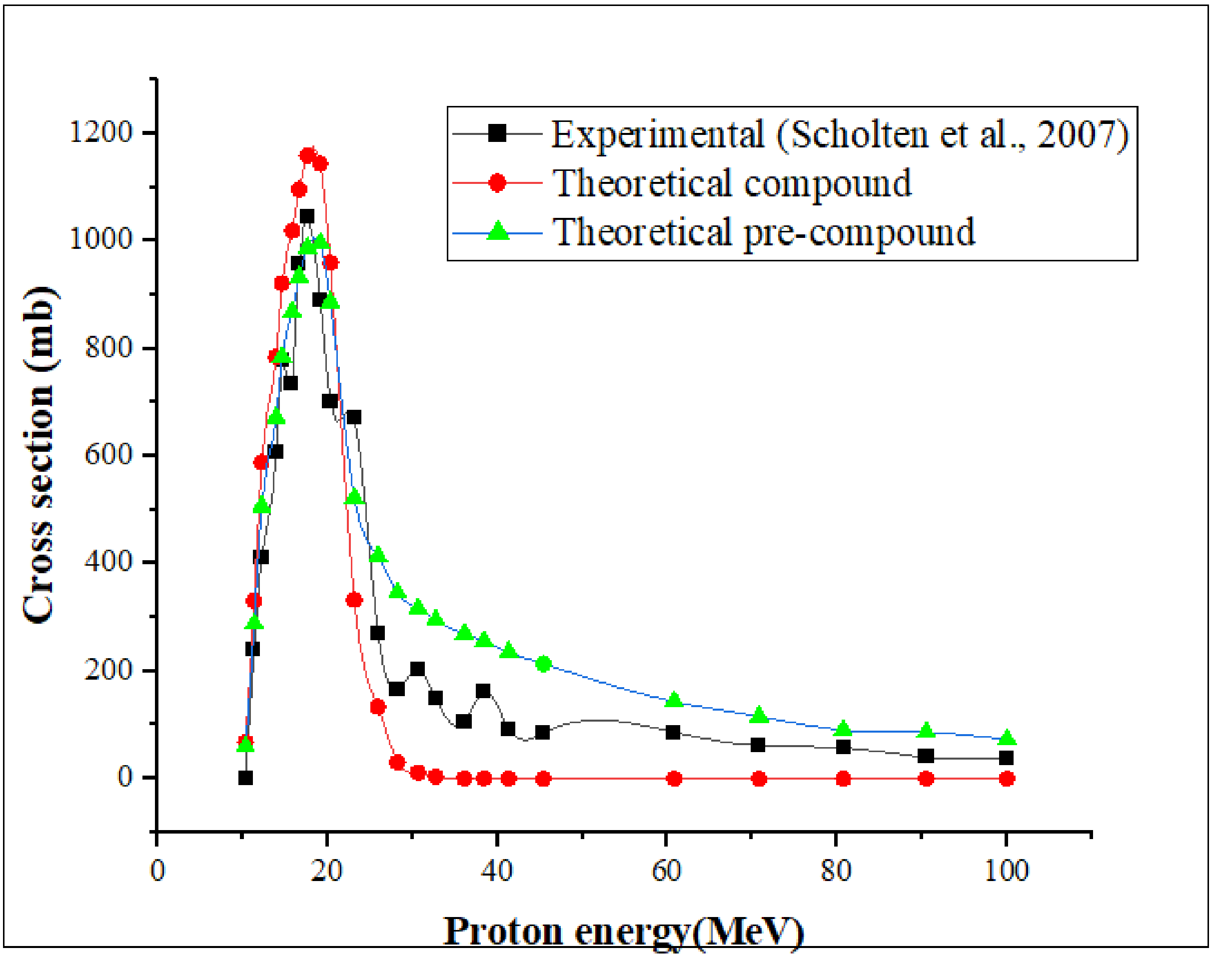

Figure 4: Experimental and theoretical excitation functions for $^{126}Te(p,2n)^{125}I$

3.1.5. Cross-Sections of the $126Te\ (p, 3n)124I$ Reaction

Both model cannot predict the cross section at 17.6 MeV and then shows sharp increase in cross-sections starting from 20.3 MeV, with the compound model predicting higher values than the pre-compound model and reaches their peak at 30.7MeV. After peaking, the compound model predicts a sharper drop and reaches zero at 55.2 MeV onwards in cross-sections compared to the pre-compound model. The correlation between the experimental and the theoretical values of nuclear reaction cross-section was positive and strong with a value of R = 0.8231 for compound nucleus & R = 0.8867 for pre-equilibrium. The pre-compound model provides a better match to experimental data, particularly at medium and high energies, while the compound model becomes less relevant as the energy increases.

Table 5: Measured and calculated cross-section for the reaction $^{126}Te\ (p,3n)^{124}I$

Proton energy (MeV)	Total cross-section (mb)		
	Expt. data	Theo.compound	Theo.pre-compound
17.6	1.6	0.00	0.00
19.1	10.8	12.37	7.92
20.3	16.3	94.94	59.33
23.2	530.1	789.30	465.20
24	457.4	988.20	576.10
25.8	862.8	1,141.00	660.70
28.2	956.7	1,317.00	769.50
30.7	1580.2	1,101.00	686.00
32.6	1176.3	738.00	542.80
36.1	514.7	225.80	350.50
38.4	642.2	109.90	302.20
40.5	424.8	51.24	271.40
41.3	238.9	34.63	260.70
45.3	155.7	6.91	231.60
49.6	158	1.36	210.50
55.2	130.4	0.23	207.20
60.7	100	0.03	187.10
66.2	100	0.00	166.80
70.8	70.2	0.00	154.30
80.7	66.1	0.00	126.20
90.3	57.1	0.00	105.20
99.9	49.2	0.00	90.30
$\text{Exciton number (n)} = 3 \text{ and Level density(a)} = \frac{A_{CN}}{10}$			

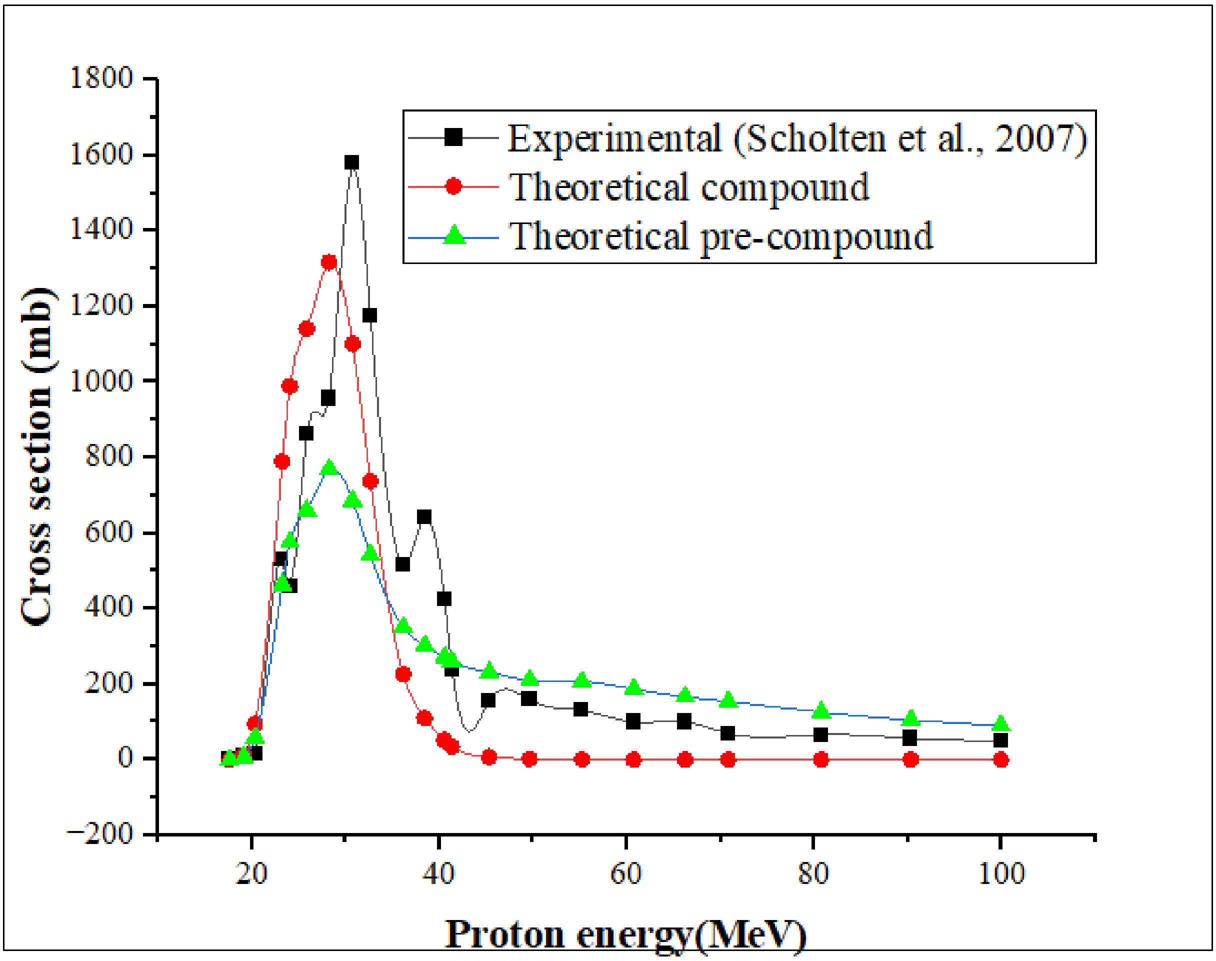

Figure 5: Experimental and theoretical excitation functions for $^{126}Te\ (p,3n)^{124}I$

3.1.6. Cross-Sections of the $126Te\ (p, 4n)\ 123I$ *Reaction*

At 28.3 MeV, both the compound and pre-compound models significantly underestimate the experimental cross-sections. At 36.1 MeV and onwards to their peak, compound model consistently overshoots the experimental values but begins to align more closely as energy increases. Whereas, the pre-compound model underestimates the cross-section but follows the trend closely, reflecting lower reaction probability than the compound model but still responding to changes in the energy level. Above 49.7MeV, both models diverge from experimental data, with the compound model underestimating severely, while the pre-compound model trends closer, particularly at 61.2 MeV, aligning almost exactly, which suggests that pre-compound processes are more relevant at higher energies. The correlation between the experimental and the theoretical values of nuclear reaction cross-section was positive and strong with a value of R = 0.8777 for compound nucleus & R = 0.9356 for pre-equilibrium.

Table 6: Measured and calculated cross-section for the reaction ^{126}Te (p,4n)^{123}I

Proton energy (MeV)	Total cross-section (mb)		
	Expt. data	**Theo.compound**	**Theo.pre-compound**
28.3	5.5	0.6795	0.3061
36.1	464.2	927.7	361.8
40.3	671.3	1137	452.6
41.4	755.4	1075	439
44.6	661.5	735.1	354.7
45.4	681.3	611.3	323.7
49.7	492.4	237.9	229.6
55.2	272.8	40.84	173.5
61.2	149	5.695	150.6
66.2	121.2	1.058	138.7
70.8	82.5	0.2694	130

$$\textit{Exciton number } (n) = 3 \textit{ and Level density}(a) = \frac{A_{CN}}{10}$$

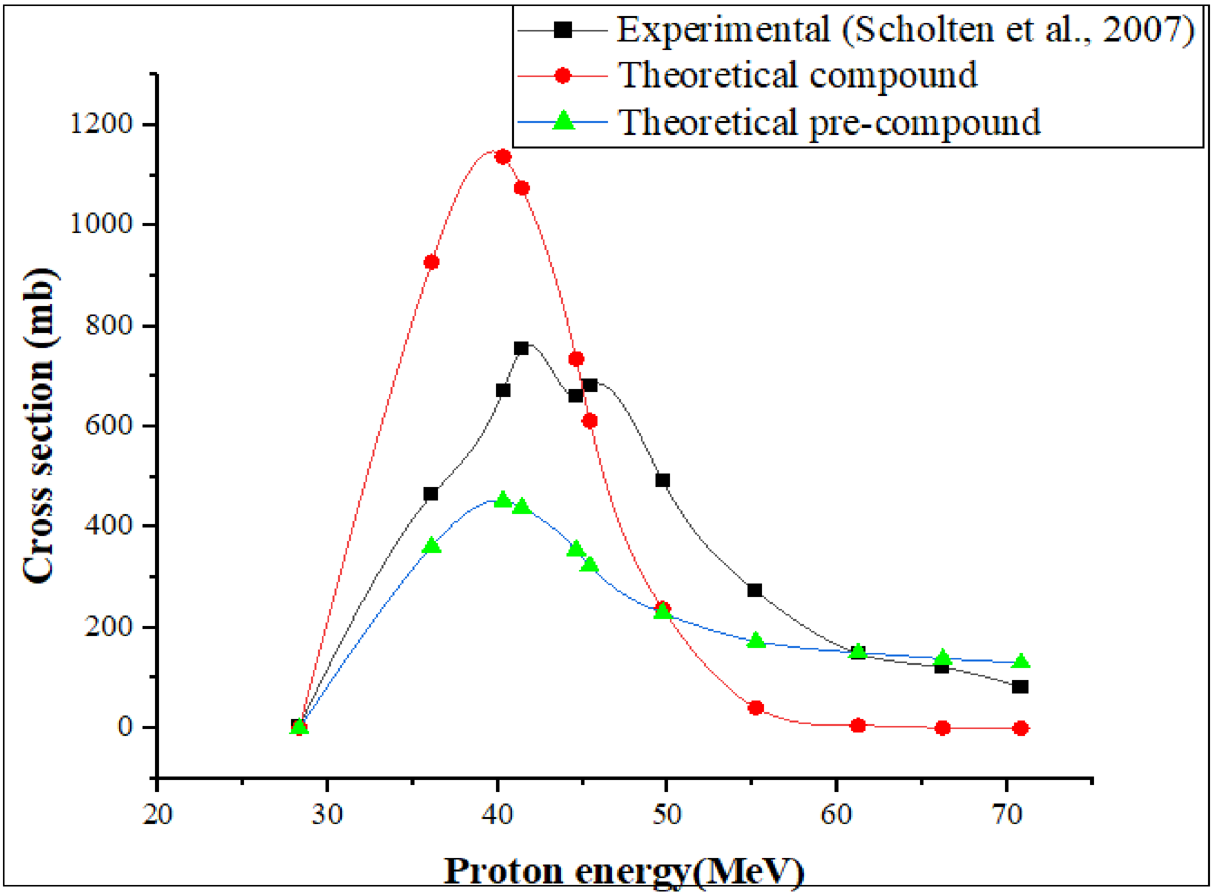

Figure 6: Experimental and theoretical excitation functions for ^{126}Te (p,4n)^{123}I

4. Conclusion

In this work, proton induced reactions on Tellurium isotopes 125Te and 126Te at intermediate energies (10-100MeV) were studied. The excitation functions for the six reactions channels $^{125}Te(p,xn)^{124,123,121}I$, x=2,3,5 and $^{126}Te(p,xn)^{125,124,123}I$, x=2-4 were studied using the computer code COMPLET in the specified energy ranges for both compound and pre compound reaction models. Theoretical values derived from model calculations with the code COMPLET have nearly good agreement and strongly correlated with the experimental values collected from the EXFOR data set, IAEA. With increasing energy, the likelihood of compound nuclear reaction cross-sections declines whereas pre-equilibrium nuclear reaction cross-sections show an apparent rise in compatibility with the experimental results. This suggests that the pre-equilibrium reaction is dominant at higher projectile energy and the compound nucleus reaction is more prominent at lower energies.

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6.Conflicts of Interest

The authors declare no conflicts of interest.

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